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A two-phase decision making based on the grey analytic hierarchy process for evaluating the issue of park-and-ride facility location

Jairo Ortega[a,*], Sarbast Moslem[b], János Tóth[a], Martin Ortega[c]

[a] Department of Transport Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, 1111 Budapest, Hungary
[b] School of Architecture, Planning and Environmental Policy, University College Dublin, D04 V1W8 Dublin, Ireland
[c] Departamento de Eléctrica, Electrónica y Telecomunicaciones, Universidad de Cuenca, 010107 Cuenca, Ecuador

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ABSTRACT

Planning a Park-and-Ride (P&R) system in an urban area of a city depends on a group of transportation planning professionals with different areas of expertise in mobility, agreeing on which criteria or set of criteria are the most important. In addition to analysing the criteria established as mobility policies in the Sustainable Urban Mobility Plan (SUMP), when establishing a set of facilities belonging to the P&R system. To find out which criterion is the most important one when combining the mobility criteria established in the SUMP with the criteria of transportation planners with different expertise, this paper applies the multi-criteria method known as the Grey Analytic Hierarchy Process (G-AHP). In this method, at first the main and secondary criteria are determined at two levels that allow building a hierarchical structure, then transportation professionals are surveyed, and finally, the formulation of the multi-criteria method is designed. The result of the study illustrates the effectiveness and usefulness of the proposed multi-criteria method to determine the hierarchy of criteria from most to least important to solve the problem of locating a P&R system. Also, the results are compared with two different multicriteria methods (FAHP and BWM) to see how they are alike and how they are different. The finding suggests that the planning of a P&R system and the criterion for the accessibility of public transport go hand in hand, regardless of the multi-criteria method employed.

1. Introduction

From the perspective of an urban environment, a city's P&R system comprises a set of facilities that are distributed throughout the city and are designed with the main objective of facilitating modal interchange between private vehicles and public transport. Consequently, their location is related to a set of specific parameters associated with public transport, and with parameters related to private vehicles. In order to explicitly evaluate multiple conflicting criteria in decision-making between the two modes of transport that are combined in the P&R system, multi-criteria methods have been developed.

The criteria for establishing a P&R system may vary depending on the mobility policies that a city has established in its Sustainable Urban Mobility Plan (SUMP). For example, a city establishes a mobility policy to reduce traffic in the city center and establishes a P&R system as an action that helps fulfill the mobility policy. On the other hand, a city that has a mobility policy that aims to reduce car dependency in the daily commute of its citizens: it employs the P&R system as a modal interchange point to increase the number of public transport users. In addition to the set of criteria of the city's mobility policy, the background of the transport planner must be taken into account. For example, a planner whose specialty is infrastructure will set the parking structure as the main criterion for establishing P&R. A planner whose specialty is the environment would set the reduction of pollutant gases as the main criterion for implementing the P&R system.

While it is clear that studies on the location of P&R systems focus mainly on mathematical models, there is uncertainty about how to combine the mobility policies established by the city in the SUMP and the approach established by the transportation planner to implement a P&R system (Fan et al., 2014; Mock & Thill, 2015). However, the application of multi-criteria techniques that rank the order of relevance is the method that can assist in determining which criteria are the most pertinent ones for determining the place of a P&R system(X. Chen et al., 2018).

Several multi-criteria approaches have already been used to conduct studies on transportation. However, no multi-criteria studies have been developed in which the mobility policies established in the SUMP concerning parking and also the planner's specialization are involved in

* Corresponding author.
E-mail address: jortegaortega@edu.bme.hu (J. Ortega).

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order to tip the balance toward a certain mobility policy. Therefore, this article develops a survey of transportation planners with different specializations based on the mobility policies on parking established in the SUMP and applying the multicriteria method known as Grey-AHP to determine which criterion is the most important one on a two-level scale to establish a P&R system.

In the light of previous research in the field of P&R location using multi-criteria methods, this study proposes as a scientific contribution a two-level scale approach using the analytical hierarchy process to prioritize the criteria based on the opinions of transportation experts and the parking mobility policies established in the SUMP. The second contribution is through the construction and development of the G-AHP formulation to determine which criteria are the most important to take into account when establishing a P&R system.

This paper is structured as follows. In the second section, the research on P&R and multicriteria methods in the literature is discussed. System criteria for the location of a P&R system are described in Section 3. The hierarchy structure of P&R facilities location is constructed in Section 4. The survey and how it is applied are described in Section 5. Grey Analytic Hierarchy Process is described in detail together with its formulation as part of Section 6. The results according to the formulation and the established criteria are presented in Section 7. A discussion of the results obtained is presented in Section 8. Finally, the conclusion shows the findings and future studies to be carried out.

2. Literature review

This section provides an overview of the various studies conducted on the P&R system's location and evolution over time. Furthermore, a sub-section describes the multi-criteria analyses performed on the P&R system.

2.1. Location of P&R

Depending on the type of city they serve, P&R systems may be placed in the urban centre or urban periphery of a metropolis (Molan & Simicevice, 2018). As a point of exchange between public transportation and private vehicles, their location is likely near public transportation stations (Norlida et al., 2007). On the other side, this would demand a P&R station at every public transportation terminus. Throughout the inquiry, numerous possibilities regarding the location of a P&R system have been proposed. In other words, city-specific criteria and parameters have been taken into account (Cherrington et al., 2017). The P&R system is dependent not only on the quantity and location of public transportation stations but also on the willingness of prospective users to utilise the system (Song et al., 2017). This suggests that a user whose residence is closer to the P&R system is a likely candidate to use the P&R system (Liu et al., 2018).

P&R systems are critical components of a potential user's journey from their house to the downtown area. Because the user or likely user chooses to utilise the system on a regular schedule for work or business purposes, the decision of the plan depends on various aspects.

In this regard, it has been discovered that the decision factors vary according to the distance travelled and the amount of time it takes to reach the P&R system (Islam et al., 2015; Lam et al., 2001). To put it another way, the position of the P&R system is the decisive factor in determining whether or not the user will make use of it (Z. Chen et al., 2014).

As it is generally accepted that the physical location of the P&R system is one of the factors that play a role in determining whether or not a potential P&R user will use the system, the authors examine which criteria ought to be taken into account, bearing in mind the perspectives of the transportation planner as well as the researcher. In this context, the issue has been complicated by employing intrinsically advanced methodology and approaches by planners and researchers (X. Chen et al., 2021; Kepaptsoglou et al., 2010; Sharma et al., 2019). For instance, using geospatial software is a way that is extensively utilised to determine the ideal site for a P&R system (Faghri et al., 2002). These types of investigations might include additional criteria like the amount of time it will take for the P&R user to go from their starting point to the P&R system, or the amount of time it will take for them to get from the P&R system to their final destination using public transportation (Farhan & Murray, 2005). Several studies (Farooq et al., 2018a, 2018b, 2021) have utilised Geographic Information Systems (GIS) and multi-criteria methods, such as the Analytical Hierarchical Process (AHP), to determine the optimal mode of transportation. There have been six modes of transport investigated. The GIS and multi-criteria analysis suggest that the construction of a new high-speed rail line is the best option.

The journey time is a cost function in an analysis that places many P&Rs in various locations across a city (Carlson & Owen, 2019; Pang & Khani, 2018). In other words, the P&R system was assessed based on its cost. The fact that the P&R system initially requires the use of a private vehicle before transferring to the P&R system and arriving at the destination by public transportation must be considered. In addition to the cost linked with the use of public transport, there are fees related to the use of private vehicles and the P&R system (Islam et al., 2015; Liao et al., 2012). Understanding that the location of the P&R system can either increase or decrease the cost of its utilisation necessitates a cost-based examination of the location. Consequently, the potential customer will choose the alternative that does not only result in the shortest length of time but also imposes a minor financial burden.

The placement of a P&R system can be calculated more precisely by incorporating additional criteria, such as travel time. In addition, research methodologies have gotten progressively more complex. The multi-objective spatial optimizations include three criteria for the location of the P&R system (Macioszek & Kurek, 2021): (i) covering as much potential demand as possible, (ii) situating P&R facilities as close to essential roadways as possible, and (iii) situating such facilities within the context of an existing system are the criteria above. It is a necessity that the demand for the P&R system is modelled as a function of both distance and coverage (Holguı´n-Veras et al., 2012; Syed Adnan & Kadar Hamsa, 2013). Consequently, a discrete linear model for the location of P&R facilities shows the adaptability and usefulness of the modelling technique developed to address a more extensive range of planning challenges. This model encompasses a broader scope of planning challenges (Wang & Du, 2013). It is also possible to use mode choice as a function of P&R usage rates to maximise benefits and reduce societal costs. The number of P&R facilities in a city has been determined by utilising linear models (Aros-Vera et al., 2013; Cavadas & Antunes, 2019; Yang & Wang, 2002). This study aims to establish the model's criteria that most closely represent reality.

A formulation of mixed linear programming is used to determine the optimal location of a predetermined number of P&R facilities to maximise their use and yield the highest benefit (Lam et al., 2007; Tsang et al., 2005; Zhao et al., 2017). A statistical method can be used to determine which P&R system facility is the most utilised, and GIS and mathematical methods need to be employed to determine where the P&R system facilities are located (Fan, 2012; Liu & Meng, 2014; Pineda et al., 2016). Passengers choose to conclude their journeys in either automobile mode or P&R mode, depending on their preference. According to the findings, factors such as the frequency of subway travels, the degree of parking capacity usage, and fees substantially impact the reliability of P&R facilities. Due to their location, it is quite probable that P&R facilities will contribute to the problem of traffic congestion (Memon et al., 2014; Parkhurst, 2000). This is because the number of automobiles that would generally circulate through the city centre is decreased by parking these vehicles in a P&R facility. Depending on the number of variables considered, the process of choosing where P&R facilities should be positioned in the urban context of a city might become increasingly complex. Demand, connection, transit design, and economic viability are some of these requirements. As previously stated, the placement of P&R systems is studied utilising a vast array of methods (mathematical models and software) and approaches (statistics) (García & Marín, 2002; Islam et al., 2015; Lu & Guo, 2015).

2.2. Multi-criteria methods applied to the P&R system

For the purpose of determining the opinion of a group of experts regarding the location of the P&R system, investigations employing multi-criteria methods with multiple primary criteria and multiple secondary criteria have been conducted. Experts analyzed the criteria to be considered when determining the location of the P&R system in the light of the findings of these investigations. There are a handful of studies worth additional examination, which are given below.

The concept of symmetry is crucial to multi-criteria decision support (MCDA) due to the fundamental characteristics of binary relationships utilised to reflect decision-makers' preferences. The study aims to evaluate the P&R system location issue from an expert's perspective, the well-known Analytic Hierarchy Process (AHP) was implemented in a fuzzy environment, where fuzzy sets can manage vague notions (Yaliniz et al., 2022). That study's primary criterion was public transportation accessibility. Comparable research employs the same criteria set but uses the Best Worst multi-criteria method (BWM). This methodology requires fewer comparisons than the traditional AHP method. This is the primary reason why the AHP-BWM model was adopted. The main criterion remained public transportation accessibility. The same set of criteria was then applied to a specific case study utilising the multi-criteria technique using only the BWM, which resulted in the accessibility of public transport as the main criterion for establishing a P&R system (Ortega, et al., 2020).

There are few multi-criteria studies that apply two-phase decision making to the P&R system location problem; thus, our research, which employs the Grey-AHP multi-criteria method, makes a significant contribution to filling this gap in the literature.

The primary and secondary criteria for locating a P&R system are defined as part of the mobility policies that a city has established in its SUMP. In addition to the transportation planners' own criteria and area of expertise. These criteria for evaluating P&R facilities have not been formulated utilising the multi-criteria technique known as the Grey-AHP.

The primary criteria and previously defined sub-criteria are described in this article. The adaptation of these criteria to the Saaty scale is described, as this scale implies a link between a linguistic interpretation and a numerical scale of expert surveys conducted for the application of the multicriteria technique. Furthermore, the Grey-AHP for determining the location of the P&R is explained.

Table 1
Main criteria for establishing a P&R system.

Criterion	Explanation
C1	Distance
C2	Traffic conditions on the route (origin-destination)
C3	Accessibility of public transport.
C4	Transport aspects.
C5	Economic
C6	Environmental

3. Criterion system for locating a P&R system

Based on previous research on multi-criteria methodologies for P&R siting, the researchers have established six main criteria and 19 secondary sub-criteria (Ortega, et al., 2020).

Table 1 presents the six main criteria and their corresponding definitions. These main criteria are numbered from C1 to C6. Some of them are part of the mobility policies established in the SUMP and other criteria are part of what transportation experts consider important and fundamental when establishing a P&R system.

Table 2 shows the sub-criteria. The primary criteria are numbered from one to six (C1 to C6). The sub-criteria carry the preceding code of the criterion to which they belong: C2 is the fundamental criterion, and its sub-criteria are listed in the following order C2.1 and C2.2.

Fig. 1 shows a clear overview of how the main and secondary criteria for establishing a P&R system should be chosen from the mobility policies of the Mobility Plan and from the expertise of the transportation planner.

4. The hierarchy structure of P&R facilities location

In order to use AHP, we should first understand the system's hierarchy structure, which serves as the basis for planning and rating the variables that can be used or considered in determining the location of P&R system facilities. The technique is established by the hierarchical structure of the criteria, in which the criteria of the same category are arranged according to their configuration in the decision criteria tree. Fig. 2 displays the coding for each key criterion comprising the first level. Additionally, the sub-criteria that correspond to level 2 of the scale are depicted. Fig. 1 is a graphical representation of the P&R system's operation, or the journey from origin to destination. Fig. 2 depicts a two-step decision-making process without requiring a graphical explanation of the operation of the P&R system, thereby facilitating the explanation of the formulation of the Grey-AHP (Fig. 3)

Table 2
Sub-criteria for establishing a P&R system.

Sub-criterion	Explanation
C 1.1	Distance from the zones to the P&R system.
C 1.2	Distance from the P&R to the CBD.
C 2.1	Time of travel by private car.
C 2.2	Time of travel by public transport.
C 2.3	Time of travel by P&R system.
C 3.1	Frequency of public transport operations.
C 3.2	Transfer time from P&R to public transport stop.
C 3.3	The distance of the P&R from the nearest public transport stop.
C 4.1	Reduction of trips by private car in CBD.
C 4.2	Increase of demand by public transport in CBD.
C 4.3	Number of public transport connections available.
C 4.4	Demand for parking at a P&R system.
C 5.1	Cost of implementation for the project.
C 5.2	Cost of land use.
C 5.3	Cost of the implementation of the telecommunication infrastructure.
C 5.4	Total cost of investment maintenance.
C 6.1	CO_2 reduction.
C 6.2	Noise reduction.
C 6.3	Area occupied by existing green areas.

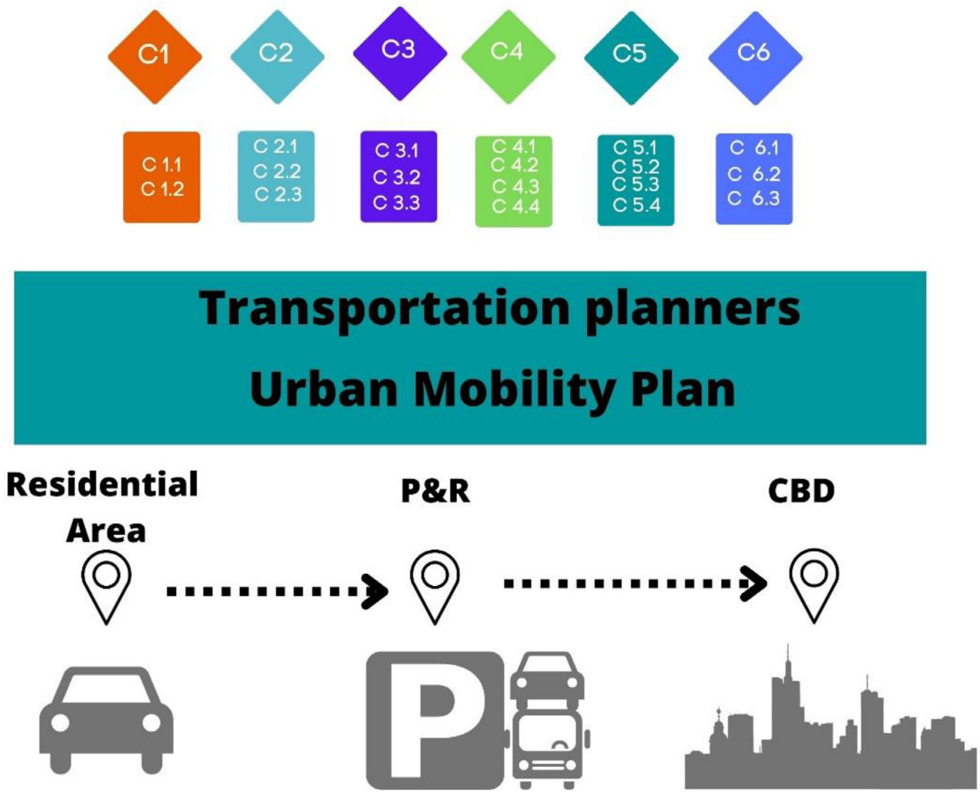

Fig. 1. Criteria related to the planning of a P&R system.

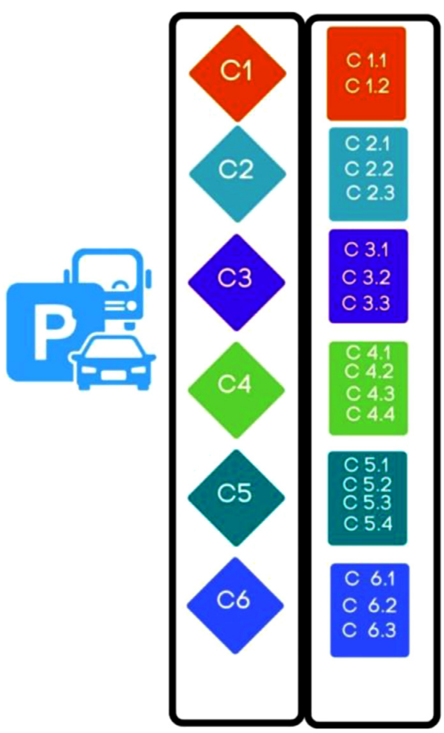

Fig. 2. Criteria related to P&R facilities location.

5. Survey

Using the established criteria and sub-criteria, questionnaires were developed to determine the most important criteria for adopting a set of facilities within a P&R system. The survey has 6 main questions that represent the criteria for level one on the multi-criteria method scale. The questionnaire also has 19 questions that represent the sub-criteria for level two.

Table 3
Linguistic scales and the Grey numbers utilized for the pairwise comparisons of G-AHP.

Importance value	Linguistic scale	Grey number
1	Equally Important	[1,2]
3	Weakly Important	[2,4]
5	Important	[4,6]
7	Strongly Important	[6,8]
9	Absolutely Important	[8,10]

As shown in Table 3, the responses are arranged on a linguistic scale. This enables the comparison of the principal criteria at both the first and second levels. Lastly, the adoption of this linguistic scale makes it possible to convert it into a numerical scale that can be utilised in the proposed multicriteria method.

Ten experts employed by the Cuenca Municipality were asked to participate in the survey. The experts are transportation planning specialists with diverse backgrounds in mobility-related fields.

The survey, which was conducted digitally in May 2022, took between 25 and 30 minutes to complete for each expert. The experts were chosen from the Municipality of Cuenca because the SUMP was developed by the Municipality of Cuenca and one of its transportation policies includes the development of P&R in the city's urban environment.

5.1. Case study

Cuenca, a city in southern Ecuador with a population of 659 317, carried out a Sustainable Urban Mobility Plan (SUMP) study in 2015. This investigation focused on the urban area of the city. It was designed to create a more sustainable city for its residents through a set of transport policies and provide solutions to mitigate the negative effects of private

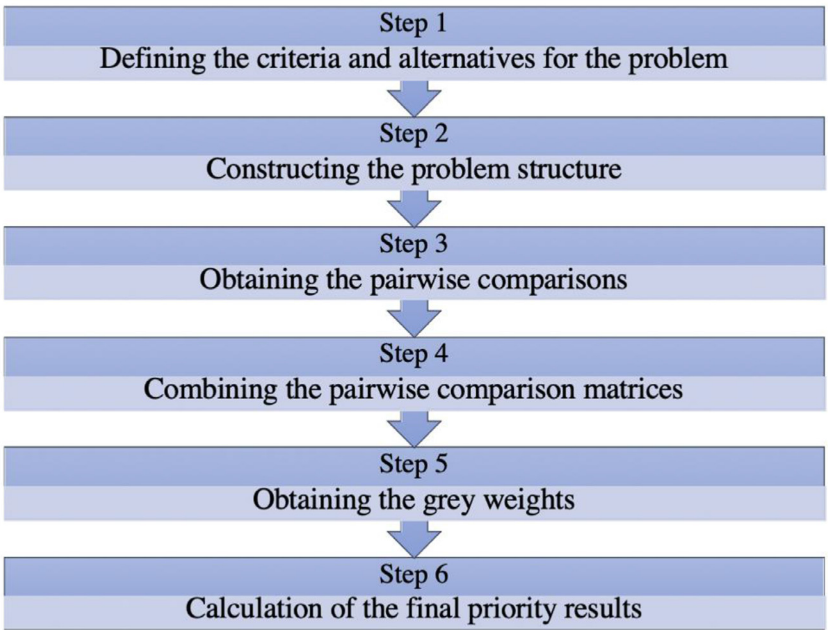

Fig. 3. Process for applying the multi-criteria method.

vehicles, such as traffic congestion and air pollution, particularly in the city centre. The SUMP divides the city into fifteen zones, or districts. There are 474 buses available, and one-way fares are $0.35 USD. There are 3,557 taxis in the metropolitan area. Additionally, a tram system exists.

6. Grey analytic hierarchy process

The adopted Grey Analytic Hierarchy Process (Grey-AHP) stems from the studies of Çelikbilek (Moslem & Çelikbilek, 2020), and it is applied to estimate P&R facility locations. The basis of the conventional AHP methodology was firstly introduced by Saaty (Saaty, 1977). The proposed evaluation model is basically a combination of Grey theory and the classic version of the AHP approach.

The proposed Grey AHP model steps for the evaluation of P&R facility location are given in detail below.

Step 1*: Defining the Aim and the factors:* Solutions of all AHP problems start with defining the aim, and then defining the factors and the alternatives related to the aim to construct the hierarchy tree.

Step 2*: Constructing the Hierarchical Structure:* The hierarchical structure of the problem is constructed by using the aim, alternatives and factors of the problem. In this problem, there are only factors related to the aim. So, the hierarchical structure has two levels.

Step 3*: Pairwise Comparisons:* Factors of the aim are compared pairwise in this step, as in classic AHP. However, linguistic scales given in the following table are used instead of the crisp scales in classic AHP.

As an example, the pairwise comparison is given in Eq. (1). $\otimes X^e_{ij},= [\underline{X^e_{ij}}, \overline{X^e_{ij}}]$ represents the pairwise comparison of the *i*th criterion and *j*th criterion done by expert e. The main diagonals of the pairwise comparisons are filled with [1, 1] given in Eq. (2), and the upper parts of the main diagonals are filled by using the opposite forms to multiplication operation of the pairwise comparisons at the lower parts of the main diagonals given in Eq. (3).

$$D^e = \begin{bmatrix} \otimes X^e_{11} & \otimes X^e_{12} & \dots \otimes X^e_{1j} & \dots & \otimes X^e_{1n} \\ \otimes X^e_{21} & \otimes X^e_{22} & \dots \otimes X^e_{2j} & \dots & \otimes X^e_{2n} \\ \vdots & \vdots & \ddots \;\; \vdots & \ddots & \vdots \\ \otimes X^e_{i1} & \otimes X^e_{i2} & \dots \otimes X^e_{ij} & \dots & \otimes X^e_{in} \\ \vdots & \vdots & \ddots \;\; \vdots & \ddots & \vdots \\ \otimes X^e_{n1} & \otimes X^e_{n2} & \dots \otimes X^e_{nj} & \dots & \otimes X^e_{nn} \end{bmatrix} \tag{1}$$

$$\otimes X^e_{ij} = \left[\frac{1}{\overline{X^e_{ij}}}, \frac{1}{\underline{X^e_{ij}}} \right] \tag{2}$$

$$\otimes X^e_{ii} = [1, 1] \tag{3}$$

Step 4*: Combining the Pairwise Comparison Matrices of the Experts:* All of the pairwise comparisons of the expert opinions are combined by using the Eq. (4), which is geometric mean formulation like the classic AHP.

$$\otimes a_{ij} = \sqrt[D]{\prod_{d=1}^{D} \otimes a^d_{ij}} \tag{4}$$

The difference is that the geometric means are calculated for the upper parts and the lower parts separately. After the combination of the pairwise comparison of the experts, the main pairwise comparison matrix D given in Eq. (5) is obtained.

$$D = \begin{bmatrix} \otimes X_{11} & \otimes X_{12} & \dots \otimes X_{1j} & \dots & \otimes X_{1n} \\ \otimes X_{21} & \otimes X_{22} & \dots \otimes X_{2j} & \dots & \otimes X_{2n} \\ \vdots & \vdots & \ddots \;\; \vdots & \ddots & \vdots \\ \otimes X_{i1} & \otimes X_{i2} & \dots \otimes X_{ij} & \dots & \otimes X_{in} \\ \vdots & \vdots & \ddots \;\; \vdots & \ddots & \vdots \\ \otimes X_{n1} & \otimes X_{n2} & \dots \otimes X_{nj} & \dots & \otimes X_{nn} \end{bmatrix} \tag{5}$$

Step 5*: Normalization of the Pairwise Comparison Matrix:* The normalization of the pairwise comparison matrix is calculated by using the Eqs. (6–7) to obtain the normalized pairwise comparison matrix given in Eq. (8).

$$\underline{X^*_{ij}} = \left[\frac{2\underline{X_{ij}}}{\sum_{i=1}^{n} \underline{X_{ij}} + \sum_{i=1}^{n} \overline{X_{ij}}} \right] \tag{6}$$

$$\overline{X^*_{ij}} = \left[\frac{2\overline{X^*_{ij}}}{\sum_{i=1}^{n} \underline{X_{ij}} + \sum_{i=1}^{n} \overline{X_{ij}}} \right] \tag{7}$$

$$D^* = \begin{bmatrix} \otimes X^*_{11} & \otimes X^*_{12} & \dots \otimes X^e_{1j} & \dots & \otimes X^*_{1n} \\ \otimes X^*_{21} & \otimes X^*_{22} & \dots \otimes X^*_{2j} & \dots & \otimes X^*_{2n} \\ \vdots & \vdots & \ddots \;\; \vdots & \ddots & \vdots \\ \otimes X^*_{i1} & \otimes X^*_{i2} & \dots \otimes X^*_{ij} & \dots & \otimes X^*_{in} \\ \vdots & \vdots & \vdots \;\; \vdots & \ddots & \vdots \\ \otimes X^*_{n1} & \otimes X^*_{n2} & \dots \otimes X^*_{nj} & \dots & \otimes X^*_{nn} \end{bmatrix} \tag{8}$$

Table 4
Final aggregated Grey comparison matrix (6 × 6) for the main criteria in level 1.

	C1		C2		C3		C4		C5		C6		Final weight
C1	1	1	0.9347	1.7818	0.2554	0.3969	0.3865	0.6300	0.9635	1.4678	0.2435	0.3709	0.0924
C2	0.5612	1.0699	1	1	0.4263	0.6300	0.3550	0.5612	0.4472	0.6538	0.4472	0.6538	0.0917
C3	2.5198	3.9149	1.5874	2.3459	1	1	1.7508	2.6153	2.8845	4.6600	2.8845	4.6600	0.3394
C4	1.5874	2.5873	1.7818	2.8173	0.3824	0.5712	1	1	2.0396	3.5636	0.4292	0.7418	0.1731
C5	0.6813	1.0379	1.5294	2.2361	0.2146	0.3467	0.2806	0.4903	1	1	0.2527	0.3891	0.0904
C6	2.6960	4.1071	1.5294	2.2361	0.2146	0.3467	1.3480	2.3300	2.5698	3.9572	1	1	0.2129

Table 5
Final aggregated Grey comparison matrix (4 × 4) for the sub-criteria in level 2. (Transport aspects branch).

	C4.1		C4.2		C4.3		C4.4		Final weight
C4.1	1	1	0.3305	0.5503	1.0000	1.5874	3.8127	5.9876	0.2849
C4.2	1.8171	3.0262	1	1	1.3480	2.1777	2.6960	3.9572	0.4127
C4.3	0.6300	1.0000	0.4592	0.7418	1	1	1.2599	1.9064	0.1992
C4.4	0.1670	0.2623	0.2527	0.3709	0.5246	0.7937	1	1	0.1033

Table 6
Final aggregated Grey comparison matrix (4 × 4) for the sub-criteria in level 2. (Economic branch).

	C5.1		C5.2		C5.3		C5.4		Final weight
C5.1	1	1	0.6310	1.1487	1.5157	2.7595	0.5957	0.9221	0.2680
C5.2	0.8706	1.5849	1	1	1.0592	1.8882	1.4310	2.2974	0.3116
C5.3	0.3624	0.6598	0.5296	0.9441	1	1	1.2457	2.0000	0.2135
C5.4	1.0845	1.6788	0.4353	0.6988	0.5000	0.8027	1	1	0.2068

Table 7
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Traffic conditions on the route (origin-destination) branch).

	C2.1		C2.2		C2.3		Final weight
C2.1	1	1	0.2184	0.3467	0.2184	0.3467	0.1211
C2.2	2.8845	4.5789	1	1	0.6300	0.9347	0.4009
C2.3	2.8845	4.5789	1.0699	1.5874	1	1	0.4780

Table 8
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Accessibility of public transport branch).

	C3.1		C3.2		C3.3		Final weight
C3.1	1	1	4.3379	6.4907	2.4915	3.9487	0.6524
C3.2	0.1541	0.2305	1	1	0.3222	0.5000	0.1089
C3.3	0.2532	0.4014	2.0000	3.1037	1	1	0.2386

Step 6: *Computing the Relative Weights:* The relative weights are computed by using the normalized pairwise comparison matrix and Eq. (9). The obtained relative weights are also with Grey numbers.

$$W_i = \frac{1}{n}\sum_{i=1}^{n}\left[\underline{X_{ij}^{*}},\ \overline{X_{ij}^{*}}\right] \tag{9}$$

Step 7*: Ranking of the factors:* The relative weights used as final weights in this study are ranked from the highest to the lowest. The most important is the one that has the highest weight, and the less important factor is the one that has the lowest weight.

7. Results

The scores obtained from raters were calculated using the Grey-AHP method. It was necessary to construct Grey-AHP pairwise comparisons for all attributes of the decision structure, as shown in Tables (Tables 4–11), in which the scores of all respondents are summed. These tables are displayed below.

According to the data shown in the Tables, the Grey weight scores for every criterion at every level reflected the possible scenarios as minimum and maximum values. Scores at Level 1 were displayed as numeric values between 0 and 1, denoting a decreased degree of significance for one criterion relative to another, and so on.

In our study, “Accessibility of public transport” (C3) is the main criterion, while "Distance" (C1), "Traffic conditions on the route (origin-destination)" (C2) and "Economic" (C5) are the secondary criteria.

The AHP technique’s each-vector method can be used to complete the necessary calculation to determine local scores. Researchers were able to decide on the significance of each component in the decision structure by calculating the eigenvector scores and weight scores, respectively. In this particular instance, the planners’ scores represented the impact of public transportation. A higher score on the criterion indicated a greater level of significance. The score ranking highlighted the importance of public transport and its connection to the P&R system. This is a significant concept to help transportation planners implement the P&R system and improve public transportation service.

Table 4 shows in the first level which criterion is the most important, which proved to be C3 (0.3394) followed by C6 (0.2129). However, the criterion with the lowest weight is C5 (0.0904). Table 5 shows criterion C4 at the second level with its respective sub-criteria. Thus, the most important is sub-criterion C4.2 (0.4127). However, the lowest is criterion C4.4 (0.1033). Table 6 represents criterion C5 at the second level

Table 9
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Environmental branch).

	C6.1		C6.2		C6.3		Final weight
C6.1	1	1	3.0262	4.7524	2.8619	4.5359	0.6480
C6.2	0.2104	0.3305	1	1	0.8409	1.4142	0.1796
C6.3	0.2205	0.3494	0.7071	1.1892	1	1	0.1724

Table 10
The weight scores for park and ride facilities main criteria in level 1.

Criteria	Weight	Rank
C1	0.0924	4
C2	0.0917	5
C3	0.3394	1
C4	0.1731	3
C5	0.0904	6
C6	0.2129	2

Table 11
The weight scores for park and ride facilities sub-criteria in level 2.

Main criteria	Sub-criteria	Local weight	Rank	Global weight	Rank
C1	C1.1	0.8294	1	0.0767	4
	C1.2	0.1706	2	0.0158	18
C2	C2.1	0.1211	3	0.0111	19
	C2.2	0.4009	2	0.0368	10
	C2.3	0.4780	1	0.0438	7
C3	C3.1	0.6524	1	0.2215	1
	C3.2	0.1089	3	0.0370	9
	C3.3	0.2386	2	0.0810	3
C4	C4.1	0.2849	2	0.0493	6
	C4.2	0.4127	1	0.0714	5
	C4.3	0.1992	3	0.0345	12
	C4.4	0.1033	4	0.0179	17
C5	C5.1	0.2680	2	0.0242	14
	C5.2	0.3116	1	0.0282	13
	C5.3	0.2135	3	0.0193	15
	C5.4	0.2068	4	0.0187	16
C6	C6.1	0.6480	1	0.1380	2
	C6.2	0.1796	2	0.0382	8
	C6.3	0.1724	3	0.0367	11

in which the highest criterion is C5.2 (0.3116), and the lowest is C5.4 (0.2068).

Table 7 shows criterion C2 and its respective sub-criteria at level 2. The highest criterion with the highest weight is C2.3 (0.4780), and the criterion with the lowest weight is C3.2 (0.1089). Table 8 shows criterion C3 and its sub-criteria at level 2, in which the criterion with the highest weight is C3.1 (0.6524), and the one with the lowest weight is C3.2 (0.1089). Table 9 shows criterion C6 and its sub-criteria, the highest being C6.1 (0.6480) and the lowest C6.3 (0.1724).

Table 10 displays the local and global weights for all main criteria in level 1 and their rankings as well. Table 10 shows the level one criterion. The most crucial criterion is C3 (0.3394) followed by criterion C6 (0.2129). However, criterion C5 is the last with the lowest weight (0.0904).

Table 11 shows the local and global weights for all sub-criteria in level 2 and their rankings as well. Table 11 shows the level 2 criteria. For example, among the set of sub-criteria, the one with the highest weight is C3.1 (0.2215) followed by C6.1 (0.1380). However, the lowest criterion is C2.1 (0.0111).

8. Discussion

This section begins with a discussion of the results obtained using the Grey-AHP multi-criteria method, followed by a comparison with the multi-criteria methods used in the literature (FAHP and BWM) to solve the P&R system location problem.

Each score on this evaluation represents a consideration that should be made during the implementation of a P&R system. The survey questions for a peer comparison were designed to evaluate multiple aspects of the P&R system.

Accessibility is of the utmost importance when developing a P&R system from a public transportation standpoint. Regarding the application of P&R, the economics component is the least significant. Numerous public transportation-related requirements should be considered in order to properly implement a P&R system, as is evident from the table presented previously (Table 11).

Taking a more analytical approach to the examined case study, it is reasonable to conclude that the frequency of public transportation is the most critical sub-criteria at level two. In other words, the installation of the P&R system is something that must be considered if public transportation is accessible and frequent. The level 2 factor with the lowest value is the amount of time spent travelling in a private vehicle. This result was expected, considering that the objective of transport planners when building a P&R system is not to reduce the time required to travel by private car. Public transportation should be given greater consideration if a P&R system is to be implemented, as it is the most influential factor in a multi-criteria analysis.

According to the findings obtained using the Grey-AHP model, to put into practice a P&R system, it is necessary, first and foremost, to ensure that public transportation is accessible. Transport planners concur that P&R planning depends heavily on the planning of public transportation to P&R facilities. In other words, public transportation frequency must be synchronised with the P&R system's peak demand. It is recommended that the planners analyse the timetables of the urban lines, because this factor is highly significant in attracting potential users of public transportation (VATANEN et al., 2000).

The findings make it abundantly evident that the used Grey-AHP model can provide the possibility of an in-depth study to support the decisions about the development of the P&R system. The criteria and the research approach can be utilised to analyse and solve random P&R development issues in any city.

A graphical representation of the rankings that were obtained from the primary criteria is presented in Fig. 4.

Fig. 5 depicts the relative position of levels one and two. When reading and analysing the radar graph, its hierarchical structure is taken into account; starting from the centre and moving towards the different levels of nodes located around the main concept, the centre of the graph represents the minimum value (C3.1) and the edge represents the maximum value (C2.1).

A multicriteria F-AHP analysis has already been performed (Ortega, et al., 2020), and the dominant result or main criterion is the accessibility of public transport. A multi-criteria analysis known as BWM (Ortega, et al., 2020) was also performed, with the main criterion being the accessibility of public transport. These studies applied the level one and two criteria developed in this G-AHP research to the city of Cuenca, Ecuador.

Table 12 compares the ranking of the main criteria of the three methods used, FAHP, BWM, and G-AHP, which was developed in this article. The main criterion C3 has the same priority in all three methods; however, the criterion in position 2 of the ranking is C6 for G-AHP, which is the same as in BWM, but in the FAHP method, C6 is in position 4 of

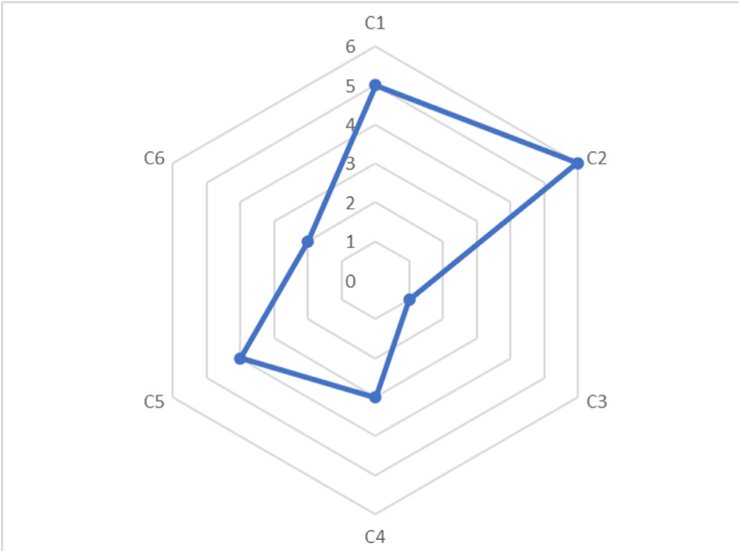

Fig. 4. Priority ranking of main criteria.

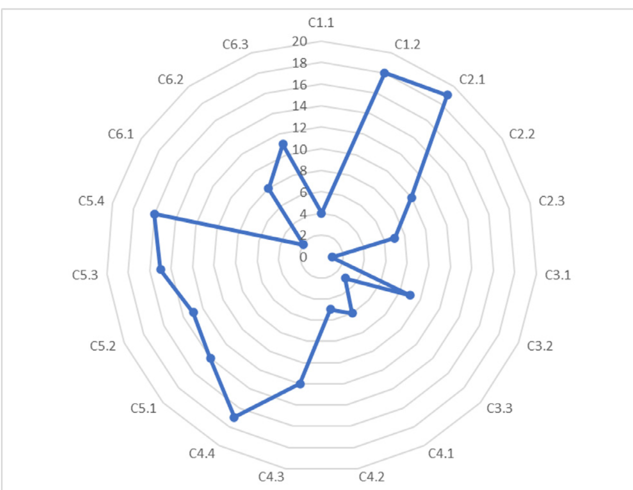

Fig. 5. Priority ranking of sub-criteria.

Table 12
The weight scores for the P&R facilities regarding the criterion of Level 1 FAHP (Ortega, Tóth, et al., 2020), BWM (Ortega, Moslem, et al., 2020) and G-AHP.

FAHP		BWM		G-AHP	
Criteria	Rankings	Criteria	Rankings	Criteria	Rankings
C1	5	C1	5	C1	4
C2	6	C2	6	C2	5
C3	1	C3	1	C3	1
C4	3	C4	3	C4	3
C5	2	C5	4	C5	6
C6	4	C6	2	C6	2

Table 13
The weight scores for the P&R facilities regarding the sub-criteria in case of Level 2 FAHP (Ortega, Tóth, et al., 2020), BWM (Ortega, Moslem, et al., 2020) and G-AHP.

FAHP		BWM		G-AHP	
Factors	Rankings	Factors	Rankings	Factors	Rankings
C1.1	5	C1.1	3	C1.1	4
C1.2	18	C1.2	15	C1.2	18
C2.1	19	C2.1	19	C2.1	19
C2.2	13	C2.2	16	C2.2	10
C2.3	11	C2.3	10	C2.3	7
C3.1	1	C3.1	1	C3.1	1
C3.2	8	C3.2	8	C3.2	9
C3.3	3	C3.3	4	C3.3	3
C4.1	7	C4.1	9	C4.1	6
C4.2	4	C4.2	5	C4.2	5
C4.3	9	C4.3	12	C4.3	12
C4.4	17	C4.4	17	C4.4	17
C5.1	14	C5.1	13	C5.1	14
C5.2	12	C5.2	7	C5.2	13
C5.3	15	C5.3	14	C5.3	15
C5.4	16	C5.4	18	C5.4	16
C6.1	2	C6.1	2	C6.1	2
C6.2	6	C6.2	6	C6.2	8
C6.3	10	C6.3	11	C6.3	11

the ranking. The most notable difference in the ranking is criterion C5, which does not match in the ranking with any of the three multi-criteria methods.

Table 13 compares the sub-criteria of the three methods, FAHP, BWM and G-AHP, developed for this work. Criterion C3.1 is the most essential sub-criterion for each of the three methods. In contrast, the G-AHP and FAHP method assigns criterion C3.3 the third most significant position, while the BWM method assigns criterion C3.3 the fourth most significant position. Ranking criteria C1.1, C2.2, C2.3, C4.1 and C5.2 do not match any of the three multi-criteria approaches.

The FAHP can categorise assessment factors into three levels: target, criterion, and factor. The BWM method makes comparisons in a more structured manner, which makes them simpler and more comprehensible, and leads to more coherent comparisons, resulting in more reliable weightings. The selection of criteria, the hierarchy, and the expert judgement used to determine the level of significance of each criterion in the FAHP and BWM methods have a significant impact on the final decision (Rezaur Rahman et al., 2019; Sabilla Ajrina et al., 2018). The G-AHP method that combines the advantages of classical AHP and grey theory for the accurate estimation of weighting coefficients (Duleba et al., 2022)

It is difficult to determine the best multi-criteria method, because it depends on how the criteria are chosen, ranked, and an expert determines their relative significance. In other words, importance rankings can vary based on the aforementioned factors. The Grey-AHP developed in this paper provides a more accurate estimation of weights based on previous research. The need for additional research on multi-criteria methods for the P&R system location problem is a limitation of this work. This means that more multi-criteria methods must be applied to the two levels of decision making to determine which one to use based on the mentioned factors.

9. Conclusion

The Grey-AHP multicriteria model can determine the criteria weights for the P&R system location problem with greater precision. This characteristic makes it a highly effective tool. In addition, the Grey-AHP model provided information on the criteria of transportation planners that work in the municipality of Cuenca Ecuador in relation to the deployment of a P&R system. This covers a list of criteria, including the environment. As a limitation of this study, it is crucial to note that only a single municipality and a single group of planners participated in the research presented.

The implementation of a P&R system through applications based on Grey theory exemplified how a specific set of criteria could be used to determine which implementation criteria are the most important. To demonstrate the efficacy and viability of the proposed method, a real-world case was applied in Cuenca, Ecuador.

Regarding the application of this case study to Cuenca, it is crucial to note that there are no differences in the order of weighting between the Grey-AHP, FAHP and BWM results in determining the main criteria for the P&R system location problem. To support the implementation of a P&R system, it is recommended to enhance the accessibility and frequency of public transportation.

The Grey-AHP model proved successful based on the results we collected. Because not all raters had the same level of comprehension regarding the relevance of ratios in pairwise comparisons, having numbers that were more malleable contributed to more reliable scoring and ranking. According to our survey results, the Grey-AHP technique can be recommended for all decision support situations in which professional participants analyse decision structure components. This holds especially true for paired comparisons. A Grey-AHP approach is a tool that can be utilised while implementing a P&R system to obtain the expert's perspective. Theoretically, every other city could gain from the methodology, survey method, and analysis offered here.

Future research should focus on integrating Grey theory with other MCDM approaches (such as the analytical network process, for example). In addition, other multi-criteria methods should be applied to the set of criteria established in this research in order to determine which method may be most appropriate based on the type of city and the set of experts.

Declaration of Competing Interest

Please check the following as appropriate:

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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Breaking commuter mode-use habits: An exploration of deliberative decision-making windows and their implications for travel demand management

Eric Adjei[1,*], Roger Behrens

Centre for Transport Studies, Department of Civil Engineering, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7701, South Africa

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ABSTRACT

It is widely accepted that travel behaviour can be habitual. It is also widely accepted that voluntary Travel Demand Management (TDM) seldom records city-wide mode-switching impacts. If travel choices are habitual, this is unsurprising, as much of the population are not making deliberative choices, and new information is not considered. Shifts to deliberative choice-making are posited to occur when a 'stressor' (e.g., changing job location) is experienced, which renders the travel habit no longer satisfactory. A common conceptualisation of these moments is that the stressor triggers deliberation, manifested in information-seeking and experimentation, to find a new satisfactory behaviour. If found and implemented, a new habit may be formed. This conceptualisation has implications for improving TDM impacts. It is tempting to assume that voluntary TDM measures should target those who have just experienced such stressors, as they are likely to be most receptive to deliberative change. This paper reports the findings of a retrospective survey of a purposive non-probability sample of ($n = 250$) Cape Town commuters who had experienced a habit-breaking stressor. A recall aid in the form of an 'event history calendar' was used to help create multiple memory recollection pathways of past commuting behaviour, and a 'deliberation calendar' was used to guide respondents in reporting the process of habit breaking. The study found that the trigger for deliberation and information-seeking was not the manifestation of a new residence or job location (together accounting for the majority of observed stressors), but around two months earlier when the decision-maker consolidated a plan of action. This finding contributes to a growing literature on the temporal dimensions of behaviour dynamics, and has implications for how TDM should be targeted. Targeting new homeowners or employees misses the 'window of opportunity' to influence deliberative decisions and new habits. These decision-makers need to be targeted sooner, while still house- or job-seekers.

1. Introduction

Travel Demand Management (TDM) measures continue to be one of the strategies proffered by transport planners in encouraging more sustainable travel patterns and in mitigating road congestion. TDM measures – such as alternative mode awareness creation, flexi-work, telework, car-pooling, etc. – aim at promoting the use of sustainable transport modes and reducing single occupancy vehicle use (Anderson et al., 1996; Badoe & Miller, 2000; Litman, 2019; Loukopoulos, 2007; Meyer, 1997; Van Wee, 2002). TDM measures may be classified as either voluntary or mandatory (Taylor & Ampt, 2003). Whereas voluntary TDM measures aim at encouraging commuters to change their travel behaviour, mandatory TDM measures force changes in behaviour. Mandatory measures are, therefore, generally more effective at changing behaviour, even though they are less likely to be acceptable to the public (Thorpe et al., 2000; Taylor & Ampt, 2003; Eriksson et al., 2006; Loukopoulos, 2007). For the implementation of voluntary TDM measures to be effective, an understanding of the processes involved in travel decision-making, the factors that influence decisions, and when changes occur, is key.

It is now widely accepted that, for periods of time, travel behaviour, particularly commuting to and from work, is habitual and non-deliberative in nature. While voluntary TDM measures, based on persuasion or incentives, are sometimes impressive at the disaggregated company scale, it is also widely accepted that such measures seldom record observable mode-switching impacts at an aggregated city-wide scale (Behrens et al., 2015; Graham-Rowe et al., 2011). If much travel behaviour is habitual, this is unsurprising, as a significant portion of the

* Corresponding author.
E-mail address: eadjei@atu.edu.gh (E. Adjei).
[1] Present address: Department of Civil Engineering, Accra Technical University, P. O. Box GP 561, Barnes Road, Accra, Ghana.

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commuter population is not making deliberative choices, and therefore new information on alternative ways of travelling is neither sought nor considered.

Voluntary TDM measures have been argued to be more successful when targeted at commuters who are most susceptible to changing behaviour (Bamberg, 2006; Litman, 2019). As will be elaborated in the following section, one such group is commuters experiencing an event that disrupts their travel habits and forces deliberative decision-making. The occurrence of these events has been argued to force commuters into deliberating on their travel choices. Many studies have been conducted to understand the influence of life course events on mode use choice (e.g. Klöckner, 2004; Stanbridge & Lyons, 2006, see Beige & Axhausen, 2008; Scheiner & Holz-Rau, 2013; Clark et al., 2014; Verplanken & Roy, 2016 etc., Busch-Geertsema & Lanzendorf, 2017; Janke et al., 2021). Little has, however, been done to unpack how mode use changes occur when commuters are experiencing habit breaking events.

This paper reports on research undertaken in Cape Town to explore these windows of deliberative decision-making opportunity. The objective of the paper is to understand the process commuters go through when changing their travel mode in response to a habit-breaking event. Through a retrospective survey, targeted at the most recent mode-switching experience, the paper will explore the dynamics of behaviour-change, and seek to establish when commuters are most susceptible to habit-breaking decisions. This insight should help inform when it may be most appropriate to implement targeted TDM measures, to improve their impact.

The paper is divided into six sections. The following section reviews the literature on the dynamics of travel behaviour, and on when mode-use habits are broken. Section 3 describes the research method employed. Section 4 presents the findings. Section 5 discusses the contribution of the research, and the implications of the results for improved TDM practice.

2. Literature review

Travel patterns, especially mode-use to non-discretionary trip destinations, have been observed by many authors to be habitual (see Verplanken et al., 1997; Gärling et al., 2001; Bamberg et al., 2003; Gärling & Axhausen, 2003; Garvill et al., 2003). These studies suggest that a commuter engages in deliberation of alternatives when faced with a travel choice problem for the first time. The choice is then codified and stored if the commuter is satisfied with the experience. This codified choice is retrieved and repeated whenever the commuter is faced with the same or a similar choice problem (Gärling et al., 2001). Commuters stop actively seeking new information and may overlook minor changes in their environment (Verplanken & Roy, 2016; Busch-Geertsema & Lanzendorf, 2017). Thus, over time, the behaviour becomes habitual with little or no deliberation. The same non-deliberative choice may be transferred to contexts other than the one within which the initial deliberative choice was made.

The habit-breaking literature contends that shifts from non-deliberative to deliberative choice-making occur when a ‘key event’ or ‘critical incident’ in the life course (or ‘stressor’) is experienced, which renders the travel habit no longer able to satisfy needs (Van der Waerden et al., 2003; Scheiner & Holz-Rau, 2013). These stressors often occur in combination (Rau & Manton, 2016). ‘Key events’ refer to expected changes in one’s personal life, while ‘critical incidents’ are unforeseen events (e.g., car crashes, public transport muggings, or retrenchment).

‘Mobility biography’ research (across predominantly Global North contexts) has revealed that the events and incidents which most commonly trigger changed behaviour include (Lanzendorf, 2006; Scheiner & Holz-Rau, 2013; Clark et al., 2014; Chatterjee & Scheiner, 2015; Müggenburg et al., 2015; Rau & Manton, 2016; Larouche et al., 2020; Grandsart, 2021; Janke et al., 2021):

- Changes in residence.
- Changes in employment.
- Acquiring a driver’s licence.
- Children starting school.
- Changes in household structure (e.g. marriage, childbirth, etc.).

Similar to these studies, mobility biography research in Cape Town found that changes in employment and changes in residence were the dominant stressors in commuter mode-use habit-breaking (accounting for a combined 67%, $n = 70$) (Adjei & Behrens, 2013).[1]

While considerable research has now been undertaken to identify stressor events, relatively less research has been undertaken to gain insight into the processes surrounding habit-breaking. The common implicit (Clark et al., 2012; Clark et al., 2016a; Scheiner & Holz-Rau, 2013), or explicit (Klöckner, 2004; Clark et al., 2016b; Farinloye et al.,2019; Chatterjee & Clark, 2020), conceptualisation of the behaviour-change process at these moments in time is that the event or incident triggers deliberation, manifested in information-seeking and experimentation to find a new travel behaviour pattern that satisfies needs. If the new travel choice produces a satisfactory outcome, and the environment remains sufficiently stable, it may also be codified and stored, and become a new non-deliberative habit.

Loukopoulos et al. (2004) posit that the experimentation associated with behaviour-change involves commuters considering options by trading effectiveness (or ‘goal achievement’) against effort and cost. Consistent with the principle of satisficing, the change process is argued to be multi-staged, starting with options requiring least effort and cost (e.g., experimenting with new departure times or routes using the same mode), and if these are unsatisfactory, continuing to options requiring more effort and cost (e.g., planning trips by other travel modes, and if necessary, acquiring the requisite mobility tools).

Fig. 1 presents arguably the most elaborate conceptualisation of mode-use habit-breaking and habit formation (Klöckner, 2004). The occurrence of an event or incident leads to changes in the availability of travel modes and/or the activity scheduling of the commuter. This, Klöckner (2004) argues, causes a sharp increase in ‘activation’, or awareness of the need to change behaviour. At the same time, the influence of ‘habitualisation’ on travel choices declines sharply. Commuters begin to seek information on, and deliberate about, their travel options. Activation, information-seeking, and deliberation lowers again once a new choice stabilises and a habit is re-formed.

This conceptualisation of the process of behaviour-change has important implications for improving the impacts of voluntary TDM practices. The occurrence of the stressor opens what Klöckner (2004) describes as a ‘window of opportunity’ within which behaviour-change interventions can be targeted (Dahlstrand & Biel, 1997; Verplanken & Roy, 2016). It is tempting, and indeed logical, to assume that voluntary TDM strategies should target those who have just experienced such events or incidents – in other words, new homeowners, new employees, and new school parents – as they are likely to be most receptive to deliberative decision-making and habit-breaking (Litman, 2019; Bamberg, 2006).

So, conventionally, the ‘window of opportunity’ is postulated to open when the event or incident occurs. The question explored in this paper is whether the window of opportunity really does start *after* the stressor. We will return to the literature on habit-breaking dynamics later, after presenting the research undertaken on this question in Cape Town in the next two sections.

3. Research method

This section describes the survey method, questionnaire and ‘deliberation calendar’ used in data collection, as well as the sample design.

[1] This study preceded the study presented in this paper. While the earlier research focussed on the nature of stressors that cause deliberate commuter choice-making in the Cape Town context, the later research focussed on the decision-making window when stressors are experienced.

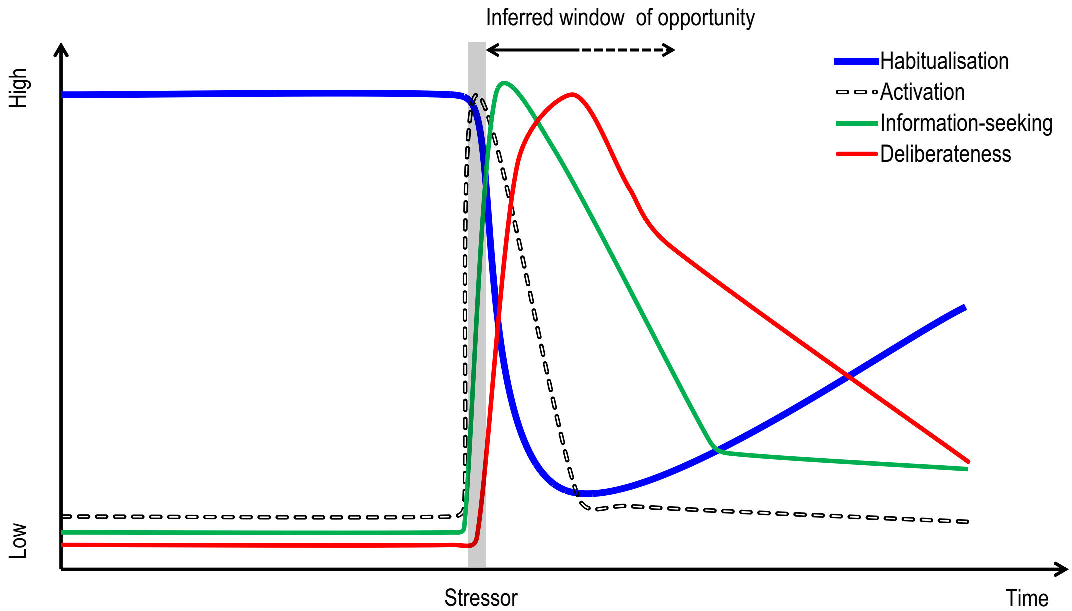

Fig. 1. Conventional conceptualisation of the influence of a stressor on habitualisation and deliberateness in mode choice habit-breaking (after Klöckner, 2004).

3.1. Survey method

Longitudinal and intra-personal data are needed to determine the influence of life course stressors on mode choice, as this type of data reveals variabilities in travel patterns (Huff & Hanson, 1986; Schlich & Axhausen, 2003). A structured retrospective survey interview method was chosen for this study, best described as an exploratory methodology. Other methods of collecting longitudinal data – namely, panel surveys or pseudo-panel analysis (Axhausen, 1995; Lanzendorf, 2003) – were not feasible because a multi-wave panel survey of sufficient duration was not possible within the time frame of the study, and a suitable secondary repeated cross-sectional survey database did not exist for pseudo-panel analysis.

Retrospective surveys rely on memory recall by respondents, with the main methodological problems relating to memory biases: forgetfulness; and forward and backward 'telescoping' (Auriat, 1991; Beckett et al., 2001; Belli et al., 2001). A recall aid in the form of an 'event history calendar' was used in the study to help create multiple memory recollection pathways, as proposed by Belli (1998). A novel 'deliberation calendar' was used to guide respondents in reporting the process of habit breaking.

3.2. Questionnaire

A questionnaire was designed to guide interviewers in asking questions aimed at documenting the process respondents went through in making a mode-use change in response to a stressor. The questionnaire was structured according to how three types of memories – of extended events, summarised events, and specific events – are stored and retrieved, as postulated by Belli (1998).

The questionnaire was divided into four sections. The first section asked questions about the respondents' demographic characteristics and their current commuting mode. The second section was aimed at helping respondents to remember, and temporally reference, the occurrence of stressors over their working career. Interviewers guided respondents in completing the event history calendar. This included recalling changes in employment, residence, co-habiting partnerships, and children, as well as recalling acquiring driver's licences, and private vehicles. The third section then focussed on the latest event or incident in the respondent's career that triggered a change in mode-use. The inter-connectivity of different stressors was tested by asking respondents whether any other event had influenced the occurrence of the event in question. Respondents were asked whether they had changed other attributes of their travel choice before changing their mode, and what information they had sought. The fourth section asked respondents to recall the process they went through when changing their mode of transport.

3.3. Deliberation calendar

The deliberation calendar was used, in the fourth section of the questionnaire, to aid recollection of the process of habit-breaking (see Fig. 2). It included questions on the duration of mode-use deliberation and information-seeking. Respondents were assumed to be capable of providing more detailed information about their behavioural changes closer to when the stressor occurred. A six-month period was provided for such records on both sides of the event. Larger aggregations of time were provided farther away from the event. This assisted in recording variations in mode-use, departure time and route choice over the calendar period.

3.4. Sample design and description

Data were collected in Cape Town, through purposive non-probability sampling. Fieldworkers were sourced from a market research company. Respondents were recruited in public places (e.g. shopping centres), and interview times were scheduled for a later date. Interviews were then conducted in person (without audio recording) at the pre-arranged time, either at the respondent's home or workplace. The duration of interviews ranged between 30 and 60 min. A diversity of age, sex and socio-economic status was sought during the sampling process. For recruitment, eligible respondents needed to:

- Be currently employed.
- Be employed in a job that, under normal circumstances, required travel at least three times a week to the same place of work (regular commuting to the same destination was deemed a prerequisite for habit formation).
- Have changed their commuting mode in response to either a change in job location, change in residence or acquired their first car, all within the past five years (the 5-year maximum cut-off was intro-

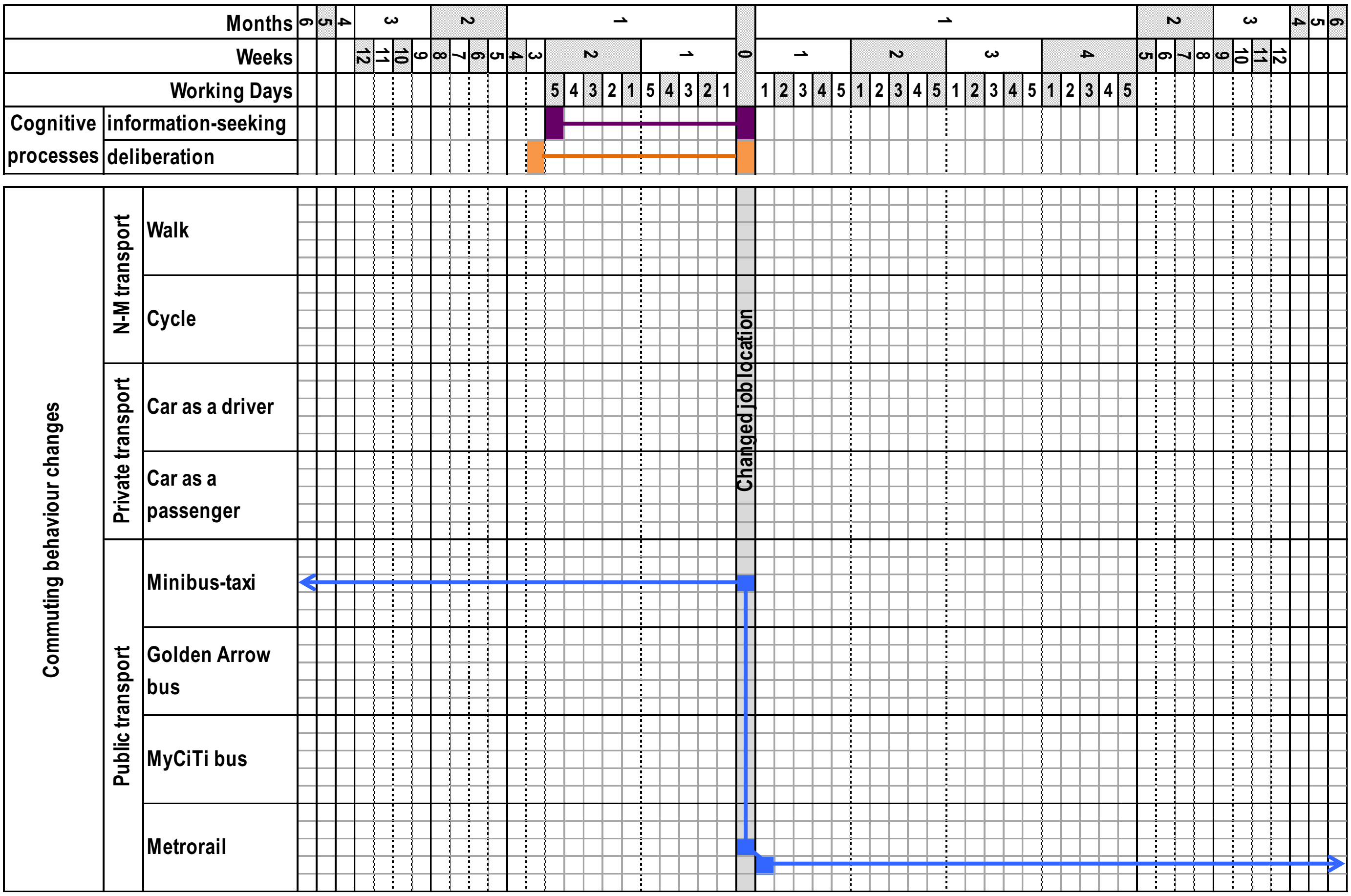

Fig. 2. An example of a deliberation calendar (Data source: Own survey).

duced to increase the probability of respondents remembering details of the relevant habit-breaking event).

As the survey was qualitative in purpose – designed to seek behavioural insight rather than statistical representivity of the Cape Town commuter population – the sample size was determined by the need for saturation, rather than an acceptable confidence interval. A total of 1571 people were approached for an interview. Of the number approached, 796 did not meet the eligibility criteria for inclusion in the study. Of the remaining 775 eligible respondents, 525 declined to participate in the study. Data collection stopped at 250 completed interviews. A response rate of 32% was thus achieved. Of the 250 respondents, 46% were male and 54% were female (see Fig. 3). This gender distribution was similar to that of observed in Cape Town during the 2016 Community Survey of about 49% male and 51% female (Statistics South Africa, 2016). Respondents covered a range of ages, between 18 and 71 years. The mean age was 36 years. The sample had greater younger adult, and fewer older adult, respondents compared to the city's adult population age distribution in the 2016 Community Survey: 35% vs 27% 20–29 year olds; 30% vs 24% 30–39 year olds; 19% vs 21% 40–49 year olds; 13% vs 13% 50–59 year olds; and 3% vs 15% 60+ year olds (Statistics South Africa, 2016).

Fig. 4 illustrates the spatial distribution of respondents' residential locations. Respondent residences were dispersed across the city, with a concentration on the Cape Flats to the south-east of the city centre. This area houses predominately low/medium-income (ZAR 4,001-ZAR 31,600 [USD 491-USD 3,881]/month) and low-income (<ZAR 4,000 [<USD 490]/month) households. Many households are captive to public transport modes. The work trip public:private:non-motorised transport modal split is 55:35:9 percent for low/medium-income households, and 71:17:12 percent for low-income households (City of Cape Town, 2018).

3.5. Limitations

Given the qualitative nature of the study, and its small sample size, the results cannot be generalised for all commuters in Cape Town. Data were collected through a retrospective survey instrument, and even though recall aids in the form of event and deliberation calendars were used, respondent recollections may not be totally free from memory losses or errors.

4. Findings

This section presents the findings of the study in relation to the stressors that caused the most recent mode-use change, stability and experimentation associated with the mode-use change, information-seeking activity, and the duration of 'windows of opportunity'.

4.1. Stressors

Changes in job location (including both starting new jobs and moving business premises), were observed to be the most common stressor leading to mode-switching (58%), followed by changes in residence (23%), and acquiring a car for the first time (19%). These findings are broadly consistent with an earlier mobility biography study in Cape Town, which found that the top three stressors for mode-switching were changes in job location (50%), acquiring a car for the first time (17%), and changes in residence (16%) (Adjei & Behrens, 2013). Unsurprisingly, acquiring a car for the first time led to 100% switching to car as a driver, whereas

Table 1
Latest stressor, mode switched to, and stressor interconnectivity (n= 250) (Data source: Own survey).

		Latest stressor							
		Acquired first car		Changed residence		Changed job location		Total	
		count	%	count	%	count	%	count	%
Mode respondents changed to after the stressor	Walk	0	*0*	1	*2*	0	*0*	1	*0*
	Train (Metrorail)	0	*0*	11	*19*	31	*21*	42	*17*
	Bus rapid transit (MyCiTi)	0	*0*	2	*3*	3	*2*	5	*2*
	Bus (Golden Arrow)	0	*0*	9	*16*	28	*19*	37	*15*
	Paratransit (minibus-taxi)	0	*0*	20	*34*	57	*39*	77	*31*
	Car as a passenger	0	*0*	7	*12*	13	*9*	20	*8*
	Car as a driver	47	*100*	8	*14*	13	*9*	68	*27*
	Total	47	*100*	58	*100*	145	*100*	250	*100*
Influencing events	Changed job location	2	*20*	8	*47*			10	*21*
	Changed residence	1	*10*			9	*45*	10	*21*
	Acquired first car			7	*0*	0	*25*	7	*15*
	Co-habiting partnership	4	*0*	1	*41*	2	*0*	7	*15*
	New child born	0	*40*	0	*6*	5	*10*	5	*11*
	Acquired driver's licence	3	*30*	1	*6*	4	*20*	8	*17*
	Total	10	*100*	17	*100*	20	*100*	47	*100*

the other two stressors led to a more diverse distribution of new modes (see Table 1).

Stressors are sometimes interconnected, thus the occurrence of one stressor can trigger another. Forty-seven respondents (17%) reported that the stressor that caused them to switch mode was influenced by the occurrence of other stressors. Table 1 illustrates that change in residence was the most influential stressor accompanying change in job location (45%), followed by first car acquisition (25%), and the acquisition of a driver's licence (20%). Change in residence was most frequently accompanied by a change in job location (47%), and a new co-habiting partnership (41%). First car acquisition was most frequently accompanied by the birth of a child (40%), acquiring a driver's licence (30%), and a change in job location (20%). These influencing stressors may have occurred before or after the stressor that respondents identified as the main cause of the most recent mode-use change. For example, changes in job location may result in a longer commute, prompting an individual to search for new housing closer to work.

4.2. Mode-use change

The minibus-taxi was found to be the most common current commuting mode (31%), followed by car as driver (27%) and train (17%) (see Table 2). The public transport modes combined accounted for 64% of current mode-use (compared to 82% before the respondents' most recent mode-use change), while car drivers and car passengers combined accounted for 35% (compared to 16% before the most recent change). The mode-use 'churn' in the respondent sample is therefore asymmetrical, in favour of private car use. The sample, however, still had relatively fewer current car commuters than the 48% found in the City of Cape Town's most recent city-wide household travel survey (Adjei et al., 2014).

Most respondents (95%) reported commuting to work fives time a week by the same travel mode for the three months preceding the interview (see Table 2). Current mode-use was therefore observed to be largely stable, if not habitual. The stability of mode-use, and the infrequency of mode-switching, is also reflected in the 75% of respondents who indicated that they had never considered changing their travel mode before the most recent mode-use habit-breaking event (see Table 3). An even larger proportion of respondents (95%) indicated that they had not considered changing mode after the most recent mode-use change. Regarding experimentation, 15% of respondents tried permutations of their previous mode before settling on their current mode (13% tried changing departure time, and 2% tried changing route).

4.3. Information-seeking

As noted in the earlier literature review, information gathering is posited to be central to the deliberation process that occurs when a stressor is experienced. To make a rational decision, an individual may seek to collect comprehensive information on all alternatives. Rationality is, however, bounded by the availability and amount of information, which is rarely complete, as argued by Simon (1957) in bounded rationality theory. In line with this, respondents were asked whether they were able to gather all the information they thought was available about the mode alternatives they were considering, and whether they were satisfied with the amount of information gathered. Most respondents (76%) indicated they were able to gather all the information they thought was available (see Table 3). This is reflected in the number of respondents satisfied with the amount of information gathered (78%). Of the 24% of respondents who indicated they were unable to gather all available information, 78% were dissatisfied with the amount of information gathered.

4.4. Window of opportunity duration

When respondents gathered information about, and deliberated upon, mode-switching was also investigated. Information-seeking and deliberation were used as indicators of when respondents' 'activation' increased (see Fig. 1). Table 4 illustrates that, on average, the period of information-seeking before the stressor was 24 working days (with a range of 1–121 days). The average period of information-seeking after the stressor was one working day (with a range of 0–55 days). The average period of deliberation before the stressor was slightly longer, at 30 working days (with a range of 1–121 days), and after the stressor one working day (with a range of 1–100 days). Thus, the typical 'window of opportunity' with respect to influencing mode-use decisions, is estimated to be 31 working days (30 days before the physical occurrence of the stressor and one day after). Assuming a five-day working week, this is equivalent to 6,2 weeks.

Table 4 also presents windows of opportunity by travel mode. Respondents changing to a Golden Arrow bus were observed to take the longest mean deliberation time (45 working days), followed by changing to a car as driver (38 working days), and MyCiTi bus (25 working days). The shortest mean window of opportunity was observed to be for switching to car as passenger (22 working days), possibly because car passengers do not have to consider the route and timetable information of public transport modes, or the arrival time impacts of congestion and route options in the same way that car drivers must.

Table 2
Current and previous commuting mode-use, and current mode-use frequency (n = 250) (Data source: Own survey).

		Previous travel mode									No. of days/ week		
		Paratransit (minibus-taxi)	Car as a driver	Train (Metrorail)	Bus (Golden Arrow)	Car as a passenger	Bus rapid transit (MyCiTi)	Walk	Total	%	3 days	4 days	5 days
Current travel mode	Paratransit (minibus-taxi)		4	39	24	7	1	2	77	*30,8*	3	1	73
	Car as a driver	29		21	15	2	0	1	68	*27,2*	0	1	64
	Train (Metrorail)	21	5		7	9	0		42	*16,8*	0	0	45
	Bus (Golden Arrow)	15	8	9		3	0	2	37	*14,8*	2	3	30
	Car as a passenger	14	0	3	3		0		20	*8,0*	1	0	21
	Bus rapid transit (MyCiTi)	0	0	0	2	2		1	5	*2,0*	1	0	4
	Walk	0	0	0	1	0	0		1	*0,4*	0	0	1
	Total	79	17	72	52	23	1	6	250	*100*	7	5	238
	%	*31,6*	*6,8*	*28,8*	*20,8*	*9,2*	*0,4*	*2,4*	*100*		*2,8*	*2,0*	*95,2*

Variations and similarities among respondents experiencing different stressors were also explored. No significant difference *($t(70) = -0.041$, $p > 0.05$)* was found in the average windows of opportunity resulting from acquiring the first car *($m = 39.01$, $SE = 7.58$)* and changing residence *($m = 39.51$, $SE = 7.99$)*. The mean deliberation period for respondents acquiring their first car was 39 working days (33 working days of information seeking), and 40 working days (33 days of information seeking) for respondents changing residence. When the stressor was a changed job location *($m = 25.28$, $SE = 3.91$)*, however, respondents deliberated for less time, at 25 working days on average (20 working days of information seeking). The difference in the time used for deliberation was however not significantly different *($t(140) = 1.672$; $p > 0.05$)* from that of respondents changing residence. The time respondents changing jobs used for seeking information was, however, significantly different *($t(143) = 2.019$, $p < 0.05$)* from that of respondents changing residence. So, deliberation periods were found to vary by both stressor and new mode.

5. Discussion

This section reflects upon whether the study's findings corroborate or refute the common conceptualisations of travel behaviour-change processes presented in the earlier literature review, and discusses the implications the findings have for improved voluntary TDM practices.

5.1. *Corroboration and refutation of concepts and theories*

Reflecting on the earlier conceptualisations of behaviour-change, the retrospective accounts of mode-use change collected in Cape Town certainly corroborate the notion that much commuting behaviour is habitual in nature. Bearing in mind that commuting to the same destination at least three times a week was a selection criterion, respondents reported that their current mode was mostly stable (95% used the same mode five times a week), and that, for most of their commuting careers, their choices were non-deliberative. The findings also corroborate that, at least in the case of mode-use, changes are associated with the experience of a stressor.

Some evidence of experimentation was found, but only in a minority of respondents (15%). These respondents reported testing new departure times, and in a few instances, alternative routes. Curiously, half (52%) of the respondents who tested new departure times indicated that they were satisfied with the resulting travel pattern (see Table 3), suggesting that further, greater effort and greater cost changes should not have been required. The finding that 85% of respondents changed mode without prior experimentation may be because they decided upon their new mode in anticipation of the occurrence of the key event, and therefore experimentation was not required to reach a satisficing decision. So, the study's findings do not provide clear corroborating evidence of experimentation occurring consistently as part of the mode-switching process.

The clearest difference between the study findings and the earlier conceptualisations of behaviour-change is in the deliberation period, or 'window of opportunity', associated with a stressor. While a deliberation period *after* the manifestation of a stressor (as advanced in Fig. 1) must explain the change process following an *unpredictable* 'critical incident' (in Cape Town this is commonly mugging on public transport, (Behrens & Mistro, 2010)), it is inconsistent with the findings of this study. The results of this study suggest that commuters who experience *predictable* 'key events' (at least the three stressors investigated here) start to deliberate on their mode-use choice *before* the manifestation of the event. Lifecycle events such as acquiring a driver's licence and a car, changing residence, new co-habiting partnerships, children starting school, and changing job location are usually planned occurrences in life, with at least some forewarning. Commuters are therefore able to plan their travel choices in advance. In some instances, the availability of a transport service may even be a key factor in choosing where to life,

Table 3
Experimentation and information-seeking before and after stressors (n = 250) (Data source: Own survey).

	Yes		No		Total
	count	%	count	%	
Experimentation					
• Considered changing mode before event	62	*24,8*	188	*75,2*	250
• Thought about changing mode since settling on current mode	12	*4,8*	238	*95,2*	250
• Tried different modes?	38	*15,2*	212	*84,8*	250
• Tried changing departure time before changing mode	33	*13,2*	217	*86,8*	250
• Satisfied with travel patterns after changing departure time	17	*51,5*	16	*48,5*	33
• Tried changing route before changing mode	4	*1,6*	246	*98,4*	250
• Satisfied with travel patterns after changing route	3	*75,0*	1	*25,0*	4
Information-seeking					
• Satisfied with amount of information gathered	196	*78,4*	54	*21,6*	250
• Able to gather all available information	191	*76,4*	59	*23,6*	250
• If able to gather all known info., satisfied with information gathered	183	*95,8*	8	*4,2*	191
• If unable to gather all known info., satisfied with information gathered	13	*22,0*	46	*78,0*	59

Table 4
Information-seeking period, deliberation period and window of opportunity, by travel mode (n=184, working days) (Data source: Own survey).

Current travel mode		Period before stressor		Period after stressor		Window of opportunity	
		deliberation	info-seeking	deliberation	info-seeking	deliberation	info-seeking
Train (Metrorail)	n	32	32	32	32	32	32
	mean	21.5	13.3	0.7	0.7	22.2	14.0
	minimum	1	1	0	0	1	1
	maximum	121	81	3	3	121	81
Bus rapid transit (MyCiTi)	n	5	5	5	5	5	5
	mean	30.6	31.0	0.4	0.4	31.0	31.4
	minimum	1	1	0	0	1	1
	maximum	121	121	1	1	121	121
Bus (Golden Arrow)	n	27	27	27	27	27	27
	mean	44.5	36.2	0.0	0.0	44.6	36.3
	minimum	1	1	0	0	1	1
	maximum	121	121	1	1	122	122
Paratransit (minibus-taxi)	n	54	54	54	54	54	54
	mean	24.6	15.3	0.4	0.4	25.0	15.7
	minimum	1	1	0	0	1	1
	maximum	121	121	4	4	121	121
Car as a passenger	n	14	14	14	14	14	14
	mean	21.8	21.9	0.1	0.1	21.9	22.0
	minimum	1	1	0	0	1	1
	maximum	121	121	2	2	121	121
Car as a driver	n	48	52	48	52	48	52
	mean	36.0	33.8	2.8	1.8	38.0	35.6
	minimum	2	2	0	0	2	2
	maximum	121	121	100	55	123	176
Total	n	180	184	181	184	181	184
	mean	30.0	24.2	1.0	0.8	30.9	25.0
	minimum	1	1	0	0	1	1
	maximum	121	121	100	55	132	176

work or send children to school, as found by Stanbridge et al. (2004) in a study on the behavioural impacts of changing residence in Bristol.

Fig. 5 illustrates that, for the respondents in Cape Town, the mean period of this preceding deliberation and information-seeking ranged between five and six weeks. The figure therefore offers a modification of the earlier conceptualisation presented in Fig. 1. At least for work trips and for the three stressors investigated, commuters become aware of the need to change their travel mode when their plans for the future lifecycle event are finalised, and before they are implemented. Activation therefore rises in advance, and commuters search for information and deliberate on the required mode-switching up to the point when the event occurs. Habitualisation, at least for the overt use of the earlier travel mode, remains high and does not change until the stressor manifests and the travel habit is broken. As with the earlier conceptualisation, the influence of habit on mode choice increases with time, steadily reducing the level of activation.

Fig. 6 shows deliberation period variation according to stressor and the new mode adopted, ranging between four and nine weeks. Notwithstanding the small sub-sample sizes (particularly for bus rapid transit), the variation by new mode suggests that public transport services with more complex networks, lower frequencies, and varying service spans require more deliberation than other, more predictable, public transport services, and that car drivers deliberate more (on timing and route choices to minimise congestion delay) than car passengers.

These findings contribute to a growing literature on the complex temporal dimensions of behaviour dynamics. This literature can be divided into three groups. The first group explore the interrelationships between, and the sequence of, different stressors in decision-making (Beige & Axhausen, 2008; McCormack & Schwanen, 2011). The sec-

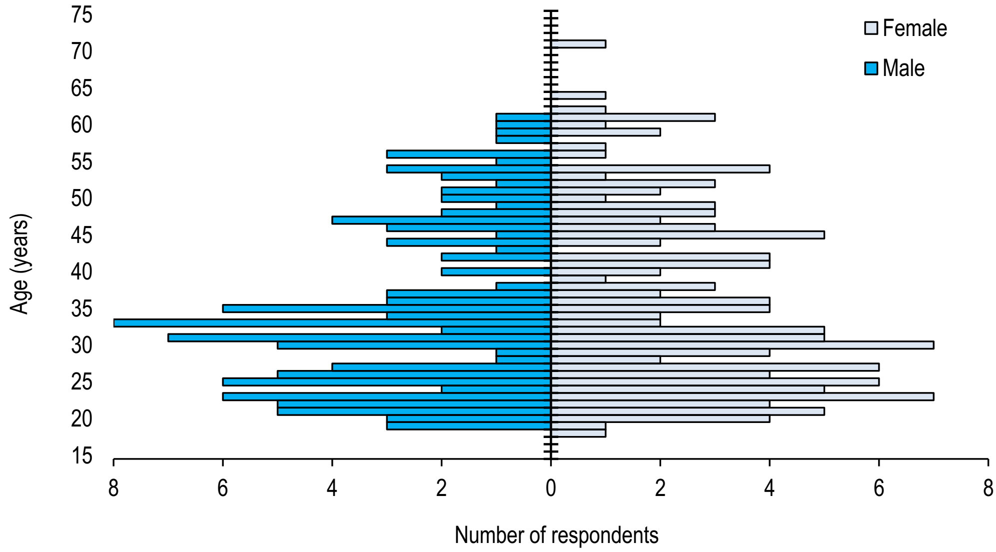

Fig. 3. Population pyramid among respondents (n=250) (Data source: Own survey).

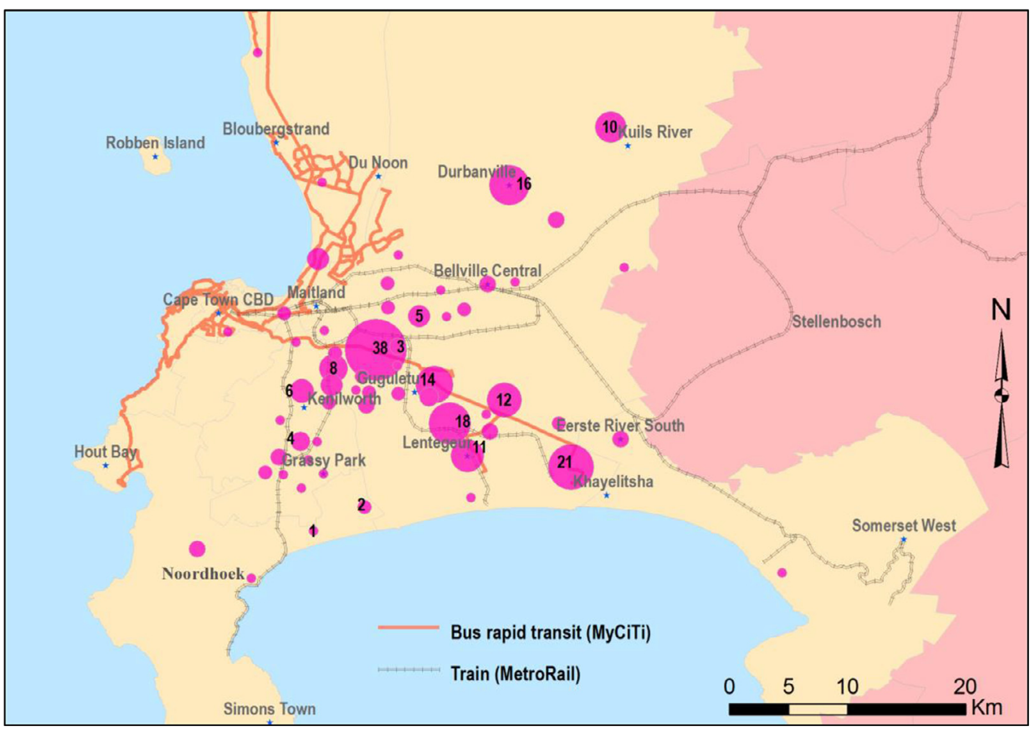

Fig. 4. Residential location of respondents (n=250) (Data source: Own survey).

ond group (most relevant to this study) explore the 'anticipatory effects' of lifecycle stressors on car ownership and mode choice decisions (Oakil, 2013; Oakil et al., 2011; Oakil et al., 2014; Choudhury et al., 2018). The third group explore a dynamic approach to modelling the impacts of stressors on travel choices (Dalal & Goulias, 2013; Choudhury et al., 2010; Ehreke et al., 2016). All these studies recognise that behaviour-change needs to be analysed from an interrelated life course perspective, and that stressors induce both proactive and reactive deliberation. The contexts considered in these studies include Germany, Switzerland, The Netherlands, and the United States.

5.2. Implications for travel demand management practices

While, as just demonstrated, the findings of the study in Cape Town are neither entirely new nor counter-intuitive, the insight developed has important implications for how voluntary TDM measures should be targeted to increase their effectiveness. Targeting commuters immediately after a stressor occurs – e.g., new homeowners, new employees, and new school parents – misses the 'window of opportunity' to influence deliberative decisions and the formation of new more desirable habits. These decision-makers need to be targeted before the occurrence of predictable stressors. It is house-seekers, job-seekers, school-seekers, etc., rather than new homeowners, new employees, new school parents, etc., who need to be targeted. The observed deliberation periods for the three stressors studied suggest at least two months before, but the variation of deliberation periods by stressor and new mode indicates a need for context specificity. Schäfer et al. (2012) draw remarkably similar conclusions in this regard, from their study of the impact of sustainability campaigns in the context of Berlin.

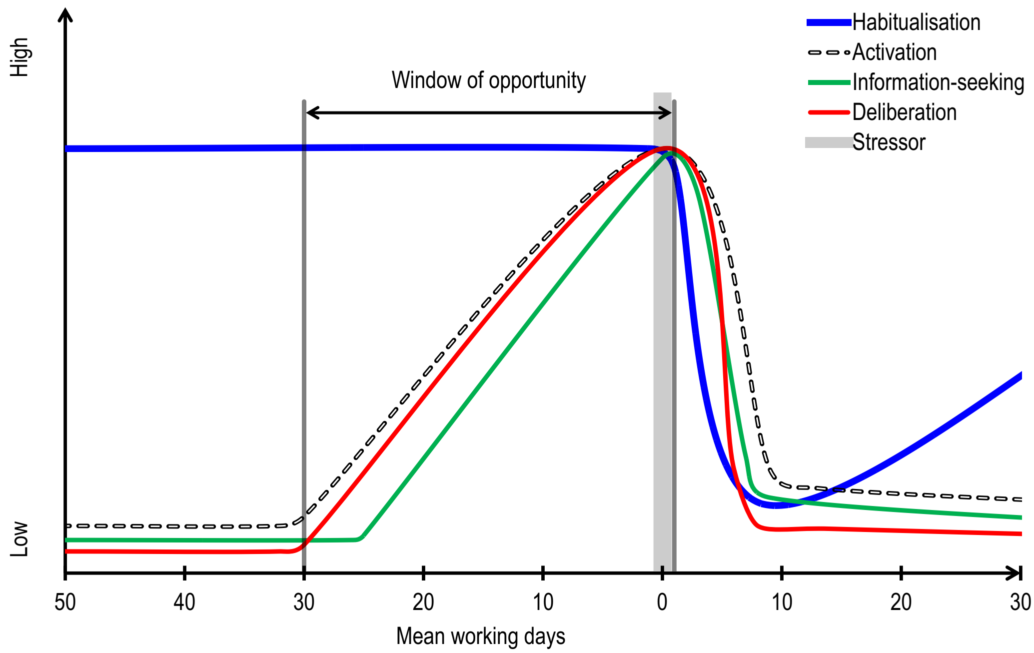

Fig. 5. Reconceptualisation of the influence of a stressor on habitualisation and deliberateness in mode choice habit-breaking (Data source: Own survey). Note: Plots on the X-axis are mean durations of all stressors combined across the respondent sample. Plots on the Y-axis are hypothetical.

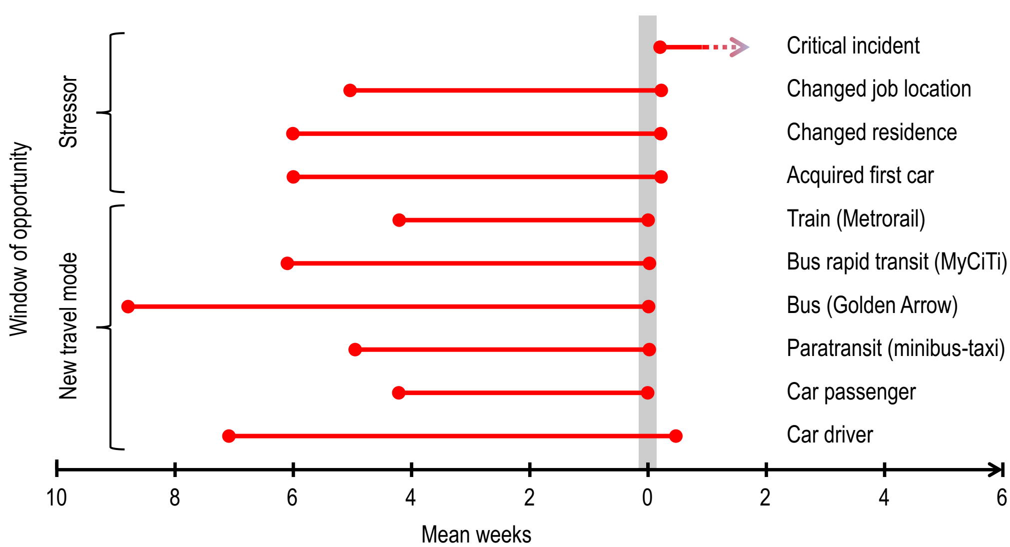

Fig. 6. Deliberation periods, by stressor and new travel mode (Data source: Own survey).

This insight adds considerable complexity to the implementation of voluntary TDM strategies, at least in the case of practices that require resourcing to engage directly with individuals (e.g., 'travel planning' in the United Kingdom (Rye, 2002), 'individualised travel marketing' in Germany (Brög et al., 2009), 'travel blending' in Australia (James et al., 2017) and 'travel feedback programs' in Japan (Fujii & Taniguchi, 2006)). The obvious problems that arise for voluntary TDM practitioners are: how to identify who is likely to experience a stressor; and how to anticipate when the event is likely to occur. Fortunately, there is often a time lag between preceding markers and such events. For instance, there is usually a time lag between acceptance of a job offer and changing job location, between acceptance of an offer of purchase and changing residence, between falling pregnant and childbirth, and between acceptance of a place offer from a school or university and starting studies. Some stressors are also precursors of others (e.g., starting pre-school before starting primary school). Thus, the occurrence of preceding markers or stressors, can be used to target individuals or households with information on alternative sustainable travel choices. Information could, for instance, be given to individuals as part of their job offer letters, when their offer to purchase a new home is accepted, or when their children are accepted into a new school, instead of after they have started working in a new job, moved residence, or joined a new school community.

6. Conclusion

This paper set out to unpack the effect of stressors on mode-switching among commuters in Cape Town, and in so doing, to establish when commuters are most susceptible to making habit-breaking decisions, and therefore when it is most appropriate to implement targeted voluntary TDM measures. An event history calendar was used to aid respondents in remembering the details of the stressor that caused their latest change in mode-use. A deliberation calendar was used to record the deliberation and information-seeking processes surrounding this mode-switching.

Analysis of the deliberation calendars revealed respondents changed their travel mode almost immediately after the occurrence of a predictable stressor. However, they started deliberating and seeking information, on average, about two months before the event manifested. This window of opportunity to influence habit-breaking decisions was observed to vary by stressor. Changed residence and first car acquisition revealed similar deliberation periods, whereas changed job location had a shorter mean deliberation period. Commuters who switched to car as driver and bus were also observed to deliberate for longer than other new modes. These findings are contrary to earlier conceptualisations of habit-breaking, which assumed that deliberation occurs after the stressor. To yield greater impacts, voluntary TDM measures – which aim at changing travel behaviour from single-occupancy car usage to more sustainable modes of transport – should therefore target individuals or households before predictable stressors manifest.

Future studies should be carried out to better understand the interrelationship between different stressors and the factors that lead to their occurrence. This will help to identify those individuals who should be targeted more effectively. Also important for future research will be to determine the timeframes over which mode use choices become habitual, as this will help in determining the duration over which TDM measures should be maintained. Residential location in relation to transport infrastructure and services could also have an influence on how much time is spent searching for information and deliberating upon travel choices. The extent to which spatial location influences the 'window of opportunity' presents another area for further research.

Data availability statement

Due to the personal nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Determinants of shared moped mode choice

Eveline Loudon[a], Nejc Geržinič[a], Eric Molin[b], Oded Cats[a,1,*]

[a] Department of Transport & Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft 2628 CN, the Netherlands
[b] Department of Engineering Systems and Services, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, Delft 2628 BX, the Netherlands

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ABSTRACT

A plethora of shared fleet services have been introduced in cities worldwide. Despite their increased presence in urban areas, it is insofar unknown what are the main determinants of travellers' choices between the usage of shared-mopeds and cars and thereby the extent to which shared moped can substitute car travel. To this end, we design and conduct an SP choice model experiment. The estimated Panel Mixed Logit model is applied to explore the potential market share for shared moped, car and bike under several scenarios which are devised based on the expert interviews. Our findings demonstrate that the return availability of shared moped is the most influential travel time attribute. Walk time from home to the shared moped is an influential factor for people without moped experience. Moreover, model estimation results show that people who have used a shared moped before value the attributes differently than people without previous moped experience. We specifically focus on choice determinants and policy measures targeting car users to facilitate desirable behavioural changes. We present results from model application to demonstrate the effect of different policy packages on the market share of each mode, showing that certain policy interventions can attract car users to switch to shared moped while avoiding a strong reduction in bike use.

1. Introduction

Cities are constantly confronted with a pressing demand for mobility on one hand and scarcity of public space on the other. Shared mobility may play an instrumental role in reducing the demand for private vehicle short distance travel (Abduljabbar et al., 2021). Shared mobility enables users to gain short-term access to transport modes on an on-demand basis (Shaheen, 2019) and has the potential to fulfill some of their mobility needs.

The rapid deployment of shared mobility services has been accompanied by increased research attention in the past few years. Empirical research into user behaviour, traveller preferences and market segmentation has focused on carsharing and bikesharing. Users have been found to be primarily young, highly educated people with higher incomes, for bikesharing (Fishman, 2016), as well as carsharing services (Burghard and Dütschke, 2019; Clewlow, 2016; Winter et al., 2020), although a lower income user group for carsharing was also found (Lempert et al., 2019). Motivations to join a bikesharing (Fishman, 2016; Fishman et al., 2015) or carsharing (Lempert et al., 2019; Standing et al., 2019) system primarily relate to financial savings and convenience, with environmental motives also being identified as a driver for carsharing (Truffer, 2003). Ease-of-use and accessibility, defined in terms of sign-up procedures and walk time respectively, have been found to be important themes that can constitute a barrier to join in case a traveller has a negative perception of these elements, in particular for bikesharing services (Fishman, 2016; Fishman et al., 2012; 2015; Hess and Schubert, 2019; Whittle et al., 2019). Other factors, associated particularly with the attractiveness of carsharing services, are their compatibility with daily life, reliability, data privacy, convenience, and parking hassle (Burghard and Dütschke, 2019; Rahimi et al., 2020; Winter et al., 2020). There is empirical evidence in support of the proposition that shared-use vehicle systems have the potential to alter mobility behaviour. Carsharing in particular has been linked to higher modal shares for public transport, cycling, and walking and reduced private car use (Clewlow, 2016; Lempert et al., 2019; Zhou et al., 2020).

Next to carsharing and bikesharing, shared moped (or scooter) services have emerged over the last decade, and their uptake has strongly accelerated in recent years (Aguilera-García et al., 2020). Moped-sharing in its current form entails a fleet of free-floating vehicles that can be reserved, unlocked and locked via an app and charges users on a per minute basis, just as many currently operational bikesharing and carsharing systems (Namazu and Dowlatabadi, 2018). To the best of our knowledge, Aguilera-García et al. (2020) and Reck et al. (2022) are the only studies that have analysed usage patterns of shared-mopeds.

* Corresponding author.
E-mail address: o.cats@tudelft.nl (O. Cats).

[1] Present address: P.O. Box 5048, 2600 GA Delft, the Netherlands.

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They investigated users' characteristics as well as their motivations to use them. Shared moped users were found to be young and highly educated, although its use seems to penetrate also other age groups. The main stated reasons for using the shared mopeds were easy parking, no traffic jams, and a well-working service. Recent findings suggest that shared e-scooters may not necessarily contribute to urban mobility and climate goals. (Luo et al., 2021) conclude from their modelling results that e-scooters are likely to substitute bus trips and the empirical findings of Reck et al. (2022) show that the substitution effect of shared e-scooters (and e-bikes) results with a net increase in CO2 emissions.

Several governments have been operating pilot or full-scale shared e-mobility systems and are quickly expanding available services, including shared mopeds (Liao and Correia, 2020). Governments in the Netherlands are currently stimulating the use of micro-mobility, including shared e-mopeds, for short urban trips (two to five km), as just under half of short urban trips are made by car (Duursma, 2020). As there are multiple shared-moped operators currently present in the Netherlands, there is a particular need for quantitative-oriented research that offers insight into the trade-offs made in relation to shared-moped travel choices (Cherry and Pidgeon, 2018).

Despite their increased presence in urban areas, it is insofar unknown what are the main determinants of travellers' choices between shared moped fleets and car. Understanding the relevant trade-offs between the two modes will allow identifying the extent to which shared moped can substitute car travel. The latter is the prime objective of many urban mobility strategies. To this end, we conduct a mode choice experiment using Stated Preference (SP) data. Potential mode choice determinants are first explored by means of a focus group and are then specified in an SP experiment. Results from the SP experiment serve as input for expert interviews which are then used to formulate concrete policy measures. We specifically focus on choice determinants and policy measures targeting car users to facilitate desirable behavioural changes. We present results from model application to demonstrate the effect of different policy packages on the market share of each mode.

The remainder of this paper is structured as follows. The methodological specifications are presented in the following section. Next, we present the estimation results of a Panel Mixed Logit model. The implications of the model are then demonstrated using a scenario analysis. We conclude by discussing the key findings, study limitations and recommendations for further research.

2. Methodology

We design and conduct an SP choice experiment. Given the novelty of the mode under consideration, shared e-mopeds, little is known about the variety of potential mode choice determinants. We therefore start by exploring the determinants that are potentially relevant for (potential) moped users when making a mode choice involving a shared moped and car, by means of a focus group. The results are then used in designing a SP mode choice experiment. A choice model is estimated to quantify the impact of each attribute on mode choices. Results from this choice model are then used as input for expert interviews that are instrumental in formulating concrete policy measures. Furthermore, the model is applied to evaluate the impact of different policy packages on the market share of shared mopeds.

2.1. Pre-experiment focus group

A focus group is a qualitative research method involving a group of people who are asked to share their views, ideas and experience with (a) certain topic(s). The key characteristic which distinguishes focus groups is the insight and data produced by the interaction between participants (Gibbs, 1997). The interactions allow participants to build upon arguments of one another. Ideas may be revealed that otherwise might have remained unheard, and participants can correct each other's thinking errors and possibly respond with counter arguments. It is especially useful in helping participants develop an opinion on a topic that is relatively new, such as shared mopeds (Krabbenborg et al., 2020).

A focus group of five individuals has been composed, varying in gender, age, household structure and residence location. All group members have access to a private car. Due to COVID-19 regulations at the time of this study, the session took place via Zoom on October 12th 2020. A short introduction of the shared moped system in question was provided, explaining that all mopeds are electric; that the system is free-floating; finding, unlocking and locking a moped is done via a smartphone app; locking is only possible within the service area; same parking rules as for bicycles; vehicles have a speed limit of either 25 km/h or 45 km/h; there is a storage space under the seat. It was also explained that users are charged for use on a per minute basis and that insurance, maintenance and charging are the responsibility of the operator.

A thematic analysis in ATLAS.ti Windows (Version 8.4.24.0) (ATLAS.ti Scientific Software Development GmbH ATLAS.ti 8.4.24.0 Windows, 2021), a qualitative data analysis software, is conducted to identify important themes and other relevant information. The following key attributes emerged from the session in determining mode choice in the presence of shared mopeds:

- **Availability:** Access time to reach the moped, return trip availability of moped, presence of public transport alternatives;
- **Convenience:** Car parking effort, car parking cost, presence of timetable, ability to reach your destination, (im)possibility to drink alcohol;
- **Hygiene:** Mandatory helmet use for 45 km/h mopeds (shared helmet);[2]
- **Environment:** No emissions;
- **Moped price**;
- **Travel time:** Congestion discomfort, mode speed;
- **Safety**

An individual's perception of safety and context variables such as weather, luggage and trip length influence the valuation of the above-listed attributes.

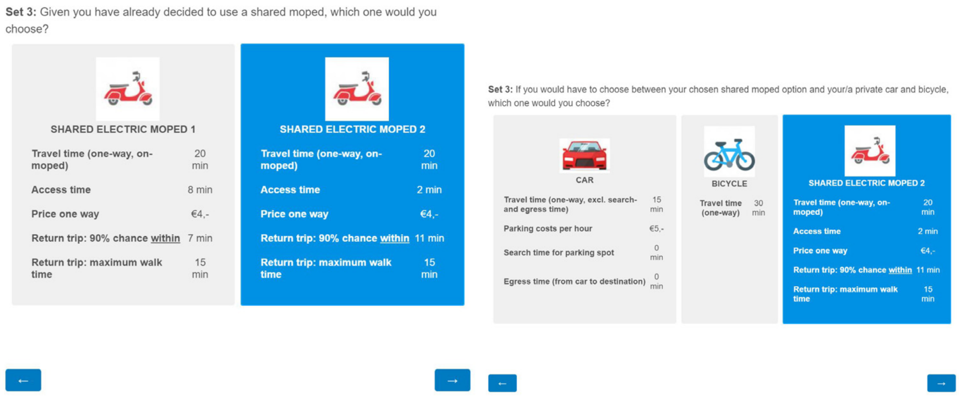
2.2. Survey design

An online survey is designed to collect stated choice data. This section explains the components included in the survey: the mode choice experiment and personal background variables. Data collection and sample characteristics are also discussed.

2.2.1. Mode choice experiment

The goal of the experiment is to quantify the trade-off in a mode choice between car and shared moped. As context, we ask respondents to consider trips that take 15 min by car, starting at home in a Dutch city. Additionally, respondents were asked to consider a trip purpose of running an (e.g. picking up a parcel), travelling alone and carrying a small bag (e.g. a backpack or shopping bag). The purpose of running an errand is chosen because those are on one hand considered occasional rather than habitual (as opposed to commuting trips), and on the other hand are still time-sensitive (as opposed to recreational trips). Weather conditions are kept as neutral as possible (19 °C, cloudy and dry), to avoid an advantage for either mode. A car trip of 15 min roughly equals a distance of 8 km, which is considered the upper limit of short-distance trips (Beckx et al., 2013). As the research objective is to determine what stimulates a car driver to use a shared moped instead of using their car, both car and shared moped are included as mode alternatives. Only the 25 km/h moped version is included for the sake of simplicity, as the helmet requirement for the 45 km/h moped has been identified in the focus group as an influential detractor. Including it would result in larger

[2] This study was conducted before the helmet obligation commencing on January 1st 2023 was announced



(a) Choice between two shared mopeds (b) Choice between car, bike and chosen moped

Fig. 1. Example of bi-level choice situation.

choice sets and therefore require more respondents. Bike is included as well, as it is a widely used mode in the Netherlands. Since the trip in this mode choice starts at home, it is assumed that respondents have a private bicycle at their disposal. Walking is not considered a viable option, as walking 8 km would take almost two hours. Included mode alternatives are thus the shared moped, private car and bike. Travel times for all modes are fixed. Attributes are chosen from the attributes generated by the focus group, based on their suitability (possibility to define levels) and relevance (does it make sense to include them, e.g. exclude attributes related to excluded modes). The bike alternative has no varying attributes, as no influential factors relating to bike emerged from the focus group. Levels for cost attributes were based on current pricing. Levels for time attributes were based on insights from the focus group: the lower levels represented the shortest time they had experienced, the higher levels represented the time they would be willing to spend on it. The following attributes and attribute levels are included:

- Access time: the walking time from the traveler's home to the shared moped position. Included levels are 2, 5 and 8 min;
- Moped costs: the total one-way trip price of the moped. Included levels: € 2, € 4, € 6, the latter is based on current pricing (± € 0,30 per minute);
- Return trip availability: represents the walking time range from the destination to a shared moped for the trip back home. Expressed as a 90% probability of a moped within X minutes. Included levels: 3, 7 and 11 min. A maximum walk time is provided for the remaining 10%, which is set to 15 min;
- Parking costs: costs for one hour of car parking, included levels are € 2, € 5 and € 8;
- Egress time: reflects the time needed to walk from the car parking spot to the destination. Included levels are 0, 5 and 10 min;
- Parking search time: the time needed to find a parking spot for the car. Included levels: 0, 5 and 10 min.

The final survey design is an efficient design created in Ngene. Ngene generated the choice sets with corresponding attribute levels. Such a design requires priors, which are obtained from the literature. The information gained in the focus group is used to improve or, in case no suitable value is found in the literature, estimate those. Respondents encountered nine choice sets of bi-level questions. First, they were asked to make a choice between two shared moped alternatives. In the subsequent question, their chosen moped alternative was put next to the car and bike. This construction is selected so as to elicit shared-moped preferences from all respondents, mitigating the risk of too few respondents choosing the moped option and thereby not receiving sufficient choice data pertaining to the shared moped service itself. An example of the bi-level question is shown in Fig. 1.

Table 1
Socioeconomic and demographic sample data.

Variable	Category	Sample proportion
Age	20–29	68%
	30–39	11%
	40–49	7%
	50–59	7%
	60–72	8%
Gender	Male	50%
	Female	50%
	Other	–
	Prefer not to say	–
Highest finished education	High school	3%
	MBO	3%
	HBO	10%
	University	85%
Household structure	Single no children	21%
	Single with children	2%
	With partner	34%
	With partner and children	9%
	Shared	36%
Household income	< € 10.000	25%
	€ 10.000–€ 40.000	30%
	€ 40.000–€ 70.000	19%
	€ 70.000 +	16%
	Prefer not to say	10%
Moped experience	Used	
	Heard of	
	Never heard of	

2.2.2. *Background variables*

In addition to the choice experiment, respondents were asked to provide some socio-economic and demographic information. The survey includes questions related to respondents' age, gender, household income, education level, household structure, travel frequency and shared moped experience.

2.2.3. *Data collection and sample characteristics*

The defined target group consists of individuals living in larger cities (100,000+ residents) with a valid car driver's licence (as a driver's licence is required for riding a shared e-moped) and access to a private car and bike. At the start of the survey, respondents were asked questions to determine whether they meet these requirements. Respondents who did not meet all requirements were excluded. Data was collected between December 7th 2020 and January 18th 2021 by distributing the survey via messaging apps, email and social media. This resulted in a convenience sample with a total of 191 complete and valid responses. Table 1 presents an overview of the sample characteristics for the collected background variables. The sample has equal shares of men and women and 56% have not yet made use of a shared moped service, allowing for the analysis of preferences amongst users and non-users. The majority of the respondents are younger than 30 years old and highly educated.

Note that the sample does not (intend to) represent the general population. Instead, the target group of our study constitutes a sub-population thereof consisting of individuals living in larger cities (100,000+ residents) with a valid car driver's license and access to a private car and bike. Since distributions of socio-demographic variables of members of this sub-population are not available, we cannot affirmatively assert whether the sample is representative of the target population or not.

This young, highly educated sample of 191 respondents, equally divided between men and women, is arguably likely to represent the segment of the population with a higher probability of using shared fleet services.

2.3. Model estimation

This subsection describes the procedure we undertake for choice model estimation. Since a sufficient number of respondents choose the moped option in the second mode choice situation, model estimation for this question was possible. The results of the experiment show that almost half (47%) of the respondents choose not to travel by moped under any realistic combination of travel attributes. For this group, there is no need to estimate a model to predict their choices for scenarios within the realistic range of attribute levels included in our survey. A subset of the data consisting of the respondents who chose the shared moped option at least once in the experiment, which amounted to 53% of the total sample or 101 respondents, was therefore created and provided as input for subsequent model estimation.

Three travel alternatives are included in the choice experiment: shared moped, car and bike. Bike is set as the reference alternative, because it has no associated attributes, and its utility is hence fixed to zero. The following models were estimated before selecting the most adequate model structure: a Multinomial Logit model, a Nested Logit model, a Panel Mixed Logit model with random parameters and a shared error component, and a Panel Mixed Logit model with random parameters, a shared error component and interaction effects. The final selected model is a Panel Mixed Logit model with random parameters, interaction effects and a shared error component. Model selection was based on the comparison of Log Likelihood values and model interpretability. Interaction effects are tested between moped experience and all parameters. The shared error component reflects the unobserved similarities between bike and moped. Each attribute is associated with two random parameters: one random parameter for the group with experience and one random parameter for the group without experience. Independent samples t-tests are used to determine whether the two separate parameters are significantly different, and if not, they were replaced by one generic parameter. Random parameters that obtained insignificant sigmas, i.e. the parameter capturing the unobserved heterogeneity for the respective attribute, were replaced by fixed parameters.

2.4. Post-experiment expert interviews

To formulate specific policy measures, expert interviews were conducted. Four interviews were carried out in March 2021 with different stakeholders to gain multiple and diverse perspectives. The stakeholders included a junior traffic engineer working for a large municipality, a mobility consultant working for a large consultancy firm, a mobility researcher working for an applied research institute and a founder and managing director of a shared moped company.

In these interviews, the results of the choice model estimation were discussed and used to come up with potential policies that can stimulate a behavioural switch from car to moped. The interviews were also used to construct relevant scenarios to be considered for further investigation in our model application.

Table 2
Results of the Panel Mixed Logit model with random parameters, shared error component and interaction.

Name	Unit	Value	Rob. *p* value
Generic parameters			
ASC_{moped}	[−]	0.690	0.389*
β_{AT}	[s]	−0.121	0.001
$\beta_{AV,lin}$	[s]	0.640	0.000
β_{PST}	[s]	−0.130	0.000
Parameters for experienced group			
$ASC_{car,E}$	[−]	2.330	0.000
$\beta_{AV,quad,E}$	[s]	−0.058	0.000
$\beta_{ET,E}$	[s]	−0.321	0.000
$\beta_{CPC,E}$	[Euro]	−0.742	0.000
$\beta_{SMC,E}$	[Euro]	−0.471	0.000
Parameters for inexperienced group			
ASC_{car}	[−]	1.680	0.000
$\beta_{AV,quad}$	[s]	−0.065	0.000
β_{ET}	[s]	−0.110	0.001
β_{CPC}	[Euro]	−0.410	0.000
β_{SMC}	[Euro]	−0.231	0.007
$v_{moped bike}$	[−]	−1.383	0.000
Initial loglikelihood		−998.639	
Final loglikelihood		−776.431	
Number of draws		1000	
Number of observations		909 (101*9)	

3. Choice model estimation results

The final model is a Panel ML model with generic as well as group-specific, and random as well as fixed parameters. In particular, it includes generic (and fixed) parameters for access time, park time, the linear component of return availability and the alternative specific constant for shared mopeds. All other parameters are group-specific, of which some are random and some are fixed.

A (random) shared error component (v), which is normally distributed, reflects the unobserved similarities between bike and moped. This model is the result of an iterative process, in which non-significant sigmas are excluded and parameter pairs that do not differ significantly are merged into one generic parameter. Models are estimated with PandasBiogeme (Bierlaire, 2020) using the following utility functions:

$$U_{moped} = ASC_{moped} + \beta_{AT} * AT + \beta_{SMC,E} * SMC + \beta_{AV,lin} * AV + \beta_{AV,quad,E} * AV^2 + v_{moped bike} + \epsilon_{moped} \quad (1)$$

$$U_{car} = ASC_{car,E} + \beta_{ET,E} * ET + \beta_{CPC,E} * CPC + \beta_{PST} * PST + \epsilon_{car} \quad (2)$$

$$U_{bike} = ASC_{bike,E} + v_{moped bike} + \epsilon_{bike} \quad (3)$$

In these equations, AT is the access time, SMC denominates the shared moped costs, AV represents the return availability, ET is the egress time, CPC corresponds to the car parking costs, and PST is the parking search time. Parameters with an E in the subscript vary based on previous moped experience. The shared error component, v, is a nesting parameter. Random parameters include ASC_{bike} (so for both groups), $ASC_{car,used}$, $\beta_{CPC,used}$ and $\beta_{SMC,used}$. Note that the return availability attribute is modelled as a combination of linear and quadratic components. This reflects the indication made by members of the focus group that with increasing return availability times the marginal increase in disutility, associated with this attribute, decreases. Furthermore, we find that the shared error component is significant for the inexperienced group.

The Rho^2 of the final model is 0.223. Model estimation results are shown in Table 2. Sigma parameters capture the unobserved heterogene-

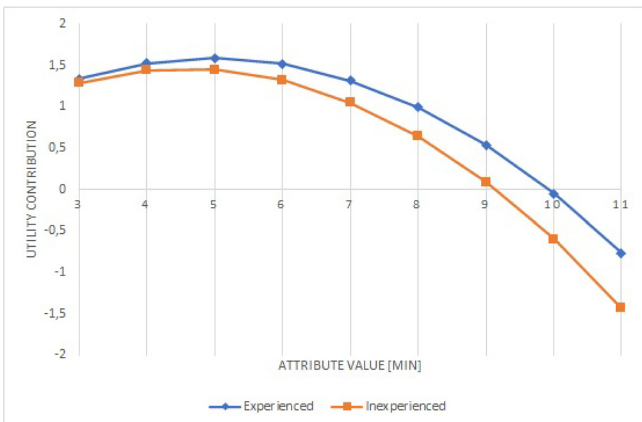


Fig. 2. The non-linear contribution of the availability parameter to travellers' disutility.

ity for the respective attribute. The Panel ML model converged using 1000 draws from a normal distribution.

All of the parameters included have the expected sign. The two return availability components cannot be evaluated individually, therefore a plot is added to illustrate the contribution of this attribute to disutility for both traveller groups (see Fig. 2). The slopes of the trendlines represent the change in utility with a one unit increase or decrease of the attribute. It can be seen that the utility for the inexperienced group is consistently lower than for the experienced one for the same attribute level. Regarding the cost attributes, car parking costs have a higher disutility than the shared moped service costs. This is true for both traveller groups.

Comparing the time attributes based on the disutility associated with one minute increase, egress time is the time attribute that is perceived most negatively by the experienced group. For the inexperienced group, the return availability is perceived most negatively. Access time and parking search time are roughly equal in this respect.

For some of the attributes, the standard deviations or sigma coefficients are also found significant. For the inexperienced group, no sigma related to a random parameter is found to be significant. This suggests that taste variation is not (widely) present in this group. Significant sigmas are found for the ASC for car and both cost attributes for the experienced group. Heterogeneity regarding car preference and taste for costs therefore is present in this group. A nest parameter is included to account for the unobserved similarities between shared moped and bike. This parameter is found to be significant for the inexperienced group. Respondents with no previous moped experience perceive hence similarities between shared moped and bike beyond the attributes explicitly accounted for in this experiment, e.g. lack of rain cover. For respondents with previous experience, this effect is not significant.

A comparison of the two groups shows that both cost parameters are higher for the experienced group. This group is thus more sensitive to a € 1 change in costs than the inexperienced group. With respect to the sensitivity to time attributes, the experienced group is most sensitive towards egress time as well as to return availability. The latter is also the attribute inexperienced group are most sensitive towards (see Fig. 2). We further investigate the differences between the two travellers groups and amongst different travel time attributes by investigating the Willingness to Pay (WtP) values for each time attribute. Table 3 presents the results, expressed in their value in hourly terms. An inspection of the share of respondents that have an experience with shared mopeds as a function of their household level does not reveal any clear relationship. Return availability is evidently an important factor for both groups, but especially for the inexperienced group. Egress time is more important for the experienced group than for the inexperienced travellers, whereas the opposite is true for Access time. The WtP for parking

Table 3
Calculated values of the willingness to pay (WtP) for a decrease of 1 h in travel time component for travellers experienced and inexperienced with shared moped services.

Value of travel time saving	Experienced	Inexperienced
Car: egress time	€ 25.95	€ 16.10
Car: parking search time	€ 10.54	€ 19.02
Moped: access time	€ 15.32	€ 31.30
Moped: return availability	€ 33.19	€ 88.70

search time amongst the inexperienced group is almost twice as much as the respective WtP for the experienced ones.

4. Model application

The estimated Panel ML model is applied to explore the potential market share for each mode under potential policy packages which are devised based on the expert interviews. A brief explanation of the scenarios, compared to the reference scenario is hereby provided:

- **Reduced city centre parking.** Parking spots are removed from the city centre; the fee for city centre parking is raised. Overall supply remains the same as (newly built) parking lots and garages outside the centre replace the removed spots.
- **Reduced overall parking.** City centre parking spots removed and increased parking fee, but no new parking locations to absorb parking demand.
- **Monetary incentives.** Parking costs are increased; moped costs are decreased.
- **Improved mopeds.** To make the moped more attractive, they become cheaper and are evenly distributed amongst clusters across the city.
- **Spatial redesign.** Car parking supply is reduced by removing parking spots from the centre. The shared mopeds are clustered and evenly distributed throughout the city.
- **Extended spatial redesign.** This scenario is similar to the previous one, supplemented with increased parking costs.
- **Masterplan.** All car attributes are set at their highest levels; all moped attributes are set at their lowest levels.

Sample enumeration is applied, which entails the construction of a synthetic population based on our sample. First, parameters were adjusted to account for unobserved heterogeneity by drawing from the estimated normal distribution. This was done for each random parameter included in the model. The final population consists of 30,941 synthetic individuals, which is an arbitrary number but considered sufficiently large to assure stable predictions. Choice probabilities per mode alternative are predicted for each synthetic traveller under each of the scenarios. The aggregate results when summed over the entire synthetic population are presented in Table 4. These numbers are interpreted as the market share per mode. Table 4 also displays the scenarios. In this model application exercise, the share of respondents that was excluded in the model estimation due to non-trading behaviour has been included again to obtain realistic market shares. The 'Ref' columns refers to the reference scenario. The reference scenario corresponds to the assumed baseline situation. Obviously, the parking situation differs per city and neighbourhood, but the chosen values are meant to reflect prevalent conditions. The same holds for access time and return availability. Moped costs are based on the current pricing level.

Simulations based on the estimated choice models indicate that making the car less attractive would have a larger influence on the market share of car than improving the attractiveness of the shared moped. Reducing the overall parking supply and raising parking fees (scenario 3) results in a substantial decrease in the market share of car from the level of 10,1% in the reference scenario down to 6,4% in the event of increased parking costs, egress time to parking and parking search time.

Table 4
Scenarios with attribute levels and market shares for all modes.

Scenario	1. Ref	2. Reduced city centre parking	3. Reduced overall parking	4. Monetary incentives	5. Improved mopeds	6. Spatial redesign	7. Extended spatial redesign	8. Master-plan
Moped costs	€ 6	€ 6	€ 6	€ 4	€ 4	€ 6	€ 6	€ 4
Access time	5 min	5 min	5 min	5 min	2 min	2 min	2 min	2 min
Return availability	7 min	7 min	7 min	7 min	3 min	3 min	3 min	3 min
Parking costs	€ 5	€ 8	€ 8	€ 8	€ 5	€ 5	€ 8	€ 8
Egress time	5 min	10 min	10 min	5 min	5 min	10 min	10 min	10 min
Parking search time	5 min	5 min	10 min	5 min	5 min	10 min	10 min	10 min
Market share								
Shared moped	20,2%	21,7%	21,9%	28,4%	30,4%	24,7%	25%	32%
Car	10,1%	6,7%	6,4%	7,1%	8,7%	6,9%	6,3%	6,3%
Bike	69,7%	71,5%	71,7%	64,4%	60,8%	68,4%	68,6%	61,8%

A small increase in bike market share is an unintended but desirable side effect. By limiting city centre parking (scenario 2), both these effects are achieved as well. A scenario that improves the shared moped offer by means of reduced costs, shorter access time and improved return availability (scenario 5: improved mopeds) is expected to decrease car market share to just under 9%. Moreover, in this scenario the predicted market share of bike decreases compared to the reference scenario, which is an undesired effect. Leaving both parking costs and moped costs unchanged but reducing parking supply and improving moped accessibility (scenario 6: spatial design) has quite a large effect as well, but mainly on the moped market share. The car market share is slightly lower than in the reference scenario, but the bike market share is lower as well. A combination of car-hindering and moped-stimulating measures (scenarios 7 and 8) leads to the lowest predicted market share for car. However, the market share for bike decreases compared to the reference alternative. This effect is stronger for scenario 8, which only differs from scenario 7 in moped costs.

5. Discussion and conclusion

We identify and quantify the role of determinants affecting a car driver's choice for a shared moped. Our analysis was guided by the goal of formulating policy measures to reduce the attraction of the car and make the shared moped an attractive alternative for it. A focus group was conducted to identify a set of potential choice determinants. We then devised a mode choice experiment to analyse and quantify the trade-offs exhibited by car users who are either experienced shared moped users or non-users. The mode choice experiment was part of an online survey which also included questions about socio-economic and demographic information. The results from the experiment were discussed in expert interviews to formulate policy measures to stimulate the switch from car to shared mopeds and those were specified and tested in model application.

People who have used a shared moped before value the attributes differently than people without any moped experience. A calculation of the Willingness to Pay (WtP) values shows that return availability of shared moped is the most influential time-related attribute for both groups. For people with moped experience, egress time is the second most important time attribute whereas for inexperienced travellers it is access time. Furthermore, travel costs, for parking as well as for moped, are important factors in explaining mode choices. Especially parking costs have a large influence on the attractiveness of the car. Raising the parking fee results in a low market share for the car and higher shares for moped as well as for bike. Lowering the moped costs makes the moped more attractive for car drivers, but also for cyclists.

Ideally, measures can be devised so as to attract car user to switch to shared moped while avoiding a strong reduction in bike use (for health and environmental reasons). To achieve that, it is advisable to focus on making car use more difficult. Raising parking fees is a good first step, which can be implemented fairly easily. A reduction of overall parking supply further enhances the negative effect on car attractiveness, while at the same time improving livability of the city. If desired, the freed-up space can be used to create moped parking spaces. Lowering moped costs is not advised, the model shows that this would primarily lead to a migration from bike to moped.

As this study is, to the best of our knowledge, a pioneering effort in conducting quantitative behavioural research in the context of shared moped services, there are hardly any comparable studies. A qualitative study investigating the shared moped is the one by Aguilera-García et al. (2020). They found that ease of parking was clearly the main reason for using shared mopeds. This is confirmed by our findings. Besides parking, they found that price, travel time and proximity to the final destination were important factors in the choice of means of transport. Apart from travel time, which was not included as an attribute in this study, their findings are endorsed by our choice modelling results.

It is important to stress that the results reported in this study are for a specific context, i.e. a 15 min car trip to run an errand, starting at home in a Dutch city (e.g. picking up a parcel), traveling alone and carrying a small bag and for a specific weather condition (19 °C, cloudy and dry) that we believe does not disadvantage either mode. Conclusions are only applicable to these specific situations. Hence, in bad weather conditions, the substitution of car travel by shared moped is likely lower than found in this study. Further research may explore the trade-off between moped and car under different trip circumstances. This can be done by extending the stated choice experiment by also varying context variables. This requires constructing context profiles that systematically vary the values of context variables. The mode choice sets then need to be nested under the context profiles to allow exploring to what extent choices change with changing trip circumstances (see van der Heijden et al. (2004) for an empirical application).

Our findings provide original insights into travellers' preferences in relation to shared moped, including for those that have not used them yet, thereby allowing to investigate the relevant determinants for both users and non-users and the extent to which they can become users-to-be under various circumstances.

Future studies might consider investigating other trip purposes and contexts. Another direction is to consider the 45 km/h moped, as this moped version has distinctive characteristics (e.g. helmet use and driving on the road) compared to the 25 km/h moped considered in this study. Future research may also examine the relationship between shared mopeds and public transport as well as walking.

Declaration of Competing Interest

Authors declare that they have no conflict of interest.

Acknolewdgements

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Exploring the elements of effective public cycle parking: A literature review

Robert Egan[a,*], Conor Mark Dowling[b], Brian Caulfield[a]

[a] Centre for Transport Research, Dept of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland
[b] Trinity Business School, Trinity College Dublin, Ireland

A R T I C L E I N F O

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A B S T R A C T

In the field of cycle policy and planning, alongside ambitions to expand segregated cycle networks, there is a push across many countries for increasing the quality and quantity of cycle parking as a critical component of cycling infrastructure. In order to support these measures, planning guides have been developed to guide the expansion and improvement of cycle parking facilities. A common feature of these policies and guides for cycle parking interventions is an absence of dialogue with, or reference to, peer-reviewed research investigating cycle parking and the potential effectiveness of different approaches to cycle parking planning. The use of such research could help to create cycle parking that may be more effective in attracting and providing for people cycling. On this basis, we engage in a literature review of a select body of cycling research whose findings could contribute to more effective cycle parking planning practice. Drawing on our review, we propose a number of tentative 'elements' for effective public cycle parking planning practice: *visibility, protection, accessibility, proximity, integration,* and *diversification*. These elements could be used in conjunction with local knowledge and context-specific assessment measures to maximise the potential effectiveness of cycle parking planning in different regions, and can be situated as part of a wider struggle to acquire public space for cycling within car-dominant contexts.

1. Introduction: cycle parking in policy and planning

Internationally, cycle parking is seen as a crucial component of facilitating and promoting cycling as a normal transport mode and as part of multi-modal journeys, as evidenced by the scale of its inclusion in international transport policies (e.g. Department for Transport, 2014; Director General for Passenger Transport, 1999; Federal Ministry of Transport & Digital Infrastructure, 2020; Le Gouvernement République Française, 2018; Tour de Force, 2017). According to Pucher, Dill and Handy (2010), both the quantity and quality of cycle parking is increasing sharply in various cities across Europe (see also, Buehler, Pucher, Gerike & Götschi, 2017), North America and Australia, as well as some cities in Asia and South America. While much parking internationally is unsheltered, there is a movement toward sheltered parking and, in Northern Europe, toward guarded parking facilities, including substantial implementation of 'bicycle stations' in the Netherlands, Germany, and Japan in terms of both the quantity of stations and station capacity. Through the provision of cycle stations situated near public transit stations, Pucher et al. (2010) report that cycle parking is the single most important integration measure in both Europe and Japan for rail and metro.

As two distinctly low-cycling sites within Europe with considerable ambitions to promote cycling, the UK and Ireland provide two particularly fruitful contexts to closely examine the status and position of cycle parking policy and planning. Within the relatively low-cycling context of the UK, specific policy directives and planning guidelines promote cycle parking as a means to increase cycling journeys. In England, actioning aspects of the Walking and Cycling Investment Strategy (Department of Transport, 2017), the Department of Transport (2020b) reported the installation/upgrade of 3380 cycle parking spaces in numerous cities across the country in addition to installing 4000 cycle parking facilities near rail stations in order to facilitate multi-modal journeys. There are various high-quality planning guides for delivering cycle parking available, such as Transport for London's (2016) 'London Cycle Design Standards'. In Scotland, national policy aims to increase secure cycle parking and to engage in a concerted effort to use the provision of secure cycle parking facilities to increase public transport integrated journeys (Transport Scotland, 2017). For Wales, the national 'Active Travel Action Plan' (Welsh Government, 2017) posits an ambition to "consider and enhance provision for walkers and cyclists" (p. 32) when directly investing in any transport infrastructure projects along with making other funding mechanisms for active travel infrastructure and projects available. More recently, the Welsh Government (2021) have released a comprehensive 'Active Travel Act Guidance' document for constructing high quality active travel infrastructure. In this document, cycle parking planning is covered in detail in relation to selecting the quantity and cycle

* Corresponding author.
E-mail address: eganr5@tcd.ie (R. Egan).

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parking type for a given destination. Lastly, in Northern Ireland's official cycling strategy (Department for Regional Development, 2015), cycle parking features as a fundamental component of the 'Build' pillar of a 'three pillar' approach to increasing rates of ridership, once again highlighting the importance of on-street public cycle parking, the availability of secure cycle parking options, and the need for cycle parking at public transport transfer locations to promote integrated journeys.

Examining the Republic of Ireland, the provision of secure parking constitutes one of the main objectives stated in the relatively dated National Cycle Policy Framework (Smarter Travel, 2009): Ireland's first and only national cycle policy to date. In this policy paper, Smarter Travel (2009) argue that the supply of "well-located, plentiful, sheltered and secure parking facilities is as important to the cyclist as the provisions for moving cyclists" (p. 27). In this respect, as a form of cycle infrastructure, cycle parking should not be considered an optional add-on for cycle networks but instead as an essential cycling infrastructure for current and potential cyclists. Among other measures, this framework proposes the construction of high-capacity guarded bicycle parks and exploring paid cycle parking stations with associated cyclist services and amenities. In this way, aspects of the National Cycle Policy Framework are arguably more expressly ambitious than some recent policy and planning emerging from the UK (e.g., Department of Transport, 2014; Transport Scotland, 2017; Welsh Government, 2021).

Complementing the National Cycle Policy Framework (Smarter Travel, 2009), the 'National Cycle Manual' (National Transport Authority, 2011) provides a guide for planning cycling related infrastructure in Ireland, including cycle parking. Overall, the manual provides a good guide for planners unfamiliar with cycling parking interventions in terms of important factors to consider (e.g., proximity to destinations, likely durations of use; 'convenience', 'cost', and 'quality') and nuances to understand (e.g., cycle parking types beyond the unsheltered 'Sheffield stand'); however, the manual is relatively inconsistent in terms of its guidance for cycle parking (e.g., where a stand should go versus a guarded compound) – prescriptive in some instances, relativist in others – and, alike other high-level planning guides (Transport for London, 2016; Welsh Government, 2021), no peer-reviewed evidence is cited to back up claims made regarding the likely effectiveness of cycle parking interventions.

More generally, cycle parking planning guidance appears to lack a coherent body of design principles that are widely and consistently used. This stands in stark contrast to cycle network infrastructure planning guidance, of which there is evidence that many design guides (e.g., Department of Transport, 2020a; Transport for London, 2016; Welsh Government, 2021), including the 'National Cycle Manual' (National Transport Authority (2011), adopt critical elements of the CROW Design Manual for Cycle Traffic (Groot, 2016); namely, that cycle network infrastructure ought to be designed in such a way that it is *safe, direct, coherent, attractive,* and *comfortable* for users. A gap in distinctive cycle parking design principles can be seen, for example, in the Welsh 'Active Travel Act Guidance' (Welsh Government, 2021), which appears to draw on CROW cycle network design principles for cycle parking planning despite the arguably very different functions of both infrastructures. Similarly, Van der Spek and Scheltema (2015) refer to CROW principles in considering how to plan optimal cycle parking in the Netherlands. The difficulty to decisively determine what elements or design principles should be incorporated in the planning of effective cycle parking is apparent in this article, as the authors refer a wide range of factors to consider but do not appear to offer a consolidated framework for good quality cycle parking planning. In this respect, there appears to be not only an lack of peer-reviewed research being used in cycle parking planning policy and guidance, but also a dearth of well-established and widely-endorsed cycle parking specific planning principles to consider.

Perhaps one explanation for this apparent policy and planning neglect for cycling parking relative to cycling mobility infrastructure is that, outside of high-cycling contexts, cycling is not considered to be a legitimate form of *utilitarian* transport relative to other modes, and thereby may not be considered a mode that requires robust parking facilities (Aldred, 2012; Bonham and Cox, 2010; Petzer, Wieczorek & Verbong, 2021; Van Der Meulen & Mukhtar-Landgren, 2021). This is evidenced by policy and planning representations of cycling with leisure journeys (which of course may not involve an end destination) and slowness (Aldred, 2012; Bonham and Cox, 2010; Van Der Meulen & Mukhtar-Landgren, 2021); reducing the externalities of the car and promoting health, rather than enabling transport accessibility (Aldred, 2012; Van Der Meulen & Mukhtar-Landgren, 2021); and local rather than nationally strategic transport objectives (Aldred, 2012; Van Der Meulen & Mukhtar-Landgren, 2021). Van Der Meulen and Mukhtar-Landgren (2021) have also alluded to the lack of quantification of accessibility provided by cycling relative to driving and rail transport as evidence for cycling's marginalisation as a strategically important transport mode in Sweden, where both accessibility and its measurement are major components of national transport policy.

A prevailing conception of cycling as a transport mode of marginal strategic significance is also reflected in the weakness of official spatial allocation mechanisms for cycle parking within the EU relative to car parking. Examining the relatively lower-cycling contexts of Birmingham and Brussels, Petzer et al. (2021) has revealed how the regulatory mechanisms for cycle parking allocation have historically been weak, whereas car parking allocation has been supported by a multitude of legally binding 'parking minimums' for new developments; Amsterdam, on the other hand, demonstrates a reversed scenario, in which car 'parking maximums' have been nationally instituted, while cycle parking minimums have been enshrined in planning policy. Importantly, Petzer et al. (2021) observes that while car parking can generate significant revenue, cycle parking is often free. This may provide another partial explanation for the apparent reluctance to consider cycle parking as intently as cycling mobility infrastructure; however, Petzer et al. (2021) points out that car parking provision is often heavily subsidized.

In light of national and international policy and planning directives to promote cycling, which explicitly highlight the importance of cycle parking but do not necessarily base their directives on peer-reviewed research evidence nor employ well-established design principles, the purpose of this review is to explore how existing peer-reviewed research relating to cycle parking can practically inform cycle parking planning efforts. In this respect, the review could complement and inform transport and cycling-specific policy in addition to cycle parking planning guidance at national (e.g., National Transport Authority, 2011) and local (e.g., Dún Laoghaire-Rathdown County Council Municipal Services Department, 2018) levels.

In relation to existing literature, this article provides a review of seminal studies examining cycle parking with a focus on guiding policy and planning practice. This complements the recent systematic review of cycle parking research by Heinen and Buehler (2019), which demonstrated empirical and methodological gaps within existing studies investigating cycle parking and the broad areas of consensus that appear across the literature (e.g., secure is generally favourable to unsheltered and unguarded; closer to destination is often preferred to more distant; free is often preferred to paid). Critically, this review is focused on extracting nuanced policy and planning insights from existing seminal studies rather than systematically reviewing the state of cycle parking research and how it can be advanced, which has already been comprehensively executed by Heinen and Buehler (2019).

First, we explain the approach taken for this literature review. Second, the review examines research that has been carried out investigating the role and impact of cycle parking in relation to cycle-public transport integration – an area that has been studied substantially. Third, the review outlines and discusses research focusing more generally on publicly available cycle parking. Fourth and last, the review presents a table of elements relating to effective public cycle parking that could inform cycle parking planning and that is based on the peer-reviewed evidence reviewed and situates these elements within a wider socio-technical consideration of the importance of cycle parking.

2. Method

The research question for this review was 'How can cycle parking-related research guide cycle parking policy and planning?' This question was used to help to identify key elements that policy-makers and planners might consider when planning cycle parking to either meet existing cycle parking demand, promote greater or more diverse cycle ridership, and/or increase public transport use by accommodating multi-modal journeys involving cycling. The databases of Science Direct, JSTOR, Taylor & Francis and SAGE were searched for peer-reviewed articles relevant to the research question due to their inclusion of various high-quality transport-related journals. Due to the scarcity of literature focusing on the area of cycle parking, the broad search terms of "cycle parking" OR "bicycle parking" OR "bike parking" were used. Article titles were initially examined in relation to their relevance to the research question and abstracts were next examined using various inclusion and exclusion criteria. Namely, articles selected were required to meet the following criteria: utility cycling as focus, cycle parking as significant variable or focus, public cycle parking, empirical focus. On the other hand, articles were excluded for consideration on the basis of the following criteria: station-based bike sharing, bike sharing focus, school parking, residential/private parking, methodological focus. Importantly, numerous methodologically focused articles were identified that were relevant to the research question broadly defined; these articles propose promising methods to aid the planning of cycle parking facilities based on various criteria (e.g., Fazio, Giuffrida, Le Pira, Inturri & Ignaccolo, 2020; Veillette, Grisé & El-Geneidy, 2018; Zhao & Ong, 2021). However, our aim was not to provide a sophisticated or innovative methodology for operationalizing various criteria for cycle parking planning but, instead, to derive in part how existing empirical research evidence can guide the development of numerous criteria for cycle parking planning policy and practice. With these grounds for inclusion and exclusion in mind, this search culminated in 24 articles which we review in this paper and use as a basis for our proposed 'Elements of Effective Public Cycle Parking Planning' section.

Overall, we examine two thematic study areas on the basis of their primary content: i) *public transport integration*, in which cycle parking is primarily examined as a measure to promote public transport integrated – and therefore multi-modal – journeys; and, ii) *public cycle parking*, in which cycle parking is explored more generally, such as in relation to cycling-only journeys. Our categories reflect a focus on publicly available cycle parking (versus private- or institutionally-specific parking) – hence the lack of inclusion of work, school, university and home parking (see Heinen & Buehler, 2019) – and are framed on the basis of the purpose of the studies (i.e., multi-modal integration, uni-modal journeys). In the following two sections, we review the selected studies in dialogue with our proposed 'Elements of Effective Public Cycle Parking' (Table 2), which originate from this review.

3. Public transport integration

There has been considerable research investigating cycle parking as measure for integrating cycling with public transport, particularly metro and rail (Appleyard & Ferrell, 2017; Arbis, Rashidi, Dixit & Vandebona, 2016; Bachand-Marleau, Larsen & El-Geneidy, 2011; Chen, Pel, Chen, Sparing & Hansen, 2012; Halldórsdóttir, Nielsen & Prato, 2017; Harvey, Brown, DiPetrillo & Kay, 2016; Jonkeren & Kager, 2021; Krizek & Stonebraker, 2011; Martens, 2007; Mitra & Schofield, 2019; Molin & Maat, 2015; Paix, Cherchi & Geurs, 2021; Ravensbergen, Buliung, Mendonca & Garg, 2018; Weliwitiya, Rose & Johnson, 2019; Yang, Zhao, Wang, Liu & Li, 2015). Table 1 below details the diverse methodologies employed in these studies and the internationally varied contexts in which the studies were carried out. These different countries and regions have very different levels of cycling and cycle parking provision and, therefore, could each be seen to have specific cycle parking challenges and needs. It is notable that the vast majority of these studies are quantitative, which arguably demonstrates a lack of more exploratory and in-depth inquiries into the likely differentiated experiences and practices of cycle parking in relation to public transport integrated journeys, which could be extremely useful in informing future promotional efforts.

The need for *protection* (refer to Table 2) – primarily protection of one's cycle from theft, but also protection from the natural elements – is one strong element that emerges as prevalent across numerous studies in the thematic area examining cycle parking as a public transport integration measure (Appleyard & Ferrell, 2017; Arbis et al., 2016; Bachand-Marleau et al., 2011; Chen et al., 2012; Halldórsdóttir et al., 2017; Harvey et al., 2016; Ravensbergen et al., 2018; Weliwitiya et al., 2019; Yang et al., 2015).

In a mixed-methods study based in New Jersey, U.S., Harvey et al. (2016) carried out a station infrastructure inventory of 214 stations, an intercept survey with 158 transit users, and a focus group with eight participants. Interestingly, Harvey et al. (2016) found major discrepancies in the supply and use of formal cycle parking across the sample of stations, in which only a small minority of stations had parking facilities that were being heavily used (i.e., only 13% of stations had cycle parking that was between 75% - 100% occupied). As Harvey et al. (2016) argue, this suggests that cycle parking installation does not equate to 'build it and they will come', as only about half of the bicycle parking spaces recorded in this study were occupied. However, 'security' was raised as a major built environment issue by participants in the intercept survey and focus group, particularly in relation to cycle theft; indeed, in the focus group, participants "recommended more and improved bicycle parking, as well as an increased presence of police or security" (p. 58). In this respect, protection could be considered from the perspective of physically protective cycle parking facilities (such as cycle compounds or lockers) and protection through the professional guarding of cycles – both of which go beyond the protection provided by open cycle racks alone. This call for improved cycle protection – and evidence of a shared concern with insufficient protection from theft, but also shelter from weather conditions – is mirrored in the survey study of Ravensbergen et al. (2018), which explored the challenges of, and barriers to, cycle-transit use amongst people living in the Greater Toronto and Hamilton areas of Canada.

Similar to Harvey et al. (2016), Weliwitiya et al. (2019) implemented a quantitative study that included both observational (i.e. cyclist counts) and built environment data to investigate cycle-public transport integration – particularly cycling as an access mode – in the context of Melbourne, Australia. They found that, out of the 203 rail stations, 73 had 'secure' cycle parking (in the form of a locked cycle cage), numerous stations had unsheltered cycle hoop parking, and all stations had some form of parking (inclusive of street furniture). Unlike Harvey et al. (2016), who did not engage in a formal analysis of data, Weliwitiya et al. (2019) found that the availability of secure caged (i.e., physically protected) parking was associated with higher levels of cycling as an access mode to rail stations; more specifically, cycling as an access mode was reportedly 0.542 times lower at stations without protected parking facilities compared to stations with protected parking facilities. Thus, alike Harvey et al. (2016) and Ravensbergen et al. (2018), the study of Weliwitiya et al. (2019) reveals a preference amongst transit users for protected cycle parking facilities (i.e., in the form of a locked cycle cage/compound) in a different context.

By drawing on police data, Appleyard and Ferrell's (2017) study on the influence of crime on access journeys to Bay Area Rapid Transit (BART) services in Northern California further supports the importance of *protection* as an effective cycle parking element which can be derived from Harvey et al. (2016), Ravensbergen et al. (2018), and Weliwitiya et al. (2019). On the basis of multinomial logit modelling analysis, they reported that cyclists to BART services were highly sensitive to property crime at BART stations and were not deterred by violent

Table 1
Cycle Parking Public Transport Integration Study Characteristics.

Author	Context	Methodology
Martens, 2007	Netherlands	Case Study / Policy Analysis
Bachand-Marleau et al., 2011	Montreal, Canada	Quantitative – Self-Reported Behaviour & Preferences
Krizek & Stonebraker, 2011	U.S.A.	Quantitative – Focus Group Survey & Manufacturer Cycle Parking Costs
Chen et al., 2012	Nanjing, China	Quantitative – Self-Report Data
Molin & Maat, 2015	Delft, Netherlands	Quantitative – Stated Choice Experiment
Yang et al., 2015	Nanjing, China	Quantitative – Self-Report Data
Arbis et al., 2016	New South Wales & Sydney, Australia	Quantitative – Observational & Spatial Data
Harvey et al., 2016	New Jersey, U.S.A.	Mixed Methods – Self-Report & Observational Data, Focus Groups
Appleyard & Ferrell, 2017	Northern California, U.S.A.	Quantitative – Survey, Crime & Spatial Data
Halldórsdóttir et al., 2017	Copenhagen, Denmark	Quantitative – Self-Report & Observational Data
Ravensbergen et al., 2018	Greater Toronto & Hamilton, Ontario, Canada	Mixed Methods – MCQ & Qualitative Self-Report Survey
Mitra & Schofield, 2019	Toronto, Canada	Quantitative – Self-Report & Spatial Data
Weliwitiya et al., 2019	Melbourne, Australia	Quantitative – Observational & Spatial Data
Jonkeren & Kager, 2021	Netherlands	Quantitative – Self-Report Data
Paix et al., 2021	The Hague & Rotterdam, Netherlands	Quantitative – Stated & Revealed Preference Survey

crimes at the station: violent crime was in fact positively associated with cycle access journeys. Importantly, the authors note that most of the cycle access respondents were male (similar to Harvey et al., 2016), so the positive association with violent crime could indeed be different if cycle access respondents were primarily women, who may face greater risks of victimisation (Kearl, 2010; Vera-Gray, 2018). In light of their findings, the authors call for more protected cycle parking facilities to address cycle property crime that appears to deter cycle access journeys to rail services. Furthermore, the study usefully shows how the degree of protection that may be suitable for a given public transport integration focused cycle parking facility can be informed by location-specific data regarding theft.

While the previous studies provide evidence for the importance of *protection* as an element for effective cycle parking on the basis of stated preference (Harvey et al., 2016; Ravensbergen et al., 2018), observed preference (Weliwitiya et al., 2019), and in relation to cycle access behaviour in the context of crime (Appleyard & Ferrell, 2017), what is not investigated is how different durations of cycle parking might influence (amongst other things) individual preferences and requirements for cycle parking protection at public transport stations. This aspect of cycle parking practice can be usefully examined drawing on the work of Chen et al. (2012), Halldórsdóttir et al. (2017) and Yang et al. (2015). First, examining cycle parking in China, Chen et al. (2012) implemented a quantitative study in which they surveyed transit users from two metro stations (500 respondents) and from the surrounding neighbourhoods of these stations (1284 respondents) in Nanjing. As part of this survey, Chen et al. (2012) measured the cycle parking time and duration at bicycle-metro transfer facilities of respondents, offering five time categories. They discovered that for one station – that was situated in a residential area – respondents predominantly parked for 8 h + (32%); in contrast, for the other station – which was located in a shopping area – respondents predominantly parked for 4–6 h (37%). On this basis, they found that cycle-transit users may be more likely to park for longer durations if their access station is in a residential area compared to a shopping area, thereby indicating the importance of land use patterns for cycle parking durations. These findings may have implications for the appropriate level of protection (i.e., from the natural elements, theft and vandalism) of cycle parking depending on station location and the associated predominant parking durations for such locations.

However, while such questions of protection are not explicitly examined in the study of Chen et al. (2012), the studies of Halldórsdóttir et al. (2017) and Yang et al. (2015) – which explicitly consider the relationship between cycle parking duration and appropriate level of protection – lend credibility to such a hypothesis. Namely, in a Copenhagen-based study, Halldórsdóttir et al. (2017) observed that the availability of sheltered cycle parking significantly increased the probability of cycling to rail stations – excluding metro stations – at the activity end; the authors comment that this increase may be due to the use of second cycle by rail users in Copenhagen. That is, with covered facilities, more rail users might be motivated to make use of a second cycle at their activity-end station, due to the shelter covered facilities would provide for long-term, overnight parking, which may not be required for home-end journeys to the same extent. Similarly, in a Nanjing metro commuter satisfaction study, Yang et al. (2015) hypothesised – but also found evidence for – a relationship between a preference for more protected cycle parking and longer parking duration. Namely, the researchers reported that their respondent group that engaged in cycle access and walk egress ('Cycle-Metro-Walk') were most dissatisfied with cycle parking availability in relation to cycle parking facilities, while, for the cycle access and bus egress group ('Cycle-Metro-Bus'), the authors reported that cycle parking security was the major cycle parking-related dissatisfier. Interrogating these findings, the authors reported that 'Cycle-Metro-Bus' users had similar duration access journeys but longer duration egress journeys compared 'Cycle-Metro-Walk' users. This difference in duration, the authors argue, likely results in longer cycle parking times at the home-end metro station for 'Cycle-Metro-Bus' users, thereby potentially increasing their concerns for the safety of their parked cycles. In this way, these results – alike Halldórsdóttir et al. (2017) – suggest that longer parking durations may warrant greater protective measures for cycles in parking planning interventions (both in these sense of protection from theft and protection from weather conditions).

In keeping with the above studies with which we have argued for multi-faceted considerations for cycle parking *protection* (see Table 2), the study of Arbis et al. (2016) likewise indicates the importance of ample and appropriate cycle parking protection for promoting cycle access journeys to public transport. However, in addition, Arbis et al. (2016) discovered a preference amongst cycle access train users for parking that is proximal to the station and highly visible to the public, and they speculate on the potential security implications of the public visibility of cycle parking. In this way, this work demonstrates how planning the degree of appropriate cycling parking protection for a given parking facility ought to be informed in part by other considerations that may negatively or positively impact the perceived and/or observed security of cycle parking: in particular, the public *visibility* of cycle parking and the *proximity* of cycle parking to public transport stations (see Table 2). Drawing on observed spatial data from 248 Australian train stations, the authors examined the use and characteristics of open-air (including use of street furniture) and protected cycle parking (cycle lockers). They found that cyclists revealed a preference to park as close as possible to public transport station entrance which, Arbis et al. (2016) argue, is a means of reducing walking distance to access the station; this is similar to the findings of Ravensbergen et al. (2018), in which survey participants raised the challenge posed by long distances between cycle parking facilities and rail

Table 2
Elements of Effective Public Cycle Parking.

Visibility	• Maximise the public visibility of open cycle parking (Aldred & Jungnickel, 2013; Arbis et al., 2016; Chen et al., 2018; Harvey et al., 2016; Hull & O'Holleran, 2014; Lierop et al., 2015).
Protection	• If public visibility is sub-optimal and/or existing open cycle parking is not well used, protected cycle parking may be appropriate (Arbis et al., 2016; Bachand-Marleau et al., 2011; Harvey et al., 2016; Ravensbergen et al., 2018; Weliwitiya et al., 2019) – which can involve professional supervision and/or physically protected facilities. • The likely duration of cycling parking (Chen et al., 2012; Halldórsdóttir et al., 2017; Pucher et al., 2010; Yang et al., 2015) may be considered in relation to appropriate protection from theft and weather conditions. • The supply of ample formal cycle parking may reduce incidents of fly-parking, thereby improving cycle protection (Aldred & Jungnickel, 2013; Lierop et al., 2015). • Station property crime data (Appleyard & Ferrell, 2017) and "passenger patronage" (Arbis et al., 2016, p. 503) may inform the appropriate level of protection needed for cycle parking at rail stations.
Accessibility	• In order to accommodate disabled cyclists and non-typical cycles, provide parking for specialist and adapted cycles, enable wheeled access to the point of cycle parking itself, and make available alternatives to cycle parking that require lifting one's cycle (Parkin et al., 2018). • In the case of high demand for cycle parking, parking management measures in relation to cost and proximity to destinations can be implemented to prioritise particular cycle parking practices and users – such home-end cycle-rail parking (Jonkeren & Kager, 2021) and frequent rail users (Paix et al., 2021).
Proximity	• Maximise the proximity of cycle parking to user destinations (Aldred & Jungnickel, 2013; Arbis et al., 2016; Lierop et al., 2015; Paix et al., 2021; Ravensbergen et al., 2018).
Integration	• Consider existing cycles (e.g., their value, type), locking and parking practices, and parking facilities – namely, the existing cycle parking system – when planning public cycle parking (Larsen, 2017; Martens, 2007). • To maximise impact, cycle parking interventions should take place as one measure amongst a "coordinated implementation of the multi-faceted, mutually reinforcing set of policies" (Pucher & Buehler, 2008, p. 525) to promote ridership, such as networked, segregated cycling facilities and restrictions to car use. • To promote public-transport integrated journeys, target cycling as an access mode for rail users through the provision of cycle parking (Bachand-Marleau et al., 2011; Martens, 2007; Mitra & Schofield, 2019; Pucher & Buehler, 2008; Pucher et al., 2010).
Diversification	• In order to satisfy diverse preferences amongst different users, public transit stations could benefit from a mix of cycle parking, particularly in terms of protection (Molin & Maat, 2015). • Diverse public cycle parking types (e.g., 'Locked', 'Guarded', 'Open') could be provided to maximise aggregate cycle journeys, improve the inclusivity of ridership, and/or facilitate diverse cycle-activities, such as cycle-shopping (Egan, Dowling, & Caulfield, 2022).

platforms in integrating their cycle-rail journeys. However, in addition, Arbis et al. (2016) hypothesise that parking as close as possible to the station entrance may also be a way of making openly parked cycles more visible to nearby pedestrians in order to prevent theft and vandalism, thereby presenting potential crossovers between *visibility, protection* and *proximity* as potential elements for effective public cycle parking from a cycle security perspective.

On the basis of both these interpretations, Arbis et al. (2016) recommend that open-air cycle parking facilities should be placed "conspicuously to the public eye" (p. 503), which they suggested was within 30 m of a transit station entrance: in other words, by increasing *visibility* (including by increasing *proximity*), less physical *protection* is required. They argue that protected cycle parking (in this case, cycle lockers), however, can be placed at a greater distance if space near the entrance is not available, since this form of parking does not require public surveillance like insecure parking: that is, with greater parking *protection*, there may be less need for *visibility* and *proximity*. Furthermore, Arbis et al. (2016) reported that more open-air cycle parking was associated with the presence of various streetscape features such as bus stops, shops, visibility from station platforms and CCTV cameras – all of which provide some form of passive surveillance (i.e. they enhance parking *visibility*). In this respect, open-air cycle parking interventions could be more effective if they are placed with these features present (Arbis et al., 2016). Lastly, Arbis et al. (2016) argue cycle parking interventions (e.g., installing protected vs open parking) can be informed by the level of use or "passenger patronage" (p. 503) of a given station. In this study, stations with less passengers displayed higher use of protected cycle parking versus open cycle parking, despite the cost of protected parking; this indicates that protected parking may be more useful and appropriate for smaller stations, potentially due to the decreased passive surveillance if one parks their cycle in an open parking facility – another potential element to consider along with crime data (Appleyard & Ferrell, 2017) to inform the protective aspect of a planned cycle parking facility.

The public transport integration studies discussed thus far lend support to the elements of *protection, visibility* and *proximity* for cycle parking as an effective public transport integration measure. Two studies in this thematic area suggest the importance of an additional element: *accessibility*, by which we mean the physical and financial accessibility of cycle parking for different potential users. Both the studies of Jonkeren and Kager (2021) and Paix et al. (2021) – which were both based in the uniquely high-cycling context of the Netherlands – suggest that particular cycle parking practices and users can be prioritised when there is an excess of cycle parking demand in relation to supply. In particular, Jonkeren and Kager (2021) found that the practice of parking second bicycles at activity-end rail stations in the Netherlands – a practice also examined by Halldórsdóttir et al. (2017) – generated a great deal more 'parking pressure' than home-end rail station cycle parking. On the basis of their analysis, they argue for various ways to free up high-demand station parking space from second bicycles, such as through pricing measures to disincentivise longer term parking and providing free facilities further away from stations for second cycles. In this way, by varying the conditions for particular cycle parking practices (e.g., charging for long-term parking and/or making it less proximal), planners can prioritise particular practices over others. In this case, they can disincentivise the use of second bicycles through increasing parking cost and distance. The work of Paix et al. (2021), on the other hand, found that 'frequent' train users for the Rotterdam and Hague region were far more sensitive to changes in both the cost of parking and walking time required from parking to platform than 'infrequent' train users. On the basis of this finding, they interpret that discounting the cost of cycle parking and reducing the time it takes to walk to the train platform from parking facilities could increase demand for cycling as a feeder mode amongst frequent train users.

The study of Molin and Maat (2015), on the other hand, speaks to questions of accessibility in terms of cost and proximity (Jonkeren & Kager, 2021; Paix et al., 2021), but instead of manipulating cycle parking accessibility to prioritise particular practices, demonstrates how cycle parking may be planned to facilitate a diversity of preferences and priorities in relation to *visibility, protection, proximity,* and *accessibility* (see Table 2). On these grounds, this study informs the element of *diversification* (Table 2), which relates to the potential cycle-promoting effects of diversifying cycle parking measures to facilitate a diversity of cycle parking practices and users. Analysing data from a stated choice experiment with 886 train travellers who parked their bicycle at Delft station in the Netherlands, Molin and Maat (2015) modelled the preference tendencies of four different types of user: 'free facility lovers' (26.5%), 'price sensitive cyclists' (34.1%), 'walking time sensitive cyclists – mode switchers' (20.3%), and 'paid facility lovers' (19.1%). Specifically, there were unique patterns of preferences amongst the four groups relating to cost of parking, security of parking, walking distance from station, and supervision of parking (i.e., in relation to Table 2, *accessibility, protection, proximity*, and *visibility*), and the younger respondents were, the more likely they were to belong to the first three types of cycle-transit user. This research suggests that stations would benefit from a mix of cycle parking – particularly in terms of *protection*, which could involve trade-offs with *accessibility* and *proximity* – to accommodate a mix of user preferences with differentiated parking priorities. Importantly, the *protection* discussed in relation to this study primarily relates to the professional supervision of cycle parking as opposed to the use of an independently physically protective enclosure in which one can park their cycle, such as a cycle compound or locker.

Lastly, various studies suggest that prioritising cycle parking for access journeys to rail is one of the most fruitful means of promoting integrated cycle-public transport journeys (Bachand-Marleau et al., 2011; Jonkeren & Kager, 2021; Krizek & Stonebraker, 2011; Martens, 2007; Pucher et al., 2010). In this respect, we derive the element of *integration* (see Table 2) as it relates to cycle-public transport integrated journeys, by emphasising the provision of cycle parking for cycle access journeys to rail as the most supported multi-modal integration measure across the literature reviewed. Martens (2007) documents the major initiatives to promote cycle-rail integration in the Netherlands, detailing the major policy initiative of the Netherlands – the 'Bicycle Master Plan' – and how it involved various experimental and research measures to promote cycle-public transport integration, such as cycle stations, cycle lockers and improved cycle parking at public transport hubs, and the subsequent policy initiative to upgrade cycle parking facilities at all train stations in the country known as 'Space for the Bicycle'. As part of this policy, guidelines were delineated to promote greater use of cycle and ride and to enhance the quality of the cycle and ride experience. In evaluating these efforts, Martens (2007) reports that the promotional measures for access trips by bike for train journeys have generally been successful in the Netherlands due to upgrades in cycle parking, with evidence of increased user satisfaction, more cycles being parked at stations, and increased access trips to rail by cycling; this contrasts with the limited success of interventions to promote cycle-bus service integration and shared cycle egress services.

Similarly, the study of Bachand-Marleau et al. (2011) supports cycle parking as a primary measure for cycle-public transport integration. Investigating patterns of cycle-transit use preferences amongst a public survey sample from Montreal, Canada (N: 1432), the authors reported that "good-quality bicycle parking facilities will be most useful to regular commuters, whereas racks on vehicles will appeal more to those irregularly using C-T" (Bachand-Marleau et al., 2011, p. 114). However, since data on the quality and quantity of cycle parking was not collected, Bachand-Marleau et al. (2011) remark that the strong preference amongst the sample for cycle-bring-cycle as a cycle-transit mode may be due to cycle parking that is not of sufficient protection or supply at present to be considered a genuine or attractive option due to a risk of cycle theft, for example – thereby bringing in the importance of *protection* (Table 2). This argument is further supported by the study of Krizek and Stonebraker (2011), who reported that their U.S.A. focus group participants generally favoured 'bike on transit' over other public transit integration strategies including 'bike to transit' – which the authors found was far more cost effective – while repeatedly raising the issue of insecure cycle parking facilities. Furthermore, using a similar methodology for the user typology to Bachand-Marleau et al. (2011), Mitra and Schofield (2019) found the 'secure' cycle parking was the most important end-of-trip facility by a substantial margin for rail user groups who were either the most frequent cycle-access rail users ('All-Purpose Cyclists'), or were the most interested in engaging in cycle access journeys ('Recreational Cyclists'). In this way, the provision of cycle parking that is perceived and/or observed as 'secure' (which may depend on the degree of physical *protection* and/or public *visibility* provided) may favour the greatest promotion of cycle-public transport integrated journeys (Krizek & Stonebraker, 2011), but there is a possibility that less frequent users may be more orientated to bringing their cycle on board public transit services (Bachand-Marleau et al., 2011) in particular contexts.

4. Public cycle parking

In the previous section, we examined research explicitly related to cycle parking as a public transport integration measure, deriving and introducing five elements for effective public cycle parking: *protection, visibility, proximity, accessibility, integration* and *diversification* (Table 2). However, research exploring cycle parking as either a variable or as a focus has been carried out not only (although predominantly) on station parking for public transport integration but also for publicly available cycle parking, in which cycling is not necessarily part of a multimodal journey (Aldred & Jungnickel, 2013; Hull & O'Holleran, 2014; Larsen, 2017; Lusk, Wen & Zhou, 2014). Studies in this area have included qualitative work looking at the status of bicycles in low cycling contexts (Aldred & Jungnickel, 2013) and cycle parking practices and how they relate to cycle parking materials (Larsen, 2017); auditing cycle infrastructure (Hull & O'Holleran, 2014); measuring public cycle parking preferences (Lusk et al., 2014); and investigating cycle theft (Chen, Liu & Sun, 2018; Lierop, Grimsrud & El-Geneidy, 2015). In this section, we will review this public parking specific work in order to further develop our proposed elements for effective public cycle parking, that may inform public cycle parking planning that is not necessarily only orientated toward multi-modal journeys (i.e., not only for the purposes of 'public transport integration').

Alike the work reviewed in the previous section, *protection* once again emerges as a clear element that can be derived to inform more effective cycle parking planning across various public cycle parking studies (Aldred & Jungnickel, 2013; Hull & O'Holleran, 2014; Lierop et al., 2015; Lusk et al., 2014). Much like the body of work examining stated and revealed preferences with cycle parking as a form of public transport integration (e.g., Arbis et al., 2016; Molin & Maat, 2015), and filling a gap examining public cycle parking in particular, Lusk et al. (2014) carried out a particularly insightful study on both forms of preference but in relation to general cycle parking using self-report and objective spatial data, in Hangzhou, China. This study is distinctive amongst the cycle parking literature in that is measures both revealed and stated preference specific to a range of cycle parking types: cycle parking sheds (this denotes a 'cycle station' like those discussed in Pucher & Buehler, [2008]), storage rooms (also described as a 'garage' in the study), rooms at home/office, areas beside office or apartment buildings (does not clarify if this is a cycle parking area), and roadside cycle parking. Drawing on data from 1150 respondents, they found that parking sheds were the both most used (used by 42.1% of women and 39.7% of men) and most preferred (preferred by 62.2% of women and 60% of men) form of cycle parking amongst respondents. However, importantly, it is not ascertained in this study what scenario specific preferences respondents may have – for example in terms of cycle parking duration (Chen et al., 2012; Yang et al., 2015). Nevertheless, the study does show in general that protected cycle parking in the form of cycle stations is highly preferred both in practice and in stated preference in this context, in keeping with public transport integration studies that support a preference for physically protected cycle parking (Appleyard & Ferrell, 2017; Halldórsdóttir et al., 2017; Harvey et al., 2016; Ravensbergen et al., 2018 Weliwitiya et al., 2019; Yang et al., 2015).

While we have derived the element of *protection* from a considerable body of studies reviewed in this article primarily on the basis of considering comparatively superior physically protective parking (such as cycle stations, lockers and compounds) to open style cycle racks (e.g., the "Sheffield stand") in particular planning scenarios, the study of Lierop et al. (2015) provides a more rudimentary consideration in relation to protection: the basic supply of formal cycle parking facilities, irrespective of type. Drawing on self-report data from 1992 respondents to research patterns of bicycle theft in Montreal, Canada, Lierop et al. (2015) discovered that 50% of reported stolen bicycles were 'fly-parked', thereby raising the importance of formal cycle parking supply itself. This finding supports the poorer ratings for cycle parking security provided in the auditing study of (Hull and O'Holleran, 2014) for the UK contexts of Cambridge and Edinburgh, where insufficient formal cycle parking supply and considerable fly-parking practices (i.e., parking one's cycle on street furniture and/or undesignated locations) were observed, compared to Den Haag in the Netherlands, where supply was considered ample and security excellent. Lierop et al. (2015) suggest that public authorities can reduce incidents of cycle theft by increasing cycle parking supply (and therefore reducing fly-parking) and installing parking that is materially robust, well-anchored, and easy to lock one's cycle to. Furthermore, in keeping with Arbis et al. (2016), they advocate for cycle parking that is both visible to other public space users and located near key destinations (i.e., for *visibility* and *proximity*): these are both elements of cycle parking that, as mentioned earlier, may crossover with overall security. Indeed, if cycle parking is proximal to one's destination, there is arguably less chance of fly-parking (Aldred & Jungnickel, 2013); likewise, for one to use a formal cycle parking facility, one must know that it is available – something which greater public visibility surely helps.

The qualitative work of Aldred and Jungnickel (2013) theoretically goes beyond the almost entirely quantitative work that has been reviewed thus far, richly adding to a consideration of the various elements of effective public cycle parking planning that we propose. This work contributes particularly to planning considerations – like the above studies – of *protection*, while problematising *visibility* and socially situating the importance of *proximity* in relation to the broader social status of cycling and cyclists in the UK. Drawing on a interviews with regular cyclists and cycling stakeholders across four relatively high-cycling contexts in the UK, Aldred and Jungnickel (2013) provide a convincing interpretation that the static (versus moving) bicycle/cycle is something which may be considered by much of the UK public as 'matter out of place' (p. 605), or, in other words, 'a transport object of dubious legitimacy' (p. 605); a claim which fits the wider policy marginalisation of cycling in the UK (Aldred, 2012). This object is threatened by the risk of vandalism, theft, removal by officials, and disapproval, and is otherwise considered, much like the cyclist in low-cycling contexts, as something 'in the way' and not in the right place, or, indeed, lacking a 'right' place. This diagnosis of the static cycle as an object 'in the way' and lacking a place usefully relates to work historically documenting the progressive displacement of cycling and cyclists from public space in the wake of growing automobility and the expansion of driver rights (Bonham and Cox, 2010; Cox, 2012). One could argue that much like cyclists in an Irish context using public space with other mobile subjects, the conditions for cycle parking in Ireland and, on the basis of Aldred and Jungnickel (2013), the UK, may be considered conditions of precarious entitlement to public space, where one may have a (limited) formal right to park one's cycle in theory that is precarious to exercise in practice (Egan & Philbin, 2021).

Aldred and Jungnickel (2013) show how cyclists deal with this precariousness in practice through parking-related practices. First, one means of dealing with the risks of cycle parking amongst participants was by using a second cheap bicycle so that theft would not cause a great deal of concern; in this way, insufficient physical *protection* from theft appears to be prevalent. By using lower value bikes, then, cycle parking protection was less important and theft was less consequential – something also found by Larsen (2017) in Copenhagen, which has high levels of cycle theft. Second, participants could deliberately neglect or even vandalise their bikes in order to reduce the risk of theft. This finding shows how *visibility* is complex: in this case, efforts to make one's cycle appear less valuable to potential thieves are undertaken to reduce the risk of theft; thus, the public visibility of cycles in this context appears to lead to strategies to reduce the visibility of one's cycle to a potential thief. Third, street furniture afforded many parking locations for cyclists, often in a sub-optimal fashion, at least in terms of official parking recommendations. Parking on street furniture, however, can come with a fear of removal by officials: "The lack of legitimacy enjoyed by bicycles in public spaces deters cyclists from using 'unofficial' locking places, yet—as participants commented— there is often a lack of 'official' bicycle parking near popular destinations" (p. 617). In this instance, a lack of formal parking supply – alike Lierop et al. (2015) – is a threat to the *protection* of one's cycle and theft, unlike other studies in this review, is not the only scenario in which one can lose possession of their cycle. However, relatedly, the lack of supply of formal cycle locations near major destinations is apparent: cycle parking in this context appears to lack *proximity*, thereby resulting in increased fly-parking – something also observed in the UK contexts of Cambridge and Edinburgh by (Hull and O'Holleran, 2014). In the context of parked cycles understood as 'matter out of place' (Aldred & Jungnickel, 2013) in particular contexts where cycling may be marginalised, this finding supports cycle parking planning that aspires toward maximising the *proximity* of formal parking to major user destinations. Importantly, this may inherently involve challenging the potentially privileged spatial positioning of driving and car parking and undoing the positioning of cycling infrastructure primarily within "redundant" and "left-over" mobility spaces (Cox, 2019, p. 182).

However, proximity to high-demand locations can be associated with higher levels of cycle theft. In a Seattle-based cycle theft study, Chen et al. (2018) found that areas "with a higher density and a greater concentration of human activity." (p. 176) were associated with higher rates of cycle theft. Although, there was an important exception to this pattern: cycle theft was less likely to occur at intersections than mid-block locations. Chen et al. (2018) surmises that this is may be due to the enhanced public visibility – described as "natural guardianship" (p. 176) – for cycle parking that intersections in this context likely provide. On this basis, both *proximity* and *visibility* of formal cycle parking may enhance security, which arguably both involve positioning cycle parking in prime public locations that may be in demand for other purposes, including car parking. With this in mind, "the conversion of car parking spaces into cycle parking" observed by Hull and O'Holleran (2014, p. 382) may provide an important strategy for effective public cycle parking planning.

Similar to the theoretically-informed qualitative work of Aldred and Jungnickel (2013), the comparative study of Larsen (2017) provides a consolidated perspective that can inform effective public cycle parking planning, particularly in relation to the importance of designing cycle parking that attends to the appropriate *integration* of a given cycle parking development within an extant cycle parking system. In a comparative ethnographic study of the primarily public cycle parking practices of cyclists in the cities of Amsterdam, Copenhagen and New York City, Larsen (2017) describes how particular designs can 'script' particular actions of users while they can also be interpreted and engaged with in creative ways, such as through the practice of fly-parking. In Copenhagen, formal cycle parking facilities generally involves 'grid racks' and one third of parking is fly-parking. Importantly, the cycles generally used in Copenhagen enable certain types of parking; namely, O-locks are the primary means of locking one's cycle in a fashion that does not require the 'mooring' of any formal cycle parking facility. Amsterdam has many more bike racks available compared to Copenhagen and these racks are generally positioned in convenient locations and provide the capacity to stabilise the user's bike. Compared to Copenhagen, Larsen (2017) remarks that cyclists in Amsterdam appear to "travel and park heavy" (p. 67), often involving large, cumbersome chain locks which can be carried in baskets or wrapped around a bike; compared to Copenhagen, 'unmoored' bikes are rare and could be viewed as risky due to the conspicuousness of an unmoored bike – thereby problematising certain kinds of *visibility* like Aldred and Jungnickel (2013). Lastly, in New York City, inverted U-racks are the main form of cycle parking, with U-locks being the main form of cycle lock. However, racks have only recently become widely available in NYC; street furniture was formerly a major style of parking when such racks were in lower supply. In this context, bikes never seem to be unmoored and there is widespread evidence of bike 'stripping' for parts as a result of theft and 'novice' locking practices.

Accordingly, Larsen (2017), shows how cycle parking practices are very context specific and how cycle parking facilities are only one component of a wider cycle parking system, that includes existing cycle parking practices, cycle theft practices, police and official practices, street infrastructure, cyclist locking competences, and – perhaps crucially – the types of bikes widely used (and the extent to which they integrate locking and stabilisation systems). On the basis of this work, Larson argues for planners to adopt a relational/systemic approach to cycle parking design, in which the various related materials, competences and meanings that make up existing cycle practices should be considered before cycle parking interventions are made. This claim regarding a sensitivity to the systemic *integration* of cycle parking is more broadly supported by the seminal comparative work on cycle promotion measures by Pucher and Buehler (2008), Pucher et al. (2010), and Buehler et al. (2017). These researchers each emphasise cycle parking as one promotional intervention that ought to be integrated with a complementary and coordinated package of measures, such as the development of dedicated cycling mobility networks, regulation of car use, implementation of compact mixed-use development, and – alike the public transport integration studies reviewed – integration with public transport systems as a primary measure for more sustainable multi-modal travel. As Pucher and Buehler (2008, p. 525) argue that "The key to the success of cycling policies in the Netherlands, Denmark and Germany is the coordinated implementation of the multi-faceted, mutually reinforcing set of policies", one of which is cycle parking.

Finally, our recent study on cycle parking type preferences explicitly considers the value of public cycle parking *diversification* (Egan, Dowling, & Caulfield, 2022). A typology development study drawing on survey data from Dublin, Ireland, we identified five clusters of cycle parking type preferences (i.e., comprised of differential preferences for 'locked', 'guarded' and 'open' cycle parking facilities) amongst the 574 respondents: Informal (low preference for any formal cycle parking), Open (high preference for 'open', low preference for 'locked' and 'guarded'), Any (favourable to any type of formal cycle parking), Accessible (preference for 'open' and 'guarded' cycle parking), and Secure (preference for 'locked' and especially 'guarded' cycle parking). Having discovered different patterns of parking type preferences, we suggested three potential strategies for cycle parking planning: i) maximising cycle parking that promotes the greatest aggregate increase in ridership, ii) prioritising cycle parking for currently underrepresented groups (i.e., cycle equity), iii) planning cycle parking to promote particular 'mode-activities' (Cass & Faulconbridge, 2016). Depending on the approach selected by planners, use of the typology could support the implementation of cycle parking provision for i) the Secure group, since they have the greatest stated interest in increasing ridership and cycle access journeys to public transport; ii) open cycle parking, since the clusters with the highest proportion of women (i.e., Open, Any, Accessible) all rated open forms of cycle parking relatively highly; and iii) using the mode-activity of 'cycle-shopping' as an example, the Accessible group, since they demonstrate the highest rates of shopping-related cycle journeys. The final mode-activity approach could be important from a cycle equity perspective, since, across many contexts, women disproportionately engage in 'vélomobilities of care' (Ravensbergen, Buliung & Sersli, 2020) that may involve household-serving trips – such as grocery shopping – compared to men.

5. Elements of effective public cycle parking

On the basis of the above review of cycle parking literature relating to public transport integration and public cycle parking, the table below (Table 2) proposes several fundamental elements derived from this review of peer-reviewed evidence that could inform effective public cycle parking planning measures. These elements could also be framed as tentative 'principles' that could contribute to efforts to promote cycle parking planning practice that is informed by peer-reviewed research along with local knowledge and context-specific assessment practices, such as surveys of cycle parking supply and demand (National Transport Authority, 2011; Parkin, 2018). These elements could be used as rules of thumb in local planning efforts but could also be operationalised in more strategic, regional-level approaches to cycle parking planning that might involve the development of indicators for *protection, visibility, accessibility*, and so on. Nevertheless, we do not propose these elements as either comprehensive or indisputable; instead, we merely propose them as useful research-derived factors that could help to improve the effectiveness of public cycle parking planning practice in light of the current lack of both well-established cycle parking design principles and use of cycle parking research evidence in planning practice. The effectiveness of any measure, of course, depends on what is the strategically desired 'effect'. In our recent research discussed above (Egan, Dowling, & Caulfield, 2022), we outlined various strategies that could be taken for cycle parking planning, which could prioritise the promotion of aggregate ridership, greater cycle equity, and/or particular cycle-activities. With these divergent approaches in mind, we propose these elements as potentially useful for both considerations to maximise general ridership and/or more targeted promotional efforts (e.g., *diversification*). Equally, Anaya-Boig (2021, p. 13) argues for a cycling policy approach which emphasises the facilitation of universal accessibility rather than cycle promotion, thereby removing a hierarchical promoter-recipient dynamic that can be inherent to policy-making orientated toward influencing individual and group behaviour; the proposed elements could also be plausibly considered 'effective' from this perspective.

Importantly, despite the apparent lack of use of peer-reviewed evidence in many planning guides – at least within the UK and Ireland (e.g. National Transport Authority, 2011; Transport for London, 2016; Welsh Government, 2021) – this does not mean these resources are not based on evidence from planning practice itself and that a flexible approach is not warranted. Indeed, as Parkin (2018)) comments, "There is good latitude for creative design of the spaces to accommodate cycle parking" (p. 155). Furthermore, the inclusivity of any given parking intervention for different groups should be considered – something which does not appear to be robustly empirically investigated in existing cycle parking research, but, by comparison, has been explored in considerable depth in relation to mobility infrastructure for cycling itself, particularly in terms of age and gender (e.g. Aldred & Dales, 2017; Aldred, Elliott, Woodcock & Goodman, 2017; Carroll et al., 2020; Garrard, Rose & Lo, 2008). As Aldred, Woodcock and Goodman (2016) have shown, increasing cycling levels does not equate with increasing the diversity of people cycling in terms of age and gender, at least for commuter cycling. Looking at disability in particular, Andrews, Clement and Aldred (2018) have pointed out how the needs of cyclists who are disabled in different ways are often marginalised in cycling strategies and policies in the UK and that there is a lack of research in this area to understand the unique challenges of disabled cyclists. In this respect, the 'Accessibility' element below could be developed much further and in more nuanced ways with future cycle parking research that explores the unique experiences and practices of cycle parking for different individuals/social groups and the particular cycles they may use. We have added the partial recommendations of Parkin et al. (2018) to acknowledge the relative absence of work in this area and the need to consider accessibility broadly in spite of this lack. This is also important from a consideration of the growth in the use of alternative cycles – most notably cargo cycles, which also overlaps with the element of *diversifying* cycle parking provision, which could help enable a broader diversification of cycling practices.

6. Conclusion

In this review, a variety of peer reviewed literature on the topic of cycle parking was examined in order to extract significant insights that can inform efforts to plan cycle parking facilities to promote/enable cycling and cycle-public transport integration. Emerging from our review, we have proposed several 'Elements of Effective Public Cycle Parking'. Aspects of these elements broadly correspond with the systematic review of Heinen and Buehler (2019), in which they point out various cycle parking characteristics that can potentially promote and facilitate greater ridership, such as adequate formal cycle parking supply, higher quality facilities that protect from weather conditions and theft, and proximally located cycle parking. Unlike the more empirically and methodologically focused work of Heinen and Buehler (2019), this review uniquely synthesises a smaller, more targeted body of cycle parking research on the basis of a well-identified gap in cycle planning guidance to conceptually propose a body of effective public cycle parking elements that can be easily adapted by planning practitioners, while situating these elements within a wider socio-technical consideration of cycle parking as part of a system of vélomobility.

Namely, viewed as a critical component for the development of a wider socio-technical system of vélomobility, implementing cycle parking with the above elements in mind will likely involve similar struggles over public space that have been documented much more saliently for cycling mobility infrastructure (e.g., Aldred, 2019; Wild, Woodward, Field & Macmillan, 2018). Achieving cycle parking that is, for example, highly visible, proximal to central destinations, and well-integrated with rail transport hubs and wider pro-cycling measures that undermine a system of automobility (Urry, 2004) will involve the acquisition of highly coveted, centrally located public spaces: spaces that are not "left-over" and "redundant" (Cox, 2019, p.182), where cycles are hidden and positioned on the peripheries of in-demand destinations. Instead, expanding high-quality cycle parking spaces – much like expanding cycling mobility spaces – will, in many cases, involve a reclamation of the spaces of automobility for vélomobility (Cox, 2019) in the context of scarcity (Petzer et al., 2021), where cycles are constituted as legitimate public objects rather than 'matter out of place' (Aldred & Jungnickel, 2013), while the users of these spaces are reconstituted as legitimate public space users (Bonham, 2006; Egan, 2021). In this way, cycle parking planning may implicitly require a process of expanding the rights of cyclists relative to drivers – not just in relation to spaces for mobility but also spaces for mooring (Adey, 2006; (Spurling, 2020)); indeed, the (illegal) moorings of drivers can greatly impinge on the mobilities of cyclists (e.g., Egan & Philbin, 2021).

Cycling has been historically marginalised in transport planning theory and practice (Koglin and Rye, 2014). As planning regulations are a major component of cycling policy (Anaya-Boig, 2021), and existing regulations can 'reify' particular claims to public space for car parking in particular (Spurling, 2020; Petzer et al., 2021), the cycle parking elements we propose in this article can potentially help planners to legitimise bolder, more ambitious efforts to embed cycle parking as part of a wider cycling system that is more favourable to the promotion and enablement of diverse cycling practices, particularly in lower-cycling contexts. Amidst the multitude of existing cycle parking design guidance (e.g. National Transport Authority, 2011; Transport for London, 2016; Welsh Government, 2021) – much of which does not draw on peer-reviewed cycling research – these elements can be used to inform specific cycle parking developments along with local knowledge, context-specific assessments (Parkin, 2018), and public deliberation (Anaya-Boig, 2021). Furthermore, our review could promote greater use and consideration of existing research evidence in the cycle parking planning process and can contribute to future dialogue regarding cycle parking design principles in research, policy and practice.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How railway stations can transform urban mobility and the public realm: The stakeholders' perspective

Alice Lunardon[a,*], Doroteya Vladimirova[b], Benedikt Boucsein[a]

[a] Technische Universität München, School of Engineering and Design, Munich, Germany
[b] University of Cambridge, Cambridge, UK

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ABSTRACT

Railway stations are massive infrastructures through which people, products, materials, and energy flow every day. They usually gather a multitude of functions and provide a wide range of services to users based on their respective specific features. Thus, railway stations have the potential to play a critical role in reshaping our cities in a sustainable manner by facilitating intermodality, green and active modes of transport and logistics, and by gathering proximity services. In this reshaping process, implementing effective and seamless mobility, as well as the proximity of services, are key challenges. However, no urban transformation process can take place without the involvement and commitment of the respective stakeholders. This paper aims to form an understanding of the views these stakeholders have towards the potential of railway stations transformation, for the broad European context, to carve out first paths towards actually achieving that transformation. This study analyses a wide range of inputs and considerations made during a series of workshops held in 2021 by the EIT Urban Mobility where experts from a wide range of fields exchanged their experiences and ideas around the topics of urban mobility and public realm. In this process, railway stations emerged as a key player to meet the challenges of cities' sustainable development. After analysing their potential and exploring policy obstacles that are currently hampering such a transformation, this paper suggests a series of recommendations to better exploit railway stations, gained from the stakeholders' perspective.

1. Introduction

The railway station occupies a unique position in the urban environment as an important part of the city's utilities, a legacy of constant transportation development, and a link of the city to the rest of the world. Viewed spatially, the station is both a node of networks and a place in the city (Bertolini & Spit, 1998). To guarantee integration between transport networks and physical urban spaces, it is necessary to take account of this dual character. Also, stations must address both negative consequences directly caused by transport infrastructures on the urban environment and critical circumstances inherent in the urban context. A good balance of these factors can ensure stations' role as living spaces and focal points for a new urbanity, while improving the respective city's urban and socioeconomic quality (Conticelli, 2011).

Over the last fifty years, the railway station's potential as a viable contributor to the cities' sustainable development has been unnoticed. As a result, challenges and opportunities have gone ignored. The existing practice and theory of station development reflects an insufficient comprehension of the location's contradictory nature. In addition, railway stations have often fallen in the gap between transport and urban agendas, as well as diverging responsibilities, being overlooked by urban planners and policy makers at local, national, and European level. As urban mobility still operates in a fragmented environment hostile to innovation, mobility systems continue to fail in meeting consumer expectations and to bring stakeholders together to collaboratively develop innovative mobility solutions and related policies (Audenhove et al., 2018). Railway companies, unreactive and cumbersome organisations, are not able to take the opportunity of realizing station's potential (Ecorys, 2012), and municipal institutions normally cannot influence their development.

Taking this unsatisfactory situation as a motivation and starting point, the objective of this paper is to analyse the views and the proposals of different stakeholders that participated at EIT UM Ideation Workshops in 2021, with the objective of understanding how stations can become a booster for cities' sustainable development.

EIT Urban Mobility is an initiative of the European Institute of Innovation and Technology (EIT), co-funded by the European Union. Its mission is to support positive changes in cities' urban mobility in order

Abbreviations: EIT UM, European Institute of Innovation and Technology (EIT), Urban Mobility (UM); MaaS, Mobility as a Service; TOD, Transit Oriented Development; HSR, High Speed Railways.

* Corresponding author. Calle Calabria 71, 5-1. 08015 Barcelona, Spain.
E-mail address: alice.lunardon@tum.de (A. Lunardon).

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to create more liveable places through collaboration between cities, industry, academia, research and innovation. In this context, every year the EIT UM organises workshops to gather all stakeholders to discuss about urban mobility and develop innovation.

2. Literature review

In the mid-19th century, rail became a key mode of transportation for goods and people in Europe. The construction of railway stations altered the urban landscape and they developed into important urban elements. The station was considered as 'volcan of life', 'palace of modern industry' and 'cathedral of humanity' (Dethier, 1981, p. 6), as well as a 'detector of urbanity', an object combining mobility and centrality (Duby 1985). However, after WWII, the railway industry declined to leave space to an increasingly car-based society (Wolmar, 2007). In this context, many stations had almost abandoned the outward signs of their civic vocation and their architectural structure of a forum of public life to progressively come to be seen as non-places, points of transit and nothing more (Detier, 1979). A huge dissociation between transport centrality and urban centrality appeared, making train stations invisible (Devisme, 2000) and rail transport losing demand (Gerkan, 1996).

Successively, in the last decade of the 20th century, fuelled by the introduction of high-speed and enhanced international rail services (HSR), stations retook importance in cities. Refurbishment projects of stations and their surroundings were launched, with the objective of increasing accessibility of station locations, in many cases leading to economic growth (Bertolini, 1998). New HRS stations have been used as a catalyst for urban redevelopment in a number of cities, and while there have been some obvious successes, the path to implementation has proven to be difficult in many other cases (Vickerman, 2015). These endeavours have been fuelled by a set of driving forces: the expansion and upgrade of rail infrastructure, the reduced demand for industrial space in central urban locations, the privatization of railways, the efforts to improve city attractiveness, the pursuit of sustainable development, and the new spatial dynamics of contemporary society. These factors have been coupled with varying emphases over time and between countries, resulting in three different ways of conceptualizing station area projects: 'property capitalization,' 'urban mega-project,' and 'transit oriented development' (Bertolini, 2012). The cases of London's St. Pancras and Paris' Gare du Nord stations are emblematic, as they have been the arenas for large-scale operations: St. Pancras' transformation boosted the renewal of the entire King's Crossroad area; and in Paris, the dismantling of a parking lot near Gare du Nord was the first phase of the entire area redevelopment (Riot, 2014). These buildings were renovated and given a central role as developers of the high-speed railway in Europe (Maillard, 2001). HSR stations have been a catalyst also in cities like Amsterdam (Zuidas), Brussels (Midi), and Madrid (Castellana), where the redevelopment projects brought a considerable economic growth (Loukaitou-Sideris et all, 2012). Hall and Banister (1994) argued that 'HSR will be the maker of some cities but the breaker of others'.

In intermediate cities, HSR opened up new opportunities by increasing their accessibility and interconnectivity, like the cases of Cordoba and Zaragoza in Spain, or Lille in France (Ureña et all, 2009). On the other hand, other cases demonstrate that HSR also facilitated territorial polarisation. For example, cities on the Shinkansen HSR line in Japan did not experience a shift of population or employment, but on the contrary, the line strengthened the economic role and primacy of Tokyo and Osaka at the expense of intermediate cities (Cervero and, Bernick,1996). Among the five most significant adverse effects of HSR stations are land speculation, gentrification and the consequential deracination of some residents and local businesses (Loukaitou-Sideris et all, 2012).

All this occurred at the same time of the partial transformation of many European railway companies from public authorities into semi-private or fully private organisations, giving them more financial autonomy and, consequently, a reduced obligation towards the public service they would offer (Wenner, 2020). This generated a strong commercialisation of stations (Hoffmann-Axthelm, 1996) while it also incentivized an active role of them in the urban development (Wenner, 2020).

Property booms had a role in the redevelopment of station areas, which were partially autonomous and partly tied to an explosion in office demand at certain places. The majority of station buildings have had a direct link to real-estate market conditions (Bertolini, 1998). Major urban development activities surrounding stations took place in conjunction with private players, giving birth to new financial models of public-private partnerships (PPP), like the case of Paris' Gare du Nord, where the French national railway company (SNCF) partnered with Altarea, a retail property developer (Schwarz, 2004). These redevelopments integrated a set of different activities inside and around stations by bringing new services into the scene. Multi-functionality was encouraged because it contributed to the station area's liveability and attractiveness (Bertolini, 1998). Integration of services brings to interaction, this is why tertiary sector firms prefer to be located around stations as they value the opportunity of interaction and exchanges that the stations can bring, especially if it is into a HSR network (Wenner & Thierstein, 2022). However, a more concrete, situation-specific commitment to multifunctionality would be needed by catering to both profitable and less profitable customers' interests (Bertolini, 1998).

From an urbanistic point of view, literature investigates also the effects that stations' redevelopments and the HSR advent have had on urban areas. A recent study shows that stations located in urban areas with available building land, coupled to a good local public transport network, easily conduct to new urban development (Wenner & Thierstein, 2022). Researchers have sought to examine such impacts of HSR in cities even though it is difficult to quantify how much development is directly attributable to a line (Givoni, 2006). But it is generally concluded that HSR cannot produce development by itself but can act as catalyst when other conditions are present (Lakatou-Sideris et all, 2012, page 10). Underlining this point, a study on Dutch cities showed that urban growth has not been a direct consequence of rail accessibility, as other factors played a more important role, such as operations of urbanisation in the areas, and the presence of multi-modality at the stations (Koopmans et al., 2012).

Cities have changed around stations. Many authors have identified the impact of stations on cities from an economic perspective as an attractive location for service industries (Pels & Rietveld, 2007; de Graaff et al., 2007). On the other hand, others authors have highlighted the negative changes brought by such redevelopments (Bertolini, 1998) by creating segregation and being drivers of injustices and urban inequalities (Camerin & Mora, 2019), like the case of Bilbao Ametzola's ancient railway station urban regeneration project. In such cases, to meet the goals of metropolisation and of internationalisation of the economy, municipalities started restructuring urban areas to implement commercial activities. Many railway lands have been demolished for the creation of quality spatial areas for a competitive economic claim (Sklair, 2017; Stein, 2019). In the Bilbao Ametzola project, which was characterised by the complete privatisation of the 11 hectares of railway facilities to be transformed in housing and commercial services, the aim was obtaining a first capital serving as a trigger mechanism to continue intervening in that territory with similar operations. This clear prevalence of the interests of the real estate system to the needs of an urban development (Camerin & Mora, 2019) can be also found in many other railway stations projects in Europe, like the case of Barcelona's Poblenou neighbourhood transformation for the Olympic games in 1992. Here, the redevelopments fuelled by the capital accumulation process transformed a large industrial and railway properties into a new urban district. These and other practices of neoliberal urbanism have been legitimized by public administrations, leading private actors to develop urban rent benefits by using urban land for a capitalist mode of production for the creation of a globalized city which, in many cases, led to the destruction of the social urban heritage (Camerin & Mora, 2019).

The competition for spaces, for users' attention, and for revenues create conflicts between stations' different functions (Zemp, 2011), which led many authors to see the negative effects of those redevelopment operations in stations and urban surrounding areas. Many stakeholders are involved in such operations, and their goals are frequently at odds and, at best, disorganized. Existing organizational structures and governance often pose insurmountable impediments even when there is enough consensus on the aims (Bertolini, 2012). At the same time, railway stations hold considerable potential for their urban surroundings, as they are offering a variety of functions in society beyond the instrumental activity of facilitating train boarding (Alexander and Hamilton, 2015) that, "they are part of community life" (Edwards, 1997, p. 26). Railway stations are potentially significant and reusable heritage assets that provide new elements needed by local communities to enhance the sustainable development of territories (Llano-Castresana et al., 2013). Bertolini (1996), with his definition of stations as 'nodes' and 'places', described very well the ambiguous function of such infrastructures. On the one hand, stations are crucial 'nodes' in growing, diversified transportation networks. On the other hand, they identify a 'place,' a portion of the city where different kind of uses and forms take place, which may or may not participate to the 'node' functions of the station. The significance of 'place' was seen as an enabler of urban redevelopments which improved the station environment by other authors as well (Maillard, 2001).

Overall, integration of transportation and urban development in station areas has been, and continues to be, a difficult task. "Railways, like other modern communication and transportation systems, pose a theoretical dilemma. Do they alienate or destroy a sense of place…or enable new connections to be made? If the latter is the case, do these new experiences of place sufficiently compensate the loss of more traditional sensibilities?" (Bishop, 2002, p. 298). In this context, it is unsurprising that stations can be seen in a negative light, as a non-place (Alexander and Hamilton, 2015). In Augé's (2008, p. 63) work, the railway station is seen as an archetypal non-place, "a space which cannot be defined as relational, or historical, or concerned with identity".

The advantages of cultivating a sense of place indicate that communities have a transformational role in such contexts (Stratton, 2000, p.3), and it is now gaining momentum thanks to the new 'placemaking' practices which introduce a process of co-designing a city with its residents, allowing them to build the spaces they want while integrating the functions they require (Schneekloth, 1995). City administrations and urban planners gradually open up to placemaking. In the context of railway stations, examples such as the Scottish "Adopt a Station" concept for local communities have already been implemented (Alexander and Hamilton, 2015). They contribute to a reclaimed sense of place (Alexander and Hamilton, 2015), a concept that is central to contemporary society and works as the geographical component of the psychological need to belong somewhere, one antidote to a prevailing alienation (Lippard, 1997). In this context, it is possible to reconnect Bertolini's research on stations as both 'nodes and places' with the importance of placemaking activities at stations, and, in general, in urban areas.

The literature review illustrates that railway stations have mainly been studied from the perspectives of urban transportation and urban development, seen in many researches, as a positive aspect for the development of cities' economy. However, there is little research about the implications of such redevelopments on local communities and local economies. Also, there is little research on the impact of the uses and functions of stations' spaces in terms of urban-local development and the daily life of citizens. Furthermore, research gaps are identified in the understanding of stations as stable industrial infrastructures in cities, and how such infrastructures - through which materials, energy, water, and people flow - can offer a potential for enhancing resource utilization in cities. There are only few recent studies about the energy optimization at railway stations and energy reuse from the rail infrastructure to the station building, such as the reuse of the train braking energy, or the self-production of energy through photovoltaic panels. Building from these considerations, this paper aims at exploring such phenomena, from multiple stakeholders' points of views, to understand how to better use railway stations as 'nodes and places', aiming at boost the sustainable development of cities.

3. Methodology

3.1. The process

The EIT Urban Mobility created an 'Ideation Process' to assist its partners in developing new projects and ideas in urban mobility and public realm. In 2021, the entire EIT UM Community together with external organisations examined innovative ideas that matched cities, citizens, and industry's needs. To begin, a series of meetings with all stakeholders were conducted around urban mobility to determine the five core topics – called "Challenge Areas" – in which innovation is required: Active Mobility, City Logistics, Future Mobility, Mobility & Energy, Creating Public Realm. Second, a series of workshops were organized with all stakeholders on each one of the five Challenge Areas using the Cambridge's Value Creation Model (Vladimirova, 2019), which is a model developed at the IfM's Centre for Industrial Sustainability of the University of Cambridge by a group of researchers, including Dr. Doroteya Vladimirova who assisted in the workshops. It is based on a structured and visual method to identify 'uncaptured value' in the form of unsuccessful value exchanges: value missing, destroyed, surplus, and absent which are examined through the eyes of each stakeholder. This method enables organisations to work together in ways that increase value and deliver positive impact, as it explores the different values with the objective of aligning stakeholders' interests and needs while developing sustainable projects.

Following the steps of the Value Creation Model, the Challenge Areas served as the workshops' "unit of analysis" (main discussion topics). Six sessions have been performed, once per each Challenge Area, with the exception of Future Mobility that was performed in two sessions. Participants were divided into "stakeholder groups" based on their type, expertise, and areas of interest (e.g., city administrations, citizens, environmental experts, railway companies and transport operators, local businesses, etc.). To ensure accurate data collection and qualitative outputs, attendees' inputs were collected throughout the workshops in an interactive platform that allowed numerous participants to support the discussion with written notes and map the debate on its course. Participants from each stakeholder group were assigned to a separated virtual room to discuss the topic from their stakeholder's point of view. Afterwards, a conclusive discussion of all participants took place in a plenary virtual room, where new ideas and projects were developed.

The total amount of participants per workshop were around 30–40 people. Stakeholders' groups were composed by 5–7 people for a total of 5–6 groups. In all workshops, stakeholders' groups were the following: Cities (for city councils' representatives from different European cities, or organisations that work for local municipalities); Citizens (including experts, sectorial organisations representing the interests of users and citizens, and universities); Environment (including experts and researchers); Public transport and Railway Stations (including railway stations companies, public transport companies, researchers experts in railway stations); Mobility Providers (especially for private companies and start-ups from the sector); Energy Providers (only in the workshop on Energy – including experts, start-ups, energy companies); Local Businesses (only for the workshop of city logistics – including representatives of local commerce). Stakeholders that participated to the workshops were all partners from the EIT UM community from public institutions and municipalities from over 20 European cities, industry, start-ups, NGOs, and Universities (Our partners - EIT Urban mobility) and additional external organisations as follows:

- International sectorial organisations and NGOs: Placemaking Europe, European Cyclist Federation, Walk21, Fondazione Innovazione Urbana, Greencity, C40, BIDs Belgium
- European organisations and bodies: ETP ALICE, Shift2Rail

- Start-ups: VOI, Citywayfinding, Geovelo
- Other private organisations: Archipel.co, Trivector
- Railway Companies: SNCF (french national railways), PKP (polish national railways), FSI (italian national railways), SBB (swiss national railways), ProRail (dutch national railway infrastructure managers), DSB (danish national railways), FGC (catalan railways).

Workshops results were utilized to further refine ideas developed during the sessions, and then published into an online tool that all participants could use to create new projects. All these initiatives were designed to lay solid groundwork for the EIT Urban Mobility Call for Proposals, an open competition to create innovations on urban mobility.

3.2. Data analysis

The data gathered from the workshops was analysed in two stages. To begin, all inputs from all groups were analysed and summarized to form the first section of the findings, which included a broad overview of the themes discussed in each Challenge Area. Second, an examination of railway station-related topics was conducted with the objective of developing this research. Many European railway companies participated in "railway stations stakeholders' groups," which were then mixed up, allowing municipal administrations, researchers, sectorial associations, and mobility and energy providers to join the discourse.

The workshop data was evaluated to simplify the identification of recurring inputs in order to extract the most relevant themes and surprising findings (Breen, 2006), with internal compliance checks and cross comparisons properly taken into account. The most essential themes mentioned regarding the Challenge Area, the most notable quotes, and any surprising results were all included in the input analysis. By applying a colour code to each topic addressed and then analysing which colours were most frequent, axial coding methodology was used to identify the most essential themes discussed. This investigation revealed how important train stations are for urban mobility and its transformation.

The following factors were used to determine the dependability of participant inputs: (a) the extent to which participants agreed/disagreed on problems; and (b) the frequency of participant opinion shift during the conversation (Breen, 2006). The most notable comments are included in the findings and allude to particular assertions made by a participant on which all of the other participants agreed.

4. Findings and discussion

This chapter firstly explains the contents treated in each workshop (the Challenge Areas), then introduces the main findings by continuously making a link between the Challenge Area and the topic of railway stations. Secondly, it discusses the results by illustrating a series of concepts that demonstrate the importance of railway stations in urban planning and transport practices.

4.1. Description of the contents

'Active Mobility' is understood as a regular physical activity undertaken as a mean of transport, such as travel by foot, bicycle, kick-scooters, and the use of them mixed with public transport. Supporting the modal shift towards active mobility requires a range of different measures to be implemented in cities, not least the allocation of space to allow for safe and accessible solutions for these modes. Still many obstacles to achieve increased active mobility exist in European cities, mainly due to decades of car-centric planning that have created organisational and cultural barriers ("EIT UM Challenge Areas", 2020).

'Future Mobility' is an umbrella-term, developed for indicating all the solutions developed or envisioned with the aim to improve the flow of people and goods within urban areas. It is crucial to understand that future mobility is not built on solutions centred around cutting-edge technologies but encompasses a portfolio of various, human-centred approaches – while a purely tech-driven way of looking at, and governing the transition, brings confusion and misunderstandings to public discussion and the way citizens imagine the future of the mobility sector ("EIT UM Challenge Areas", 2020).

The sector connecting 'Mobility & Energy' is currently undergoing a large-scale transformation. New solutions are absorbed and tested, existing ones upgraded, and cutting-edge technologies of the future anticipated. Some of the challenges are real bottlenecks and visible every day on the streets of European cities – rising demand for public e-charging points or rapid increase in the number of e-vehicles. At the same time, the growing market of renewable energy production and storage remains decoupled from the transport ("EIT UM Challenge Areas", 2020).

'Sustainable City Logistics' is about connecting the methods of fast deliveries of goods and food in cities with the ways citizens can collect them in a environmentally sustainable, comfortable, and time-efficient way ("EIT UM Challenge Areas", 2020).

'Creating Public Realm' is a Challenge Area focussed on the development of liveable public spaces connected with mobility. Public space represents a complex urban fabric confronted by various competing demands from public and private stakeholders. Dialogue and efficient governance models for public space are key to preventing potential conflicts and ensuring high quality of it ("EIT UM Challenge Areas", 2020).

4.2. Main findings

Levels and culture of active mobility differ throughout Europe, but as a common challenge is the adaptation of the existent mobility infrastructures to the new mobility services popping up in cities. But, policies for encouraging people to switch from cars to active modes of transport are still too weak, combined with a lack of positive narratives, creating discouragement among citizens as well as the still too high number of accidents between cars and active mobility users. Quantification of the benefits of walking and cycling in citizens' health still lacks consistent methodologies and is not included into transport decision-making. The physical and mental health impacts of active mobility need to be showcased to encourage people and also employers to the use of active modes of transport.

In addition, many cities lack of appropriate infrastructures. A study made in Helsinki shows that home location in a pedestrian zone or near a green area and higher proportion of cycling and pedestrian networks contribute to higher levels of commuting physical activity (Mäki-Opas, 2016), highlighting the importance of having appropriate infrastructures to enable citizens to switch from cars to active mobility modes. Improving the efficiency of a single trip made with more than one transport mode, offering travellers a seamless journey, it is crucial for enabling intermodality. This requires the creation of integrated transport systems through the harmonisation of different transport services and modes. Many cities have installed sharing bike systems that can be used by citizens at an affordable price. But, due to the high maintenance costs of such systems, these offerings seem not to be rentable for the municipalities. Consequently, this leaves the floor to private companies that, on the other hand, municipalities struggle in controlling. And in both cases, for maintenance and charging of electric vehicles such as bikes, kick-scooters, but also sharing cars, providers spend too much effort and energy. Trips back and forth with vans for repair damaged vehicles invade the streets and generate additional pollution, as well as trips for recharging electric vehicles far from the parking spot. In this context, railway stations, being the departure and arrival points of public transport in-and-outside cities, and as an aggregator of different mobility modes, could host all these services, thus becoming an enabler of intermodality.

For sharing mobility, in many European cities, there is often an uneven distribution of providers in stations' surroundings, which creates a network coverage with gaps and long walking distances. A participant from a sectorial transport organisation said: ***"Too many mobility devices – competing between them – are currently present in the urban scene, which privileges individualism to the detriment of a social culture of mobility"***

(Video n.23, 04/02/21, min.28). Therefore, many people choose to possess personal mobility devices and carry them on the public transport. But taking bikes on trains, buses, and metros is often limited to foldable bikes and excluding peak hours when people might need it the most. The lack of bicycle parking around stations, especially in south-European cities, represents an impediment for citizens to switch from cars to public transport. In north-Europe, instead, where the bike culture is massively diffused, bike parking around stations support effective intermodality – like in Rotterdam Central Station and Utrecht Station where huge facilities for personal mobility devices have been constructed underground offering in this way an accessible and seamless commuting to travellers. On the other hand, in such places bicycles often invade streets and there is a need of finding innovative ways of parking.

Facilities for enabling active, sharing, and micro mobility do not concern only parking spots for these devices, but also charging stations for public and private electric vehicles.

Cooperation between public-and-private stakeholders is crucial, together with a proper financing for innovative solutions. A participant from a railway company said: *"Proper financing instruments are missing, especially from the public side"* (Video n.1, 20/01/21, min.1:07).

Railway stations are the connection point between private, shared, and public transport. Stations managers, public transport operators, and municipalities lack of data about trips of travellers on private and shared mobility devices, which leads to missing opportunities for them to know users' needs and trends. Private mobility operators do not share data with public institutions so that they are not able to provide travellers with an appropriate transport offering. Additionally, a lack of ticketing integration between all transport offerings do not facilitate seamless journeys for users. All these factors make that "Mobility as a Service" (MaaS) cannot be effectively implemented. A participant from the group of stations said: "*An effective MaaS should be based on open platforms supporting collaboration between companies and stakeholders and should also integrate other services related to mobility offerings, such as bike parking or other facilities that users can find inside and around stations*" (Video n.1, 20/01/21, min.37). To meet the growing expectations of society in terms of faster-commuting times and smarter commuting ways, the topic of MaaS must be brought to the forefront. Its goal may be expressed as *public but personalised*. Big data and machine learning should be better embedded in the strategic planning to promote effective transport development. But in parallel, as an opposite tendence, industry is developing new technologies for cars enhancing the comfort for vehicle owners, which incites people to continue use cars. Also the pandemic has brought to the preference of private vehicles like cars, instead of continue using public transport. The pandemic that has made loss trust in public transport, therefore, a better use of railway stations as nodes and places could probably make people regain trust in public transport and sharing mobility. MaaS solutions can represent a significant lever for the future of mobility, especially in guiding people through the stations and their surroundings, to find the services they need and the mobility offering. As an example, the public transport operator of Warsaw (ZTM) is currently dealing with the development of MaaS solutions for railway stations to enhance intermodality. In Milano, the public administration is developing a MaaS application that integrates all public and private mobility modes, with all options available in the app. Looking at future further developments of MaaS, a participant of the Future Mobility workshop proposed a new concept of '*selling mobility management instead of selling single trips*' where users could find both transport services and all the other daily services they need that require ticketing, while also including their working and personal calendars to pre-calculate trips time.

The central point of almost all discussions in the workshops has been the public transport, which seems to be crucial to achieve the 'mobility of the future' that the stakeholders envision. What is currently working well in public transport systems, is the fact that operators can handle very complex technological systems. Such knowledge should not be wasted. Industrial capabilities are there, but still not used effectively to satisfy the market and the social demand. Public transport is the backbone of transport to sustainably and inclusively move large numbers of people. Its assets are going to be redefined and adapted in light of future challenges. While technology enables a smooth integration of different services to provide seamless experience, it is a non-technology task that is needed to rethink spaces and assets, optimizing resources, avoid the multiplication of efforts and the waste of resources, and to develop synergies between investments. A participant from the group of cities said: "*Innovation is not yet seen as an opportunity to gain understanding of all stakeholders*" (Video n.1, 20/01/21, min.55).

As big industrial plants located in the hearth of cities, railway stations represent a node of networks of people, materials and energy passing through them. Such resources should not be wasted, especially when it comes to energy as it is one of the main topics on the top of all cities' agendas. Transport and urban mobility need to become energy efficient, and the current situation in Europe is mostly divided into two scenarios. First, Northern European countries host public charging stations in their cities, but they are not sufficient to meet the current demand. Second, Southern European countries are most populated by private charging points which are not well developed and not sufficient for the demand either, but in any case overloading public grids. Additional energy injected to the grid should be produced locally and in a sustainable way. A participant from a start-up said: *"Cross-charging point operators' collaboration is missing, and the charging infrastructure is not centralised, which is a waste"* (Video n.29, 10/02/21, min.31). Therefore, solutions promoting smart local energy generation elements and integration of such connected elements into the already built-in distribution grid are needed, and railway stations could be a good candidate for local production as they are nodes of energy networks, where flux of energy can fuel trains, station buildings, and urban mobility devices. Thanks to these characteristics and to their crucial positioning in the heart of cities, stations should be seen as an asset to combine energy production with socially inclusive and energy efficient mobility. There are large unused capacities in off-peaks for energy coming from train brakes in railway stations which represents an underuse of their potential. Regenerative braking from trains is an energy recovery mechanism during braking that converts the kinetic energy into electrical form (Akbari, 2021). A participant from a start-up said: *"There are no e-vehicles charging during the acceleration or braking time of a train"* (Video n.31, 10/02/21, min.36).

As the public energy networks are already overwhelmed in many cities, the energy that the station can hold and eventually produce, could directly fuel electric vehicles avoiding overcharging public networks. Systems integration and smart grids implementation require long term planning as well as coordination with the electric grid providers and other key value chain stakeholders, which is not yet happening in European cities, as many investments promote models with the shortest return on investment periods. There exist also other ways to balance the supply-demand equation with an emphasis on sustainability, most notably decentralized energy storage (batteries). But for the integration of such technologies into urban areas, it would be necessary to free up space to destinate to such storages, which is not always feasible, especially in dense cities. Moreover, costs of such infrastructures are difficult to estimate, and the process to install them is long. For battery storage, the suitability of using second-life batteries and battery recycling policies was identified to reap the benefits of local renewable energy production (e.g., photovoltaic panels - PV), that even in this case could be done at railway stations, for instance in their rooftops or in the rooftops of train platform shelters. PV requires proper management and monitoring, especially in its strategic points or at peak hours where a high concentration of moving passengers puts additional stress on the network. Data integration and analytic tools can satisfy these needs, but require a proper collection, analysis, storage, and management. Providing a structured system for real-time visualization is a challenging task, but of key importance when talking about energy interventions for the mobility sector.

While awareness of optimization of energy consumption is rising among European railway stations' managers, the lack of collaboration between stakeholders represents an obstacle to innovation. Some countries are making progress, like in the Netherlands where solar panels have been installed on the rooftops of stations, and the energy produced is managed by the public energy supplier that then use it to fuel stations but also other public transport modes, such as the metro. Station managers closely collaborate with the public energy provider to optimize energy efficiency. Each station is connected to the public grid, and they are looking if it is possible to reduce the number of connections in order to easier re-use the energy produced by solar panels installed on the stations' rooftops. This would be enable stations to locally produce energy and use it, while discharging the public energy network. Nevertheless, a concrete connection between stations' energy production and the fuelling of e-vehicles for urban sharing mobility is still missing. The city of Helmond denounces a lack of smart grids and a lack of charging solutions for all e-vehicles. A participant from the energy infrastructure industry said: *"There is still a lack of interoperability between systems and grids, and public authorities still cannot monitor the demand of the infrastructure to provide additional resources on spot"* (Video n.31, 01/02/21, min.48). Innovative solutions to develop such concepts must think about the most appropriate way of fuelling these spots to optimize costs and ensure supply continuity. To do this, the charging demand prediction at stations should be improved and its data properly collected.

Talking about lack of interoperability, in the urban mobility panorama, there is also another sector that suffer of such a lack: urban logistics. Currently there is poor cooperation between delivery companies, which is hampering trips optimisation. In such strongly competitive and customer-oriented market, there is no incentive either for delivery companies to introduce sharing economy practices into operations, potentially scarifying market shares and delaying deliveries. Due to the pandemic and the new consumption trends, the exponential increase of food and goods delivery has led to the rapid multiplication of trips in cities as well as the multiplication of delivery points (Hess, 2021). A participant representing local businesses said: "*Habits that people are taking by compulsively buying goods online are increasingly damaging local commerce by privileging global chains that actually have more efficient infrastructure and use of data"* (Video n.7, 27/01/21, min.17). Incentives for people to shop local are low, and local businesses lack cooperation in competing against global chains. While this emerging situation creates new jobs, business, and helps citizens in making their daily life more time-efficient, authorities are reporting collateral effects: poor condition of employees, more trucks congesting and polluting urban areas, and reducing the spaces for other traffic participants. Therefore, solutions must be found to optimise trips, for instance by combining delivery options, and to make this sector environmentally sustainable while also inciting citizens to shop local.

Policies and regulations are outdated and city administrations don't have access to data to be able to effectively organise urban logistics and gain visibility on the processes. The use and management of the entire logistic infrastructure is therefore too fragmented. A better exploitation of data could enable better optimisation of resources and capacities, but the current lack of coordination between stakeholders, as well as lacking regulation, makes the system inefficient and unsustainable. To address this issue, many cities are creating a zero emission zone in the centre town where new regulations hamper the entrance of polluting vehicles, giving more space to electric and green vehicles (e.g. cargo bikes, e-trucks), which are also smaller and can access small streets. For instance. the city of Eindhoven has created an hub at the entrance of the city around the main train station to collect materials and then distribute them by green vehicles into the city. The city is also thinking about new policies to stimulate the use of the hub by all logistic services, as it is currently mostly used by the city's own projects.

In the spatial context, city logistics have been discussed from the viewpoint of channels of goods distribution. Next to roads there are waterways and railways, including underground networks that are currently underused. If thinking about the opportunity of exploitation they could offer, urban underground, tramways, and trains are currently only set for passengers' transport, whereas they could combine both passenger and freight, especially when they run half-empty. In addition to new uses of public transport infrastructure, a breakdown of large warehouses into micro hubs would be an opportunity to significantly improve network resilience. Some European cities are already working on the creation of logistic micro-hubs, like for example, the 'city depots' in the Netherlands that gather goods and then dispatch parcels in the neighbourhoods by cargo e-bikes. In Madrid, smart lockers that people can easily access are popping up in some areas. In Greece, the macro consolidation centres are coupled with low emission fleets for the last mile delivery. The problem of all these systems is that they have high costs of maintenance and management, which can represent an obstacle to many cities for their implementation. A participant from a research institute said: "*Holistic planning is missing, and business models for new solutions are not yet well defined*" (Video n.8, 27/01/21, min.49). Thus, efforts should be joint to optimize the creation of such solutions.

In this context, railway stations could offer the opportunity to link freight transport with last-mile deliveries thanks to their central urban locations and direct connections with the rail network, improving the logistic chain as pivotal points between the city's peripheral and urban areas. A participant from a railway company said: *"For instance, goods arriving to the airports could be delivered in the cities by train and arriving to the stations they can then be dispatched in the city"* (Video n.8, 27/01/21, min.39). Currently, the only thing that some European railway stations implement are 'smart lockers', like almost all big SNCF stations in France. Offering 'hop-on hop-off' unmanned collecting points along the frequently travelled routes, smart lockers offer an alternative opportunity to home-delivery, avoiding at least the multiplication of trips for delivery trucks, while offering greater flexibility for both companies and customers. But, to decisively improve city logistics, much larger efforts have to be made. Stations have a lot of space on the underground that is currently used mainly for parking and maintenance. This space could be optimised and used for logistics and also for waste management. A good example can be found at the SNCF station of Marseille, where, in addition to waste management, they also produce energy through the waste treatment.

Adding an additional layer to the transport and logistics function, railway stations have the potential to become a 'one-stop service' for most of the needs that citizens have during their daily life. Opportunities for testing new solutions and raising awareness for behavioural change should be experimented. For instance, testing sharing mobility solutions and new models for their subscription combined with the available public transport infrastructure could be a lever for people to use public transport and sharing mobility instead of buying a car. Moreover, it is necessary to synchronize social activities and services with transport services. For instance, in Paris' St. Lazare Railway Station new permanent and temporary services for users are implemented, such as shops of local farmers. A good example of synchronisation of services and transport is the kindergarten installed inside the station. In this way, parents can drop-off children and then take the train to go to work. Changing behavioural patterns can be done by both pushing and pulling measures as well as new policies, and testing new services and activities.

The mobility of the future is not only about improving transport services, but also better managing public spaces in urban areas. Municipalities have a key role here since they own public space and bare high maintenance costs for the provision of basic services, including safety, accessibility, and connection. From this perspective, it is crucial that projects for public spaces are well coordinated internally, which would help achieving a systemic change in a long run. Some cities are already applying holistic approaches to take advantage of their cultural and historical background, for instance the design-culture in cities like Milano, or the "Superblocks" in Barcelona where streets for cars are transformed into spaces for active mobility and social activities by gathering a mix of uses, allow social interaction. In this way urban spaces become more attractive. The objective is to achieve a healthier, greener, fairer, and safer public spaces favouring social relations and boosting local economy. In Milan, the organisation of multiple social events is as a way of living the city and moving around. These events are a showcase for the city, a first taste of car-free streets and zero emission areas to be developed. Similar initiatives can be found in Stockholm where, every year, a number of places are transformed into pedestrian streets, pop-up parks, summer and winter squares. Here, spaces are created for social activities, meetings and art, where people are encouraged to participate. One of the most important aspects that emerged during the workshop is that ensuring such vicinity and proximity is crucial for a more sustainable urban mobility, meaning that citizens have equal access to services and can avoid long trips. A participant representing citizens said: *"Time and energy are still wasted in commuting, as often the services that citizens need to access are far from their homes and job places"* (Video n.1, 20/01/21, min.44). To improve connectivity, services need to be brought to the vicinity. To this extent, emerging concepts like the '15-minute city' promote the access to proximity services at walking distance (Moreno, 2021). This concept became more popular during the pandemic when having services at walkable distance was essential for people. Such urban planning concepts like the '15 min city' implemented in cities like Paris and Milan, and '1 min city' in Stockholm, allow for a coherent implementation of proximity. In this context, railway stations were identified by participants as places with a great potential of bringing proximity and mobility services together.

Despite this, many cities still struggle with implementation of such planning concepts as per strict regulations and complex certification procedures that have a discouraging effect. One of the gaps highlighted during the workshop was the underuse of architectural know-how. A participant from a city council said: *"Cities are not applying the extensive existing architectural know-how to urban design practices*". Another participant from another city council affirmed: "*This is because of a lack of cooperation between stakeholders and between the different departments in city councils*" (Video n.10, 17/02/21, min.26–28). Participants from industry and research entities have declared interest in deploying tactical urbanism solutions at their own cost, to be able to demonstrate their effectiveness to municipalities.

In this context, railway stations have been seen as a possible potential player in the development of 15-minute cities, as they could play a role here of mediation between the needs of public transport operators, the private mobility service providers that occupy the urban space, and the local communities that need to use the public space. Stations, as seen in literature, can be nodes and places (Bertolini, 1998) and gather network of transport while also offering their (public) spaces for relevant activities and services for city inhabitants.

Some railway companies are already taking a role in urban planning practices, like for example the French SNCF that is working closely with local governments to develop masterplans around French stations, but beside these specific examples, in European cities there is still a fragmentation between the transport infrastructure and the urban tissue, which leads to a barrier effect both within the station's building (barriers between transport uses and commercial uses) and the surrounding city. Cause of this is often due to physical boundaries between the station and the city's public soil, as well as a lack of coordination between both stakeholders. In addition, the time of use of the station – which is currently dependent only on the railway company's needs, and is consequently used only during daily hours – doesn't allow use of this place for other purposes at night, which enhance even more such a fragmentation.

In addition, participants have highlighted the fact that stations are still perceived without much reference to identity and cultural value, which makes difficult their "conceptual" transformation into centres of life and proximity. Before the emergence of the automobile, stations were closely connected to their urban surroundings, functionally and spatially knit into the adjacent urban fabric. But, as seen in literature review, most stations successively lost that function mainly due to the raise of cars' use, and their surroundings have been destinated to parking or other functions with no social either cultural value. A participant from a university said: *"Cultural value and identity is missing. The station could be a place with an identity as it is a public and shared space. The identity can come partly from the station itself and partly from its surroundings"* (Video n.15, 17/02/21, min.41). Therefore, new functionalities, more quality and features of public spaces are needed inside and around stations, to allow people to transit, work, meet, but also stay in these spaces. This would foster the sense of community and neighborship that is currently missing. A participant from a research institute said: *"Currently, stations are not places where the people want to spend time or have activities – such as working, learning, enjoying the space – as they are only transfer points, for short stays where you feel obliged to buy something or leave"* (Video n.25, 04/02/21, min.18). A 'social value' is therefore missing, and the potential of a station as a 'social public space' - with no commercial sense - has not been considered yet. Stations, with a smart combination of mobility services with other auxiliary functions, can become the connection between the transport network and the public space of the city; they can potentially support sustainable behaviours among citizens and mobility users, while creating new opportunities for local businesses and services. For this to be achieved, in Poland for example, the national railway company (PKP) is developing a project around stations inspired on the Dutch idea of Woonerf (a good public spaces for pedestrians) by converting areas around stations into parks and public spaces to enable social interaction and give citizens spaces for their social activities.

4.3. Discussion

Changing travellers' modes of transportation from car to rail is a crucial European strategy (Brons et al., 2009) to improve public transportation, and terminal services quality is acknowledged as a significant factor affecting travellers' behaviour (Cascetta & Cartenì, 2014). In this context, the intermodal hub – like the railway station – is an important part of door-to-door travel, especially when it is well integrated into a network of hubs, as demonstrated in the literature review. It can aid in the development of public transportation by offering a way of connecting public transportation services to establish a network and improving mode integration and transfer (Hickman et al., 2015). Connecting public transport modes with the new fast-emerging sharing mobility and personal-mobility devices can improve intermodality (Doe, 2019), and this can happen at railway stations where multiple transport networks and a variety of transport modes can be found. As advocated by the TOD model in literature, the intermodal hub can therefore perform two key functions: a key element of the multiple-links public transport journey, and an enabler of surrounding urban areas' development (Hickman et al., 2015). However, the integration of transportation development with urban development and the coordination of related activities is a challenging undertaking. Literature demonstrates that, to successfully develop a TOD, a planning framework and a public-private funding strategy facilitating transportation and urban development are required (Bertolini, 2012). Many decades of modernist urban planning based on the implementation of different categories of activities in separated zones of the city (Sim, 2019) now make it difficult to redevelop urban areas in 15-minutes neighbourhoods and TODs. In 1961 Jane Jacobs, pioneer of criticisms to this model, raised the flag by perfectly describing how the separation of functions in cities led to a car-based scenario where people need to travel many kilometres to reach their jobs, commercial malls, and other services in and around the city, far from their residences. Today, fundamental changes are difficult to make as cities cannot adapt quickly and be rebuilt. A thorough examination of local planning documents may shed light on the role of local players and methods in enabling or regulating such development (Wenner & Thierstein, 2022). Despite the fact that many governments are eager to capitalise on accessibility advantages for urban growth, much remains to be done in terms of transit-oriented development.

Re-thinking railway stations as “multi-modal and proximity services hubs” could allow to sustainably move large numbers of people while boosting the compactness of the city by offering proximity. As illustrated in literature review, it seems important to understand through the analyses made so far by researchers, is that stations have a potential in urban regeneration (Lakatou-Sideris et all, 2012). If looking at stations as social infrastructures, instead of just transport infrastructures, it is possible to imagine them serving citizens in their daily life by integrating socio-economic activities while hosting active-and-micro mobility facilities such as parking, e-charging stations, and related services, facilitating in this way the modal shift. Additionally, if connected when possible with disused rails transformed into greenways for active mobility users (Rovelli et al., 2020), stations could become a node of active mobility network in cities. Intermodality can be enabled through stations also by including other mobility modes, and optimising existing resources: in stations where people still arrive by car, such car-trips could be shared with other users (e.g. car-pooling). Incentives to this could enable such a system if users are awarded when hosting other passengers during their trips. Systematically integrating such services in stations can enable citizens to use multi-modal combinations.

Factors that made the success in some intermodal hubs, like in Tokyo, are related to both public incentives for TOD’s development (most importantly, a transportation policy that restricts automobile ownership and usage while actively promoting public transportation, as well as a land-use strategy that encourages construction near stations), and the business strategies promoted by the railway companies (Bertolini, 2012). Developing a sustainable multimodal system thus needs the removal of numerous impediments, which can only be accomplished through suitable policy frameworks that include public participation (Szyliowicz, 2004), which in parallel can also lead towards the creation of new business opportunities for stakeholders.

In addition, railway stations represent one of the most industrial structures that are still located in the centre of cities, supporting in this way the cities’ functions as a complex facility (Ferrarini 2005). Consequently, they have a potential for serving the city and its inhabitants not only as a transport departure-arrival points, but also as valuable assets that may assist cities’ transition to more sustainable production and consumption modes. They act as ‘resources-optimizators’ for logistics and material flows, and as ‘greening engines’ for energy production from different sources and the distribution to urban mobility. Studies and experiments have been done on energy efficiency and self-production at the station, but very few research connects such production with the fuelling of urban mobility devices. Regulations allowing such connections and energy infrastructure’s optimisation are currently missing. A study made in France, investigates energetic concepts in order to store the braking energy of the trains with a stationary electrical saving system, and to reutilize it for the power supply of electric and thermal consumers or actuators in a railway station thanks to a microgrid (Galaï-Dol et al., 2016). In this study, the RATP (the Parisian urban railway operator) developed an experiment in which reutilises the braking energy from trains for the power supply of electric equipment in a railway station thanks to a microgrid. Results demonstrated that, due to differences in the existing equipment, it would be difficult to change all the already existing equipment into a station, as it generates high costs, but it can be interesting to forecast it for new railway stations concepts. The study is a first step to a multi physical micro grid, which is a trampoline to the micro grid and the urban living of the future when the micro grid will integrate many kinds of energy resources (Galaï-Dol et al., 2016). Another study that compares different types of energy supply for station buildings, shows that railway station loads can be supplied by grid, photovoltaic panels or energy storage systems. Electrical railway system can be charged by either utilizing regenerative braking energy, photovoltaic panels or grid. It demonstrates the relevant cost reduction when producing energy with such systems, and how the increase in photovoltaic panels size results in a significant decrease in daily operational cost of the smart railway station (Sengor, 2018). Such studies demonstrate that an organised system may serve various loads from various energy sources in an efficient and cost-effective manner for the station, which can in this way become an energy-hub (Akbari, 2021) thanks to the high reusable energy potential lying behind the electrical railway system. Storing brakes energy and using it during daily consumption peaks would allow to help decrease carbon emissions while also lowering energy bills (Galaï-Dol et al., 2016). Consequently, it seems important to advance the research on these topics and discover new technologies, but this needs cooperation between stakeholders and a proper data collection and analysis.

When talking about resources’ optimization, a more sustainable urban logistics chain might be accomplished by considering the possibility of railway stations as middle-point hubs in the chain, between warehouses located outside of cities and last mile delivery services. Stations would help the entire value chain in cutting journeys by optimizing the flow of goods by collecting goods more centrally but still in a fine-grained mesh, bridging the gap between freight transport and urban logistics. Also, combining train transportation with emissions-free parcel delivery through cargo bikes could help decouple neighbourhoods from vehicles while also addressing the curb-management issue. By doing so, the positive contribution to the energy layer is also expanded: fuel consumption is drastically reduced and replaced by energy, ideally from renewable sources, that may be produced at the station. Due to railway stations’ central function, the supply-demand balance may be monitored and optimized. Simultaneously, the station can serve as a hub for logistical waste management, eventually also generating electricity from its treatment.

Development of TODs is not only about transport, but also about urban development around intermodal hubs. To enable sustainable mobility in cities is fundamental to work on ‘proximity’, as seen in the previous chapters, and logistic services are also part of such proximity. If primary services and shops are placed at a walking or cycling distance from inhabitants’ homes, active and sustainable mobility is enhanced while environmental footprint is reduced, and time is saved in commuting. In addition, proximity promotes social interactions (Moreno, 2021), as advocated also by urban theorists like Jacobs (1961).

Mediating between transport and urban needs in the space of a station could help manage the urban and infrastructural development. Integration of services brings interaction between stakeholders, which facilitates exchanges and enable business (Wenner & Thierstein, 2022). As a node, the railway station must guarantee a seamless journey and a high quality space. As a place, it should have a urban centrality role, thus becoming part of the city through the development of mixed-use environments and services inside and around it (Conticelli, 2011). As advocated by Bertolini (1998) a more concrete, situation-specific commitment to multifunctionality would be needed when (re)developing stations, by catering to both profitable and less profitable customers’ interests. Moreover, coupling transport functions with other socio-economic activities enable urban compactness, which is key for reduce consumption of resources and energy (Yin, 2015).

Nevertheless, obstacles to such stations’ redevelopments are multiple. The most evident concerns property value which ‘obliges’ stations managers to rent its spaces to very high prices, often not affordable by local commerce and other kind of services. This was the consequence of property booms in the 1990s, where real-estate market conjunctures have had a driving relevance in most station projects (Bertolini, 1998). Consequently, small and local businesses and public services are excluded from these spaces. The involvement of new (public and private) stakeholders in the co-financing of stations’ development should be explored, to be able to integrate local businesses offering proximity services while a better understanding of users’ needs would also bring new business opportunities for all stakeholders. Co-funding mechanisms as well as the use of green and social bonds should be explored for launching or testing the funding of such new activities.

So far, research has paid little attention to stations and the urban design of their immediate surroundings as part of the urban transformation processes (Ponzini, 2013). Stations redevelopments in the 1990s, even though they were intended to improve rail transport and generating sustainable urban areas, often led to an economic polarisation and hierarchisation (Wenner, 2020; Chen & Hall, 2015; Garmendia et al., 2012; Vickerman, 1997), especially of local communities. But recently, the literature on urban studies has shifted from the idea of the transport infrastructure as an element that produces discontinuity with the urban tissue to an infrastructure that generates places for citizens while still creating urban continuity (Ferorelli, 2016), which represents an improvement and a fertile ground for giving the station a role of urban connector. As a result, stations can be used to generate such public linking areas while also allowing social interactions.

Building from these considerations, it seems crucial to understand how new uses of such areas could impact local communities and travellers. In this context, a response to can be found in the emerging 'placemaking practices' that, through the co-design of such public spaces, would allow local communities regaining ownership of them, while implementing activities tailored to their needs. Customers and citizens - rather than transportation companies - can define which services must be offered; and transportation operators can just provide customers with an operating system they can utilize according to their needs.

As highlighted during the workshops, people do not move between stations; they move between activities. Consequently, if transfers between activities can be made easier, faster, more convenient, productive – and more pleasurable – then public transportation will likely be used for better, more diverse, and more frequent travels (Chen et al., 2014). To do this, it is necessary to understand what engages people in the design of public spaces, what draws them away from their everyday routines to generate value in these areas, and the station might be transformed into a place where people can have an experience. Currently, when people get to the station feel compelled to buy or leave. There are no services or activities where users are not required to purchase.

Thompson et al. (2012) observe how the railway experience is created through complex interactions between the railway and the people who use it. Because rail travel is a socio-technical system, social interventions may be required to preserve favourable experiences. As seen in literature review, the experiment conducted in Scotland where community groups and individuals have been invited to gardening activities inside some stations, demonstrates that the station has been appropriated as an extension of urban activities, making it a part of a larger community agenda to make a more meaningful place for visitors and residents (Alexander and Hamilton, 2015). Appropriation leads to an increased sense of ownership of the station. Adopters engender and create a sense of place as a result of their sense of ownership, which leads to emotions of responsibility and a vision of the future (Alexander and Hamilton, 2015). Through adoption, instead, citizens come to see stations more as community assets than transport hubs (Alexander and Hamilton, 2015). Thus, providing free-creative places for station users (such as the pianos already installed in many stations) could be part of a solution to understand what citizens need in that specific location. Obstacle to this is that stations are private spaces that need to be rented to generate revenues. Therefore, co-creating spaces inside and around stations is a challenge that needs policy adaptation and collaboration between private and public stakeholders.

5. Conclusions

The findings presented in this paper show that stakeholders around European railway stations see the potential of better using stations to improve urban transportation and related urban spaces, citizens' daily life, and city's resources optimization. To achieve this, specific topics needs to be investigated to generate new knowledge and industry achievements.

Analysing the role of the station as a public space dedicated to citizens is fundamental. Developing stations as spaces and infrastructures at the service of the public would imply transforming them into mobility hubs where both local and global businesses serve residents' demands and promote effective and sustainable travel. Urban policies and regulations, as well as stations governance, must be adapted. In this context, the position of the urban planner could be a change agent. However, in order to build cooperation among stakeholders, ideas must be tested and possible impacts analysed, to then build roadmaps for transformation.

Second, an upgrade in the utilization of the stations' energy infrastructure should be explored through experiments, as it represents a key asset for urban energy challenges. More in-depth research utilizing a data-driven strategy to generate an energy map and identify the most vulnerable spots, both within infrastructure and governance of railway hubs, can help develop unique solutions for stations' energy efficiency. Similarly, the circularity of resources moving through the station is vital for helping the city in its sustainable growth, such as greening urban logistics and waste chains. To create a regulatory adaption lever, tests of novel models of material and logistics management should be done.

Third, there is a need for a general overview of the value of such assets, from the station's construction to all assets that pass through it every day, to the value of its catchment area, not only from a financial standpoint, but also considering social values and environmental challenges that such innovations may bring.

As is the case in most transformation themes connected to sustainability, the transformation and better utilization of railway stations and their surroundings needs a concentrated, collective effort by all stakeholders involved. As shown in this paper, the paths for European railway stations are clear and the motivation of many involved actors is high; it is thus a strong argument for political actors to activate the existing potential and set transformation into motion.

As highlighted in the literature review, redevelopment of station areas is a challenging task where no single model has yet been found that can be applied to all situations. This is the case from both a planning perspective and a policy and governance perspective. The reason behind this is that each context has local peculiarities, different driving forces and obstacles. Therefore, as suggested by Bertolini (2012), an experimental attitude and a willingness to learn from both others' and one's own experiences seems essential to tackle such a challenge.

Building from these considerations, this paper represents the starting point of a wider research of which the next steps will be the study of the impacts of experiments in different stations in Europe that will be conducted in the following months. Three projects let by EIT UM with three different cities in Europe (Milano, Toulouse, and Madrid) will take place in railway stations contexts. They concern the development of intermodality at these stations and the construction of a model to be scaled up to other places. New services for micro-mobility and active mobility will be tested during 6–12 months at these stations, together with additional services for citizens and placemaking activities. During the test period, activities of involvement of local communities and users will be undertaken to observe and analyse the impact of such tests, while also collecting the feedback and ideas from citizens about the development of such models. The research will be based on these outputs.

Declaration of Competing Interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Alice Lunardon is a PhD candidate at TUM, and, in parallel, works at the EIT Urban Mobility (Home - EIT Urban mobility), which is a European initiative supported by the European Institute of Innovation and Technology (EIT), working on developing innovations for urban mobility and more liveable public spaces. The EIT Urban Mobility funds projects for its partners and other external organisations. Alice Lunardon works at the EIT UM to support these organisations in developing innovations and projects in European cities. She does not have any interests in supporting a specific organisation or another, or any specific project. As she is working on a PhD thesis on railway stations, which is

a main topic for urban mobility field, she develops synergies between her work at the EIT UM and her academic research with the objective of improving the research and projects of the organisations that collaborate with the EIT UM, and at the same time, enriching her research by collecting data from the projects on railway stations that are developed within the EIT UM.

CRediT authorship contribution statement

Alice Lunardon: Conceptualization, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Doroteya Vladimirova:** Methodology, Validation, Data curation, Supervision. **Benedikt Boucsein:** Validation, Supervision, Formal analysis, Writing – review & editing.

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How to promote the environmental sustainability of shared e-scooters: A life-cycle analysis based on a case study from Lisbon, Portugal☆,☆☆

Ana Filipa Reis[a], Patrícia Baptista[b,*], Filipe Moura[a]

[a] CERIS, Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal
[b] Centre for Innovation, Technology and Policy Research (IN+), Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal

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A B S T R A C T

Electric scooter sharing systems have emerged as an innovative short distance transport mode. Since these systems are dockless, they require collection for maintenance and charging, as well as rebalancing operations citywide, justifying the need for an integrated analysis. This work performs a Life Cycle Analysis to assess the environmental impacts of all stages of a shared e-scooter, based on the use case of Lisbon, Portugal. Results indicate that an e-scooter emits 804 to 1679 g CO_{2eq}/km, which is justified by its low use rates and reduced life span. Its production accounts for more than 70% of impacts, collection and distribution processes for 6% and vehicle use corresponds to 17%. Increasing the shared e-scooter life expectancy reduces environmental impacts by 26 to 47%, while increasing the kilometers per day reduces the impacts between 50% to 80%. Also, a less frequent collection of e-scooters would improve the results between 7 and 42%. These results enabled defining specific strategies and policies to guarantee a more sustainable deployment and operation of shared e-scooter systems.

1. Introduction

The transport sector is responsible for one-third of the final energy consumption in the European Union (EU) (EC, 2020). Most of that energy consumption is associated with the consumption of petroleum products, which means that transports are responsible for around one-fourth of the EU's greenhouse gasses (GHG) emissions (EC, 2020). For the specific case of Portugal, in 2017, the transport sector accounted for around 24% of GHG emissions (APA, 2019). As a result, to reduce the adverse effects of transports, less polluting and more efficient modes of transport are being promoted by implementing alternative technologies, energy sources and business models (EEA, 2018; IEA, 2020). With the increasing awareness for environmental problems, most companies are looking for less polluting alternatives, increasing the need to promote more sustainable solutions, with electric mobility playing a fundamental role in this matter. The main trend has been to promote more efficient vehicles, which eliminate local pollution from urban centers, while also reducing noise pollution (EEA, 2018).

Electric scooters (e-scooters) recently arose in the urban context, mostly directed to micro-mobility focused on the first-and-last-mile trips (Baek, Lee, Chung & Kim, 2021), but also creating conflicts on urban space and safety, requiring adequate policies to support their introduction (Gössling, 2020). Even if they do not emit CO_2 during its use, one drawback is its reduced lifespan, with reports saying it can last only one month due to battery failure ((Künzel, 2020; Louisville Metro Government, 2020)). Considering the uncertainty on the sustainability of e-scooters, this work focuses on performing the life-cycle assessment (LCA) of shared e-scooters, accounting for all life-cycle stages and detailing the influence of variables often disregarded (collection frequency, daily distance travelled, e-scooters' lifespan and recycling pathways), focusing on the case study of Lisbon, Portugal. This topic is particularly relevant for the promotion of sustainable cities by being an important mobility option within the 15-Minute City concept, while guaranteeing that the promotion of these alternative mobility solutions are effective in reducing current environmental externalities.

Many cities faced the same reality as Lisbon, as no regulatory directives were given on the specification of the e-scooters and on the utilization levels that had to be fulfilled. Operators faced an open and deregulated market, raising the question of how sustainable e-scooters operation levels are.

2. Impact assessment of personal transport modes

For electric vehicles (EV), many studies have already focused on their LCA, ranging from motorcycles (Cherry, 2007; Weiss, Dekker, Moro, Scholz & Patel, 2015), bikes, and light-duty vehicles, demonstrat-

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* Corresponding author.
E-mail address: patricia.baptista@tecnico.ulisboa.pt (P. Baptista).

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Table 1
– Summary of literate on LCA of e-shared scooters.

Reference	Location	Method	Main result
(Chester, 2019)	USA	GREET Model for e-sccoter production in China, typical US distance traveled, Washington DC energy mix for recharging	200 to 400 g CO_{2eq}/km
(Hollingsworth et al., 2019	Raleigh, North Carolina, USA	E-sccoter production in China modelled using data from Ecoinvent 3.3, Raleigh distance traveled from surveys, local energy mix for recharging	94 to 305 g CO_{2eq}/km
(Bird, 2020)			61 g CO_{2eq}/km
(Holm Moller et al., 2020)	Paris, France	E-sccoter production sites in Europe, distance traveled for Paris, local energy mix for recharging, end-of-life treatment included	35 g CO_{2eq}/km
(Severengiz et al., 2020b)	Berlin, Germany	GaBi Model for e-sccoter production in China, Berlin usage patterns, German energy mix for recharging	77 g CO_{2eq}/pass.km
(Kazmaier et al., 2020)	Germany	E-sccoter production in China modelled using data from Ecoinvent 3.5, Usage patterns based on interviews, average German energy mix for recharging, end-of-life treatment included	165 g CO_{2eq}/km
(Moreau et al., 2020)	Brussels, Belgium	E-sccoter production in China modelled using data from Ecoinvent 3.4, using Simapro 8.5 Usage patterns based on local survey, average Belgium energy mix for recharging	131 g CO_{2eq} / pass.km

ing that EV have lower impacts during their use, but their production has at least the same impact as a conventional vehicle (Paulino et al., 2018)(Hawkins, Singh, Majeau-Bettez & Strømman, 2013). Also, the EV end-of-life may have a higher impact due to process complexity in battery dismantling and recycling (Paulino et al., 2018). As for electric motorbikes and electric bicycles, there are some studies that compare the environmental performance between these two modes of transportation and their conventional counterparts, indicating the same trend of increased impacts due to energy-intensive processes for battery production and use of electricity that can have higher environmental impacts associated to its generation ((Cherry, 2007; Weiss et al., 2015)). Also, the use of these types of vehicles can lead to increased energy consumption and environmental burden if they replace the use of conventional bicycles or public transport (Weiss et al., 2015). S. Fang et al. adopted a distinct analysis focusing on the influence of charging behaviors (users' charging time, and frequency of usage) and to understand the optimal placement and numbers of charging points (Fang, Chang & Yu, 2014).

As for studies focused only on electric bicycles, C. Zhang et al. considered an electric bicycle (e-bike) as a potential substitute for a gasoline motorbike, concluding through an LCA that the e-bike consumes less energy and emits less pollution during use, however, it generates more solid waste, acidification potential and heavy metals than a motorbike (Zhang, Wang, Sullivan, Han & Schuetzle, 2001). D'Almeida et al. evaluated the life-cycle impacts of a public bike sharing system in Edinburgh, UK, showing it saved 200 tonnes of CO_2 over a period of 5 years, corresponding to 9.6 g of CO_2 per km (D'Almeida, Rye & Pomponi, 2021). Also, H. Luo et al. compared the life cycle of a bicycle sharing system (BBS) with docks and a dockless electric BBS (Luo, Kou, Zhao & Cai, 2019). Although considered a sustainable mode of transport, BSS still have environmental impacts generated by its operation (replacement of bicycles using cars) and the system's production. Dockless BSS result in 82% higher GHG emissions than a BSS with stations, mainly due to bicycle replacement. However, BSS can bring environmental benefits when replacing other transport modes, with the replacement of a car journey being the most important factor, with sharing services being most cost-efficient below 5000 km travelled annually (Schröder & Gotzler, 2021). Consequently, several approaches can be undertaken to improve the environmental performance of a BSS, such as: 1) optimizing the bicycles' distribution and of their replacement route; 2) use of more sustainable vehicles for bicycle collection and replacement; 3) encouraging more car users to switch to BSS; 4) extending infrastructure lifetimes for BSS with docks; and 5) increasing the use of BSS.

Nonetheless, few studies have dealt with the LCA of e-scooters, as summarized in Table 1. Chester assessed the full life cycle of an e-scooter and concluded that it emits between 200 and 400 g CO_{2eq}/km, depending on how the scooter collection/distribution process is carried out (Chester, 2019). Hollingsworth et al. also published a detailed LCA of e-scooters concluding that the CO_{2eq} emissions range from 94 to 305 g CO_{2eq}/km, in which 50% of total impacts are due to its production and 43% result from the collection and distribution process (Hollingsworth, Copeland & Johnson, 2019).

Bird, which is one of the most widely spread operators on the market, states in its official site that their e-scooters emit 61 g CO_{2eq}/km (Bird, 2020), but does not specify their assumptions in detail. Also, Voi made a micro-mobility report with a complete LCA of their e-scooters for their European operations, resulting in emissions of 35 g CO_{2eq}/km, justifying such a low carbon footprint by the electrification of vehicles used in the collection/distribution, to the use of replaceable batteries and the use of renewable energies, as well as to recycling of materials (Holm Moller et al., 2020). However, these two analyses (Bird and Voi) are very context-specific and do not specify assumptions and the details for collecting/distributing and recycling.

In 2020, various studies have been published focusing in cities of Germany (Kazmaier, Taefi & Hettesheimer, 2020; Severengiz, Finke, Schelte & Forrister, 2020a, 2020c). S. Severengiz et al. published a life cycle assessment for shared e-scooters in Berlin Severengiz, Finke, Schelte and Wendt, (2020b). The base case scenario indicates that an e-scooter, with a lifetime of 24 months and an average distance per day of 10.2 km, emits 77 g CO_{2eq}/pass.km. The disaggregation of results shows that 63% are related to materials and manufacturing (especially the production of aluminum parts), 1% is from transportation and 35% is associated to the use phase. The study considered various scenarios namely: 1) a shorter lifetime of 6 months; 2) a non-swappable battery in which the e-scooter is collected by a van; 3) a battery swapping with e-vans; 4) a battery swapping with e-cargo bikes; 5) a scenario using solar power energy; and 6) a scenario where the transportation between origin and destination is made by plane. The results obtained were: scenario 1 - 237 g CO_{2eq}/pass.km (82% contribution from production); scenario 2 – 121 g CO_{2eq}/pass.km (58% contribution from use phase); scenario 3 and 4 result in a 12% and 17% reduction from the base case, respectively; using solar power (scenario 5) would decrease impacts in 14%; and if the e-scooters were transported by air (scenario 6) results would increase by 20%. The authors also conclude that, in the worst-case scenario, e-scooters have the worst environmental impact compared to all modes of transport (bicycle, e-bicycle, e-motorcycle, bus, tram and passenger car) (Severengiz et al., 2020b).

Kazmaier et al. developed a life cycle assessment to quantify the environmental impacts of an e-scooter and this analysis was based on a user survey and on expert interviews to generate new data and determine if e-scooters are in fact a climate-friendly mode of transport (Kazmaier et al., 2020). The results show that an e-scooter in Germany emits 165 g CO_{2eq}/km due to the material and production phase, which represents about 73% of the total environmental impact. The value can be reduced by 12% with the use of swapped batteries. If the life span of e-scooters increases in 15 months, the emissions can reach 46 g CO_{2eq}/km (Kazmaier et al., 2020).

Moreau et al. studied and compared the environmental impacts of shared dockless e-scooter use in Brussels from a life cycle assessment (Moreau et al., 2020). The study concludes that an e-scooter emits 131 g CO_{2eq} / pass.km. The high impact is seen in the materials phase and is mainly due to the amount of aluminum. The study also conducted a survey in which it was possible to calculate the mode of transportation displaced by the e-scooter (with an impact of 110 g CO_{2eq} / pass.km), concluding that shared e-scooters have a higher impact than the transportation modes they replace. E-scooters need a lifespan of at least 9.5 months to be a green solution for mobility in the current use situation. The high results for the shared e-scooter are mainly caused by the short lifespan. Finally, no end-of-life treatment was included in the assessment because none was taking place.

Severengiz et al. focus their study on how the reliability characteristics, like durability, can affect product sustainability of mass customized products like e-scooters using the life cycle assessment as a methodology. The results show that for the base case scenario, an e-scooter emits 130 g CO_{2eq} / pass.km, ranging values between 116 and 164 g CO_{2eq} / pass.km depending on reliability aspects. The study also demonstrates that a battery upgrade could improve electricity demand and logistics in the use phase by 20%. Different models of e-scooters are also compared, concluding that producing a heavier e-scooter will increase the emissions. In another scenario, an e-scooter with a lifetime of 2100 km is compared with a recent model with a lifetime of 4200 km, emitting respectively 159 and 130 g CO_{2eq} / pass.km. The paper also indicates a high optimization potential in e-scooters by increasing the durability of the components without simultaneously increasing the GWP of production. However, it recommends that e-scooters in private use should use light materials and fewer durable components to reduce de GWP of production because they are treated more carefully and are less affected by vandalism. But e-scooters sharing systems need higher durability (Severengiz, Schelte & Bracke, 2021).

Other important variable often disregarded in the assessment of e-scooters is the type pf pavement they are used and the influence in their maintenance requirements and associated lifespan. E-scooters are used both on the road and on sidewalks (even if most city regulations require their circulation on the road network). In older cities within Europe, it is normal to associate bad conservation to road pavement and higher rolling resistance associated to traditional sidewalks, resulting in higher wear of components and reduced durability of components. Additionally, there typically is no supervision on operation of e-scooters, resulting in very limited reliable available information on operational variables and on the environmental performance of such transport modes.

In this context, the main contribution of this paper is to define regulatory and implementation strategies that guarantee the sustainability of shared e-scooter systems, by quantifying their lifecycle environmental impacts. This analysis includes the production, use, and end-of-life of an e-scooter, thus incorporating the material components, but also the energy intensity of the processes used from the extraction of raw materials to the production of the vehicle. Also, maintenance, collection/distribution processes, and electricity use.

This work focuses on the case study of Lisbon, Portugal, highlighting the need to consider specificities in terms of regulatory void and unique driving conditions (ranging from rough pavement conditions, steep slopes, and traditional sidewalk pavements using black and white stones of basalt and limestone). Another innovative contribution of this work is that it provides evidence on the performance of such vehicles under extreme operation conditions (rough pavements and sidewalks) and deregulated riding conditions (e.g., it is unclear whether e-scooters can ride on sidewalks).".

3. Methodology

The approach applied to analyze the environmental sustainability of e-scooters is presented in Fig. 1. When the work was carried out, very few published bibliographic references were available, and even few commercial information was available on the e-scooters and respective shared systems. Intense research had to be carried out on the constituent materials of an electric scooter, weights, and respective production processes. For those reasons, operator workers were interviewed, and real-world operational data related to maintenance and the collection process was collected. This was essential to understand the collection and maintenance processes, on how long an e-scooter lasts in Lisbon's pavement conditions, how many kilometers a collection van actually travels to pick up the e-scooters, and how much maintenance an e-scooter undergoes throughout its lifetime.

The next step consisted on the definition of the base case and alternative scenarios, requiring the implementation in SimaPRO of an e-scooter model. SimaPRO enables modeling complex life cycles in a systematic way to evaluate the sustainability performance data of products and services. Since SimaPRO did not contain a model of an electric scooter, so a new model was created for the electric scooter (based on the adaptation of structurally comparable transport modes, in this case, an electric motorcycle and an electric bicycle), which is currently available upon request.

This enabled performing several scenarios based on realistic variables for the case study of Lisbon. Lisbon has rough pavement conditions, steep slopes, and traditional sidewalk pavements using black and white stones of basalt and limestone. This work provides evidence on the performance of such vehicles under extreme operation conditions (rough pavements and sidewalks) and deregulated riding conditions (e.g., it is unclear whether e-scooters can ride on sidewalks).

3.1. Data collection and interviews

During this research, there was very little available information available on specific details associated with e-scooters logistics in Lisbon, Portugal. Even if specific data requests were performed to several operators, no information was provided. As such, two interviews with workers from different operators were conducted to obtain relevant information. The main conclusions from both interviews were:

- E-scooters are collected every day due to constant vandalism. However, for most operators, the collection is only done for scooters with batteries loaded below 30%;
- The collection is done in vans with fossil-fueled internal combustion engines;
- Quick maintenance is made to ensure the safety of users: tests that guarantee if the e-scooters structure is in good condition, if screws are well tightened and if brakes are working;
- Most e-scooters are disassembled, and pieces are used for other scooters. In other words, the scooter never gets scrapped as a whole, because pieces are continually being replaced;
- The mechanical part of an e-scooter fails first because they are structurally fragile to be used in extreme pavement conditions and suffer constant vandalism, but engines and batteries suffer significant wear due to the local specificities of road pavement and slopes;
- Day trips made by e-scooters are uncertain, since they can either make three trips in one day or be stopped for several days; and
- In Portugal, there are no reported procedures to deal with damaged e-scooters and batteries in their end-of-life, at least at the time of the interviews.

We also had access to the one-month (mid-October to mid-November 2019) operation data of e-scooters from a company that worked with

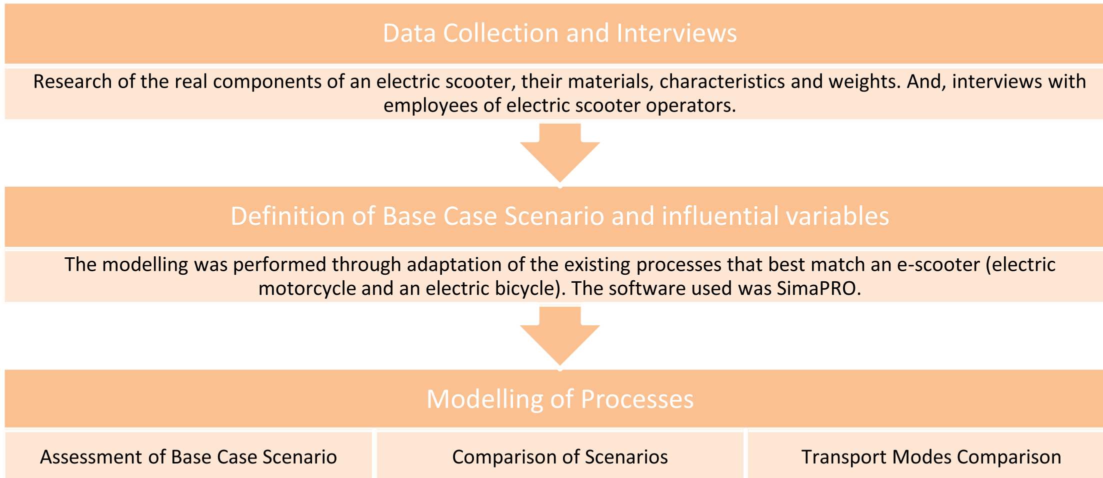

Fig. 1. – Flowchart of the applied methodology.

one of the operators. The maintenance data were categorized into "hard fixes" (mostly, substitution of batteries and electric motors) and "easy fixes" (quick replacements performed on the e-scooters). Each e-scooter is maintained 2.76 times in a month (easy fixes), while battery and/or the electric motor is changed 0.68 times a month (hard fixes). Considering the extreme pavement and slope conditions found in Lisbon, it was assumed that each e-scooter reaches its end-of-life when it changes the battery and/or the electric motor, which corresponded to an average lifetime of one month and a half. We also had access to data regarding collection and redistribution operations during that month, enabling the characterization of a typical ICEV trip of 82 kms per day carrying, on average, 52 e-scooters, which corresponded to an average load factor of 53% (by assuming a maximum load of 99 e-scooters from the maximum load verified). From the data analysis, it was also possible to estimate that, on average, 97 scooters were collected per day and that e-scooters are collected on average eight times per month, which is equivalent to an average collection of around 3.5 days.

3.2. Definition of base case situation and influential variables

A thorough characterization of the components of e-scooters was performed, in terms of its respective materials, characteristics and weights. This allowed combining real-world data with existing data in the Ecoinvent 3 database from the SimaPro software (Goedkoop, Oele, Leijting, Ponsioen & Meijer, 2016). The evaluation method used was the ILCD 2011 Midpoint+ with the APOS model (European Comission, 2011). Since the database did not have a process for an e-scooter, the existing electric motorcycle and electric bicycle processes were adapted with specific real-world e-scooter data for obtaining the e-scooter process. The functional unit for the analysis is performing 1 km with an e-scooter, even if the implementation in SimaPro was performed by simulating the full lifetime of the e-scooter.

3.2.1. Production

The production of an e-scooter includes the manufacturing of a lithium-ion battery, the vehicle's structure, and the battery charger, as shown in Fig. 2. This process was based on the SimaPro electric motorcycle process. The remaining structural part - electric scooter without a battery - is subdivided into glider and powertrain, with the powertrain consisting of the controller and the electric motor.

One e-scooter is considered to have a total weight of 14.06 kg (including the charger) based on the average weights of the *Momas E-Scooter 1.0* (Review, 2020) and the *Glion Electric Scooter Model 200* (Reviews, 2020). This scooter has an average weight of 13.45 kg, a battery with 2.22 kg, an electric motor with 2.74 kg, a charger with 0.61 kg, and the weight of the controller (0.18 kg) was collected separately for the same voltage used in batteries of both models of scooters, 36 V (Amazon, 2020). The powertrain is the sum of the electric motor's weights and the controller (2.92 kg), and the glider is the difference between the electric scooter without the battery and the powertrain (8.31 kg). The glider constitution was based on the materials used in the process of an electric bicycle since the mechanical and structural constitution of an e-scooter is similar to an electric bicycle. The main materials are aluminum, steel, plastic, and rubber. The weight values of the glider's constituent materials were calculated for 1 kg of e-scooter.

Table 2
- Total mileage (in km) for 1 month, 1.5 months, 3 months, and 6 months (Baseline Scenario presented in bold and underlined applied to all tables).

Distance per day (km)	Lifetime			
	30 days	**45 days**	**90 days**	**180 days**
1 km	30 km	45 km	90 km	180 km
2 km	60 km	**<u>90 km</u>**	180 km	360 km
5 km	150 km	225 km	450 km	900 km

3.2.2. Use

The use phase includes: maintenance; energy consumption on the road during the e-scooter's useful life; and the electricity production stage (see Fig. 2). These impacts are modeled for every kilometer driven by the e-scooter, but the simulation in Simapro was implemented for the full lifetime of the e-scooter. The use phase processes are identical to the use processes of an electric motorcycle and of an electric bicycle.

The e-scooter use process unit is the distance driven in kilometers (km), which is a combination of the lifetime of the e-scooter and the daily distance travelled. Based on the information collected, four scenarios were considered for the total lifetime of an e-scooter: **1 month** (30 days), **1.5 months** (45 days), **3 months** (90 days), and **6 months** (180 days). Additionally, three scenarios were considered for the daily mileage of the e-scooters: **1 km; 2 km**; and **5 km** per day. Table 2 shows the total mileage that an e-scooter makes over its total lifetime.

Based on the data collected on the performed interviews regarding the use case of Lisbon, a **Base Scenario** was considered for a **life span of 45 days** and **daily use of 2 km** (bold and underlined value in Table 7). This Base Scenario reflects the situation in the first years of operation of shared e-scooters in Lisbon.

The maintenance is mainly the replacement of plastic and steel pieces, and it does not include the replacement of the battery. Maintenance was adapted from the electric motorcycle's process (mainte-

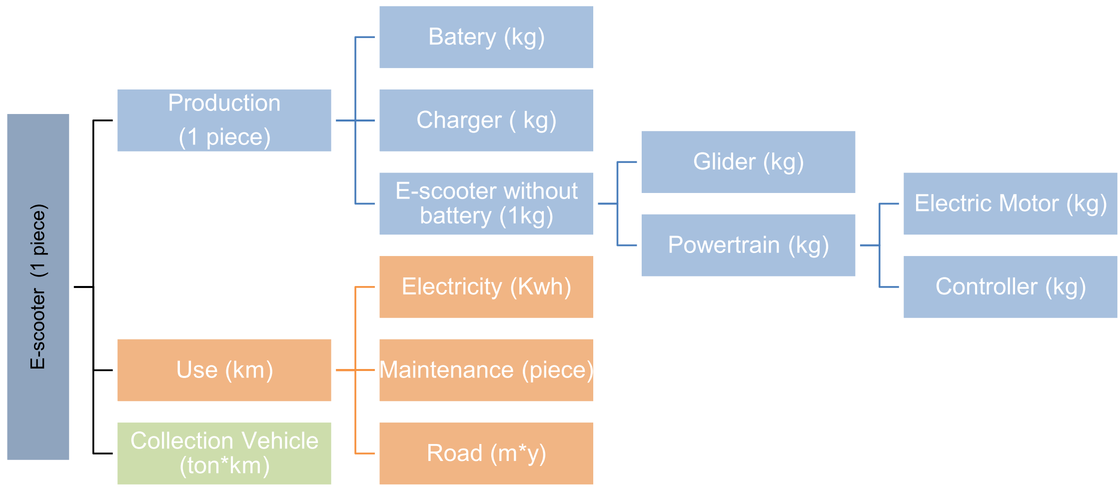

Fig. 2. – Final process of production, use, and collection of an e-scooter.

Table 3
Maintenance values for 1 month, 1.5 months, 3 months, and 6 months.

Distance per day (km)	Maintenance (pieces) per km			
	30 days	**45 days**	**90 days**	**180 days**
1 km	3.11E-03	2.07E-03	1.04E-03	5.19E-04
2 km	1.56E-03	**1.04E-03**	5.19E-04	2.59E-04
5 km	6.22E-04	4.15E-04	2.07E-04	1.04E-04

Table 4
- Number of collections for 1 month, 1,5 months, 3 months, and 6 months.

	Number of collections			
	30 days	**45 days**	**90 days**	**180 days**
Collection every day	30	45	90	180
Collection every 3 days	10	15	30	60

nance value for 1 km is 2E-05 pieces, which corresponds to one maintenance in its total lifetime of 50.000 km), through a weight scaling procedure. For the e-scooter's process, based on the ratio between weights of 13.45 kg for the e-scooter and 144 kg for the electric motorcycle, a weight correction was calculated ($9.34E-02$). For the e-scooter's process, it is also necessary to know the number of pieces maintained per kilometer, so this scale factor is divided by the kilometers driven by an e-scooter throughout its total lifetime for each scenario. Table 3 indicates the maintenance done per kilometer for each total lifetime scenario.

The energy required to charge the e-scooter during its use was assumed to be low-voltage electricity (in kWh) selected from the current Portuguese electricity mix (European Comission, 2011). The battery's state of charge is not included in the calculations, since the electricity charged depends on the kilometers travelled by the e-scooter throughout its life. The road component represents the costs and requirements for building roads, tunnels, bridge infrastructures, the recovery of different roads and their eventual disposal, with all these environmental expenses referring to one meter-year (m * y).

3.2.3. Collection and distribution operations

According to the obtained data, it is assumed that the e-scooters are collected either every day or every three days. Table 4 indicates the number of times that a scooter is collected in its total lifetime for each scenario.

The collection and distribution operation of e-scooters is done with a light commercial vehicle between 3.5 to 7.5 tons of gross vehicle weight. Although a default load factor for this vehicle (3.5 - 7.5 tonnes) is 20%, it was increased to 53% (in weight), based on the average Lisbon value. This vehicle is associated with a unit of 1 ton.km, with the following formula: **ton.km** = $\boldsymbol{P} \times \boldsymbol{d} \times \mathbf{N}$, where P is the weight of the e-scooter transported by the vehicle in tonnes (0.01345 tonnes), d is the distance travelled for the vehicles' collection (on average, 82 km) over its total lifetime (measured in kilometers) and N is the number of collections per run. In a round trip to a warehouse where scooters are charged and later distributed, they travel 82 km based on Lisbon's collected data. As an example, for the base case scenario, the collection/distribution phase corresponds to 15 trips at 82 km/trip corresponding to 1230 km, which accounting the 0.01345 tonnes associated to each e-scooter corresponds to 16.50 ton.km.

Table 5 indicates the distance travelled by the collection vehicle over the life of an e-scooter for each scenario. As already stated, maintenance is independent of collection, because otherwise the transport would happen as often as the number of maintenances.

Thus, it is possible to complete the collection operation by converting to ton.km, which is done by multiplying the weight of the e-scooter (0.01345 tons) with the values presented in Table 5. The resulting values for the collection phase are shown in Table 6.

Fig. 2 shows e-scooter's process without the end-of-life phase. The simulation in SimaPro is performed for the total lifetime of an e-scooter. The variables that change the type of scenario are maintenance (pieces), use (total mileage), and collection vehicle (ton-km). Production of an e-scooter is the production of its components and, therefore, the values associated with each material/component are fixed for each scenario. Electricity and road are also fixed values for every scenario.

3.2.4. End-of-life

The end-of-life considers that all vehicles undergo a manual dismantling process by disaggregating their various material components. The treatment involves dismantling the glider and powertrain, which are later disposed of in specific waste disposal facilities. The remaining waste materials are treated differently, whether recycling, energy recovery by incineration, or landfill. The materials selected for the end of life are the main constituents of the scooter glider: aluminum, steel, rubber, and plastics (polyethylene (PE) and polyurethane (PU)). Due to the lack of definition of the end-of-life of e-scooters, to account to its high uncertainty, three end-of-life scenarios were created:

- **Scenario 1**: Most materials go to a landfill, and the remaining percentage is recovered energetically. This is a scenario without recycling;
- **Scenario 2**: Most materials are recycled, but the battery and powertrain are 100% recovered energetically; and

Table 5
– Distance travelled (km) due to collection over total lifetime of 1 month, 1,5 months, 3 months and 6 months.

	Distance travelled in collection operations over the total lifetime (km) 30 days	45 days	90 days	180 days
Collection every day	2460	3690	7380	14,760
Collection every 3 days	820	1230	2460	4920

Table 6
– Distance travelled (ton-km) due to collection over total lifetime of 1 month, 1,5 months, 3 months, and 6 months.

Collection Frequency	Collection Vehicle (ton-km) 30 days	45 days	90 days	180 days
Collection every day	33.10	49.60	99.20	198.40
Collection every 3 days	11.00	16.50	33.10	66.10

- **Scenario 3:** Same as Scenario 2, but the battery and powertrain are recycled according to their constitution, i.e., the battery is 10% recycled, and the powertrain is 83% recycled. These percentages correspond to aluminum, steel, rubber, and plastic that constitute battery and powertrain.

3.3. Modeling of processes

Finally, all scenarios are summarized in Table 7 with the respective input data. These data refer to the total lifetime (total kilometers driven) of an e-scooter, the total ton.km of the collection vehicles, and maintenance for each end-of-life scenario. In short, we created three equal processes that only differ in their end-of-life. Therefore, the values which are inserted in the three processes are the ones presented in the following table. The results are different in each process because the end-of-life varies. Scenarios 1, 2, and 3 correspond to end-of-life scenarios, each divided according to the lifetime, the frequency of collection and the mileage performed by trip.

The main limitation of the developed methodology has been the lack of real-world data on shared e-scooter systems, making the collaboration of system operator essential to provide more detailed analysis. This encompasses details on materials components, usage patterns in terms of trips and kilometers, regarding recharging operations as well as end-of-life procedures.

4. Results and discussion

Throughout this section more emphasis will be given to the impact categories "Climate Change" ($kgCO_{2eq}$), "Human toxicity (non-carcinogenic and carcinogenic)" (CTUh) and "Particle Formation" ($kgPM_{2,5eq}$), as the former relates to global impacts emissions, while the other categories are relevant in terms of impacts on human health and air quality in the urban environment respectively. We begin with a detailed analysis of the Base Scenario's main impact categories (1, 2, and 3) and then focus only on the Climate Change impact category (expressed in g $CO_{2\text{eq}}$/km), where the various scenarios are compared according to frequency of collection, daily kilometers travelled and e-scooters' lifetime. Finally, we compare the e-scooters environmental performance with several transport modes (namely, electric vehicle, electric motorcycle and electric bicycle).

4.1. Assessment of base case scenario

Fig. 3 illustrates the distribution of impacts along the different lifecycle stages for the main impact categories. 13 different impact categories are distributed according to the different stage of the e-scooters value chain. The glider, charger, powertrain and battery components refer to the production of these components; the road, maintenance and energy components refers to the use stage of e-scooter, while the end-of-life (EoL) component refers to dismantling and recycling of the e-scooter at the end of its lifetime. The end-of-life stage assumptions vary between base scenarios 1 to 3 (see section 2.2.4.).

The impacts in terms of climate change (in kg $CO_{2\text{eq}}$), human toxicity (non-cancerous and cancerous) (in CTUh) and particulate matter (in kg $PM_{2.5\ eq}$) for all life stages (production, use, collection/distribution, and end-of-life) for the Base Case, divided by the main components, are presented as supplementary material (Tables SM1 to SM3).

For **Climate Change**, the production is responsible for more than 70% of the total impacts, which corresponds to 115 kg $CO_{2\text{eq}}$. Usage corresponds to 17% of impacts, of which 16.9% corresponds to maintenance, while collection emits 5.8%. In the impact category of **Non-Cancerous Human Toxicity**, the production of an e-scooter corresponds to more than 80% of the impacts. Utilization contributes 12.2%, in which maintenance corresponds to the total value, and collection represents 0.9%. For **Cancerous Human Toxicity**, this category's total impacts are almost exclusively due to the production of the e-scooter (more than 90%). The vehicle's use represents 3.7% of the total impacts, and the collection stage contributes with 1.1%. For **Particulate Matter**, the production of the e-scooter represents about 85% of the total impacts, while its use corresponds to approximately 10% and the collection stage contributes about 2.5%.

The main difference in the base scenarios regards the end of life. In the **Base Scenario 1**, the end of life contributes 1% to the Climate Change category, with positive impacts, instead of reducing them by recycling materials. In total, the e-scooter emits 1680 g $CO_{2\text{-eq}}$/km for a lifetime with 90 km. For Non-Cancerous Human Toxicity, the end-of-life contributes 1.1% to a total emission of 2.47E-04 CTUh per kilogram. For Cancerous Human Toxicity, the end-of-life represents 0.2% with a total emission of 3.79E-05 CTUh per kilogram. For Particulate Matter, the end-of-life phase corresponds to 0.2%, emitting a total of 1.69 g $PM_{2.5\ eq}$ /km.

In **Base Scenario 2**, for Climate Change, recycling and material recovery reduce impacts by 40%, which corresponds to less than 62 kg $CO_{2\text{-eq}}$, while total emissions are 974 g $CO_{2\text{-eq}}$/km. The Non-Cancerous Human Toxicity is the one that presents a lower negative contribution to the total impacts, as its end-of-life corresponds only to - 3%. On the contrary, for Cancerous Human Toxicity, recycling plays a large part in reducing positive impacts, by around - 35%. In total, the Non-Cancerous Human Toxicity corresponds to 2.36E-04 CTUh, while the Cancerous Human Toxicity corresponds to 2.44E-05 CTUh. As for Particulate Matter, the end-of-life contribution is around 42%, with a total emissions value of about 1 g $PM_{2.5-\ eq}$/km.

As for **Base scenario 3**, for Climate Change, if the main materials are recycled, the production, use and collection impacts are reduced by 52%. This scenario corresponds to the emission of 808 g CO_{2eq}/km. As for the Non-Cancerous Human Toxicity, the recycling of the end-of-life of materials represents around −7%, while for the Cancerous Human Toxicity it reduces the impacts by 42%. Overall, the Non-Cancerous Human Toxicity category results in 2.26E-04 CTUh/km and the Cancerous Human Toxicity category in 2.21E-05 CTUh/km. For the Particulate Matter category, recycling allows 52% of impacts to be fully recovered, with a total emission of 0.81 kg $PM_{2.5eq}$/km.

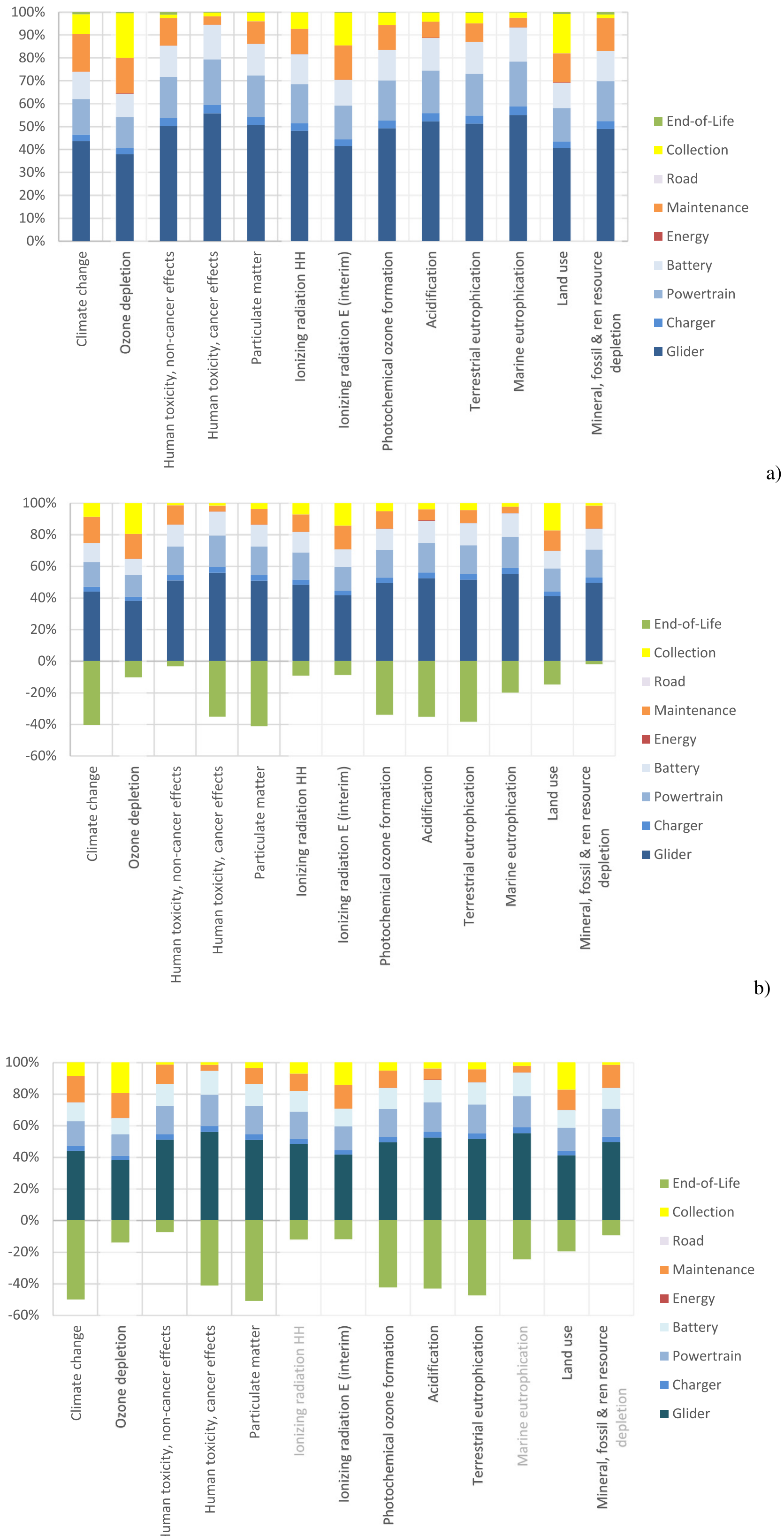

Fig. 3. - Results for all impact categories (in% terms) a) for base scenario 1, b) for base scenario 2, and c) for base scenario 3.

Table 7
- Input data for simulation in SimaPro of life cycle of e-scooter for each end-of-life scenario (scenarios 1, 2, and 3) (Baseline Scenario presented in bold and underlined).

	Collection	One trip per day of 1 km for Scenario 1, 2 and 3		
Lifespan (days)	Frequency	**Total mileage (km)**	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	30	33.10	3.11E-03
	3 in 3 days	30	11.00	3.11E-03
45	**1 in 1 days**	45	49.60	2.07E-03
	3 in 3 days	45	16.50	2.07E-03
90	**1 in 1 days**	90	99.20	1.04E-03
	3 in 3 days	90	33.10	1.04E-03
180	**1 in 1 days**	180	198.40	5.19E-04
	3 in 3 days	180	66.10	5.19E-04
	Collection	**One trip per day of 2 km for Scenario 1, 2 and 3**		
Lifespan (days)	**Frequency**	**Total mileage (km)**	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	60	33.10	1.56E-03
	3 in 3 days	60	11.00	1.56E-03
45	**1 in 1 days**	90	49.60	1.04E-03
	3 in 3 days	**90**	**16.50**	**1.04E-03**
90	**1 in 1 days**	180	99.20	5.19E-04
	3 in 3 days	180	33.10	5.19E-04
180	**1 in 1 days**	360	198.40	2.59E-04
	3 in 3 days	360	66.10	2.59E-04
	Collection	**One trip per day of 5 km for Scenario 1, 2 and 3**		
Lifespan (days)	**Frequency**	**Total mileage (km)**	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	150	33.10	6.22E-04
	3 in 3 days	150	11.0	6.22E-04
45	**1 in 1 days**	225	49.60	4.15E-04
	3 in 3 days	225	16.50	4.15E-04
90	**1 in 1 days**	450	99.20	2.07E-04
	3 in 3 days	450	33.10	2.07E-04
180	**1 in 1 days**	900	198.40	1.04E-04
	3 in 3 days	900	66.10	1.04E-04

Glider stands out as the most polluting element due to the high concentration of steel and aluminum. aluminum accounts for 45% of the glider constitution of the electric scooter and steel corresponds to approximately 39% of the glider structure. Batteries are also identified as a source of interference with human health due to the high number of chemical elements they contain.

4.2. Comparison between the baseline scenario and previous works

In summary, for climate change, the **Base Scenario 1** emits **1680** $\boldsymbol{gCO_2eq/pkm}$, the **Base Scenario 2** emits **974** $\boldsymbol{gCO_2eq/pkm}$ and the **Base Scenario 3** emits **808** $\boldsymbol{gCO_2eq/pkm}$, which contrasts with the literature results presented in Table 1. Comparing to Hollingsworth et al., the base case represents the emission of 125 gCO_2eq/pkm for the climate change category, in the North American context (Hollingsworth et al., 2019). For Voi scooters the emissions correspond to 35 gCO_2eq/pkm for the city of Paris (Holm Moller et al., 2020) and according to Bird, an electric scooter emits about 61 gCO_2eq/pkm, these are assumed to be for the North American context as they correspond to official data from Bird's website (Bird, 2020). However, these studies do not identify the total kilometres travelled by the electric scooter. Only Hollingsworth et al. perform a sensitivity analysis for electric scooter use, in which they vary the kilometres from 4 to 16 km per day, showing that emissions can range from approximately 94 a 305 gCO_2eq/pkm (Hollingsworth et al., 2019). This huge difference is reflected in the lifespan of each electric scooter and, in turn, the distance it covers. A scooter that is used more frequently will have less environmental impact.

Chester, on the other hand, estimates that an electric scooter makes 500 trips in its lifetime, corresponding to 1207 km (Chester, 2019). Considering that a scooter makes 1 trip per day as adopted in this study, the 500 trips correspond to a lifetime of between 16 and 17 months. For Chester, the collection and distribution of scooters influences CO_2 emissions between 199 and 461 g/km. However, this variation is only due to the way the scooters are collected and distributed.

According to Hollingsworth et al. the production of an electric scooter for a base case scenario in the Climate Change impact category, corresponds to 50% of the total impacts. The use of the vehicle and the operations of collection and distribution correspond to 43% (in which, the energy used in charging is about 4%), leaving 7% for the disposal of materials (Hollingsworth et al., 2019). The micro-mobility report of Voi electric scooters shows that about 84% of the impacts correspond to production. Approximately 10% correspond to the use, maintenance and collection/distribution of the electric scooters. End of life allows to reduce half of the final impacts (Holm Moller et al., 2020).

Here, the production of an electric scooter in the Climate Change impact category corresponds to 76% of the impacts. The use and collection/distribution correspond to approximately 23%. End-of-life, depending on the scenario corresponds to +1%, −40% or −52% for Base Scenarios 1, 2 or 3 respectively. These percentage values are closer to Voi's micro-mobility report, however the absolute values differ greatly, as the lifetime considered by Voi for a scooter is 24 months. The Base Case Scenario considered in this work is of 45 days.

The inequality in the percentage of production and collection between previous studies and this study is mostly due to the initial assumptions made for the lifetime of an electric scooter. The lifetime that is used in this study (1 month to 6 months) is low relative to the lifetimes considered by Hollingsworth et al. (6 months to 2 years), by Voi (2 years) and by Chester (16 to 17 months). As the lifetime is so short, the use phase and the collection/distribution operation, turns out to be less relevant as the impacts all fall under production. Producing a scooter is a similar process as in the study of Hollingsworth et al., the values being in the same order of magnitude. As for use, the American reality indicates that the electric scooter is used more often. In the Lisbon reality, the use of the scooter does not compensate for its production as it is

Table 8
– Comparison between the modeling in SimaPro and the reference values for lifetimes adopted in the literature.

Lifetime	SimaPro Modelling (gCO_2eq/pkm)	Reference Value (gCO_2eq/pkm)
6 months	494	450
17 months	239	≈ 199 a 461
2 years	198	≈ 150
2 years (considering recycling)	144	34.70

very little used, until it is removed from the operation for scrapping or dismantling for replacement parts.

The fact that most of the impacts are associated with production lies in the product's short lifespan: as the electric scooter does so few kilometres over its lifetime, it is not possible to offset the impacts of its production through its use. In addition, the less an electric scooter is used, the less energy it requires to recharge and the less often it is collected by a collection vehicle (it makes fewer collection journeys, therefore fewer kilometres). The emissions during the use of an electric scooter (in this case, the low emissions due to the generation of electricity and the emissions of a conventional vehicle used for the collection of an electric scooter) do not reduce the emissions from production due to its short duration.

The electric scooter was also modelled for the lifetimes considered in the studies by Hollingsworth et al. (6 months to 2 years), Voi (2 years) and Chester (17 months). Table 8 summarises the results for each situation.

For Scenario 1 with a daily trip of 2 km, collection every 3 days and a lifetime of 6 months, the electric scooter emits 494 gCO_2eq/pkm. According to the study by Hollingsworth et al., a scooter that lasts 6 months emits 450 gCO_2eq/pkm. The results are relatively close.

For the same input data, but with a lifetime of 17 months, the emission of the electric scooter is 239 gCO_2eq/pkm. For Chester the emissions are in the range 199 to 461 gCO_2eq/pkm, in which this variation depends only on how collection and distribution is optimised.

Finally, modeling the electric scooter for scenario 1, use of 2 km per day, lifetime of 2 years and collection every 3 days, results in emissions of 198 gCO_2eq/pkm. Hollingsworth et al. show values close to 150 gCO_2eq/pkm. The results show a difference of approximately 50 gCO_2eq/pkm which may be related to the daily use of the scooter. Hollingsworth et al. consider greater daily use.

For the same lifetime (2 years), Voi emits 34,70 gCO_2eq/pkm. However, Voi considers a very optimal recycling scenario. When modeling again the scooter for Scenario 3 (daily trip of 2 km, lifetime of 2 years, collection every 3 days), because it is the one that considers the recycling of the materials, the emissions correspond to 144 gCO_2eq/pkm.

To better understand how these variables affect the results, a sensitivity analysis was carried out, where a comparison between the different scenarios will be made later.

4.3. Comparison of scenarios

Table 9 presents the results climate change impacts in grams of CO_{2eq} per kilometer for all scenarios, portraying how the e-scooters' collection frequency, daily kilometers travelled and the scooters' lifetime are very influential variable in the sustainability of shared e-scooters. We focus on Climate Change impacts since it is currently the most widely discussed impacts category in policymaking.

The worst scenario corresponds to the emission of 5325 g CO_{2eq}/km, for a lifetime of 30 days, daily use of 1 km, and daily collection for the Scenario 1. Lifetimes between 30 and 45 days, with daily use of 1 km to 2 km, considering Base Scenario 1, tend to have higher impacts. On the other hand, the better performing scenarios occur for lifetimes of 90 days and 180 days, with daily use of 5 km. It is also expectable that the best results correspond to end-of-life scenarios 2 and 3 due to the recycling and treatment of materials. Therefore, the best scenario corresponds to the emission of 112 g CO_{2eq}/km, with a life span of 180 days and daily use of 5 km for scenario 3. The worst scenario emits 47.5 times more grams of CO_{2eq}/km than the best scenario. Scenario 1 is the one that most probably corresponds to the current reality in the use case of Lisbon, Portugal, since, based on our interviews, systematic disposal and recycling procedures of the materials are still missing.

4.3.1. E-Scooters' collection frequency

Table 10 shows the percentages of reduction from a daily collection to a collection every three days in each scenario. Here the percentages of reduction remain constant according to the number of kilometers travelled per day for each end-of-life scenario, as they are values in the same order of magnitude. The variations between end-of-life scenarios 1, 2, and 3 are low, with no more than 10% varying from scenario 1 to scenario 2, and varying 3% to 4% from scenario 2 to scenario 3. Lifetime is the variable that most influences those percentages, as they present more significant differences between scenarios, ranging from −7 to −42% reductions (see Table 10).

The best scenario (Scenario 3 for 180 days) reduces its impacts in about 42% when changing a daily collection to a collection every 3 days. According to the lifespan, the difference in the frequency of collection varies between −7% to - 28% for Scenario 1. Scenario 3 ranges from −15% to −42%. For Scenario 2 and Scenario 3, the difference between the values is not significant. However, Scenarios 2 and 3 allow reducing approximately half of the total impacts, and the collection system can be further improved, for example, using an electric vehicle to collect e-scooters.

To confirm that, we modelled an electric vehicle (EV) in SimaPro to compare its impacts with the use of an internal combustion vehicle (ICEV) for the e-scooters' collection, for scenarios 1 and 3 (daily travel of 2 km, the life span of 45 days). Replacing the ICEV by an EV can reduce the Climate Change impacts by 10% to 23% for Scenario 3, and 5% to 12% for Scenario 1, whether daily collection or a collection every 3 days is considered.

4.3.2. Daily distance travelled

Table 11 outlines the impacts of changing the number of kilometers traveled per day, from 1 to 2 km; 2 to 5 km; and 1 to 5 km enabling 50 to 80% reduction in climate change impacts. The percentages are the same for the End-of-Life Scenarios 1, 2, and 3, and remain constant for different e-scooters lifetimes.

4.3.3. E-scooters' lifespan

Table 12 presents the percent-reduction differences for daily collection and collection every 3 days. The smallest percent-reduction corresponds to a life span variation from 30 to 45 days. The impact is reducing CO_{2eq} emissions between 26% to 30% for daily collection, whereas for 3-days collection, it varies between 30% and 32%. Conversely, the highest percent-reduction corresponds to a life span variation from 45 to 90 days, with CO_{2eq} reductions varying from 35% to 42%, and 44% to 47% for daily collection and 3-days collection, respectively. The percent-reductions vary less than 10% between Scenarios 1, 2, and 3, and less than 15% for different the lifetimes analysed.

The reduction percentages become less relevant as the end-of-life scenario is optimized, and as the life span increases. The longer the e-scooter lasts and operates, the smaller the impacts between the scenar-

Table 9
– Results for every scenario for the Climate Change category in g CO_2 eq/km (red indicates worst results; green indicates best results; the base scenario is in bold and underlined).

Lifespan (days)	km/day Collection	Scenario 1			Scenario 2			Scenario 3		
		1km	2km	5km	1km	2km	1km	2km	5km	5km
30	1 in 1 days	5325	2665	1067	3199	1602	642	2699	1352	542
	3 in 3 days	4932	2469	988	2806	1406	563	2306	1156	463
45	1 in 1 days	3746	1875	751	2328	1167	468	1995	1000	401
	3 in 3 days	3353	**1679**	673	1936	**971**	389	1602	**804**	323
90	1 in 1 days	2169	1086	436	1461	731	294	1294	648	260
	3 in 3 days	1778	890	357	1069	535	215	902	452	182
180	1 in 1 days	1380	691	278	1025	514	207	942	472	190
	3 in 3 days	988	495	200	633	318	129	550	276	112

Table 10
- Percentages of reduction from daily collection to collection every 3 days for each scenario.

km/day		Scenario 1 1km	2km	5km	Scenario 2 1km	2km	5km	Scenario 3 1km	2km	5km
Lifespan (days)	30	−7%	−7%	−7%	−12%	−12%	−12%	−15%	−15%	−15%
	45	−10%	−10%	−10%	−17%	−17%	−17%	−20%	−20%	−20%
	90	−18%	−18%	−18%	−27%	−27%	−27%	−30%	−30%	−30%
	180	−28%	−28%	−28%	−38%	−38%	−38%	−42%	−42%	−42%

Table 11
- Reduction percentages between a daily trip from 1 to 2 km and 2 to 5 km, for each scenario.

		Scenario 1, Scenario 2 e Scenario 3 km/day		
Lifespan (days)	**Collection**	**1–2 km**	**2–5 km**	**1–5 km**
30, 45, 90 e 180	**1 in 1 days**	−50%	−60%	−80%
	3 in 3 days	−50%	−60%	−80%

ios. For example, the scenario that changes from 45 to 90 days (with 3-days collection) has a reduction ranging from 44% to 47%. This reduction corresponds to a difference of 45 days. When the life span varies from 90 to 180 days, the difference of 90 days corresponds to a smaller impact reduction, varying between 39% to 44%.

4.4. Transport mode comparison

According to our assumptions, an e-scooter emits between 855 and 1731 g CO_{2eq}/km for a life span covering 90 km. According to the literature, EVs emit, on average, 177 g CO_{2eq}/km for an average life span covering 150 thousand kilometers (Hawkins et al., 2013),(Pero, Delogu & Pierini, 2018), electric bicycles emit 51 g CO_{2eq} /km for 85 thousand kilometers ((Cherry, 2007), (Luo et al., 2019), Weiss et al., 2015), (Zhang et al., 2001), and electric motorcycles emit 52 g CO_{2eq} /km for 31 thousand kilometers ((Cherry, 2007; Weiss et al., 2015)). Fig. 4 indicates the emissions of CO_2 per kilometer for each mode of transport and the respective lifetimes, on a logarithmic scale.

Fig. 4 shows that the electric bicycle and the electric scooter are the transport modes with the lowest CO_{2eq} emission values, followed by the electric vehicle and, finally, by the e-scooters which have the highest values. All types of transport (except for the e-scooter) have long life spans, allowing emissions to be offset by their use, something that does not occur with the use of the e-scooters since they have very short life spans. Notably, EVs can carry at least four people, while the e-scooter only carries one passenger.

The e-scooter emits about 4.5 to 9.5 times more than an EV for Base Scenarios 3 and 1, respectively. As presented in Table 13, e-scooters would have to drive 450% to 950% kilometers to emit the same as an EV. The same happens in the comparison with an electric bicycle, which is a very similar transport modes, both focused on micro-mobility. E-scooters emit 15.8 times more than an electric bike for the Base Scenario 3 and emit 33 times more than the electric bicycle for the Base Scenario 1. For an e-scooter to emit the same GHG as an electric bicycle, it would have to operate for 1580% to 3300% kilometers. These values correspond to a life span ranging from 24 months (2 years) to 49

Table 12
- Percent-reduction between scenarios with lifetime changes from 30 to 45 days, 45 to 90 days, and 90 to 180 days, considering daily and 3-days collection.

km/day		Scenario 1 1km	2km	5km	Scenario 2 1km	2km	5km	Scenario 3 1km	2km	5km
Daily collection										
Lifespan (days)	30 → 45	−30%	−30%	−30%	−27%	−27%	−27%	−26%	−26%	−26%
	45 → 90	−42%	−42%	−42%	−37%	−37%	−37%	−35%	−35%	−35%
	90 → 180	−36%	−36%	−36%	−30%	−30%	−30%	−27%	−27%	−27%
3-days collection										
Lifespan (days)	30 → 45	−32%	−32%	−32%	−31%	−31%	−31%	−31%	−30%	−30%
	45 → 90	−47%	−47%	−47%	−45%	−45%	−45%	−44%	−44%	−44%
	90 → 180	−44%	−44%	−44%	−41%	−41%	−40%	−39%	−39%	−39%

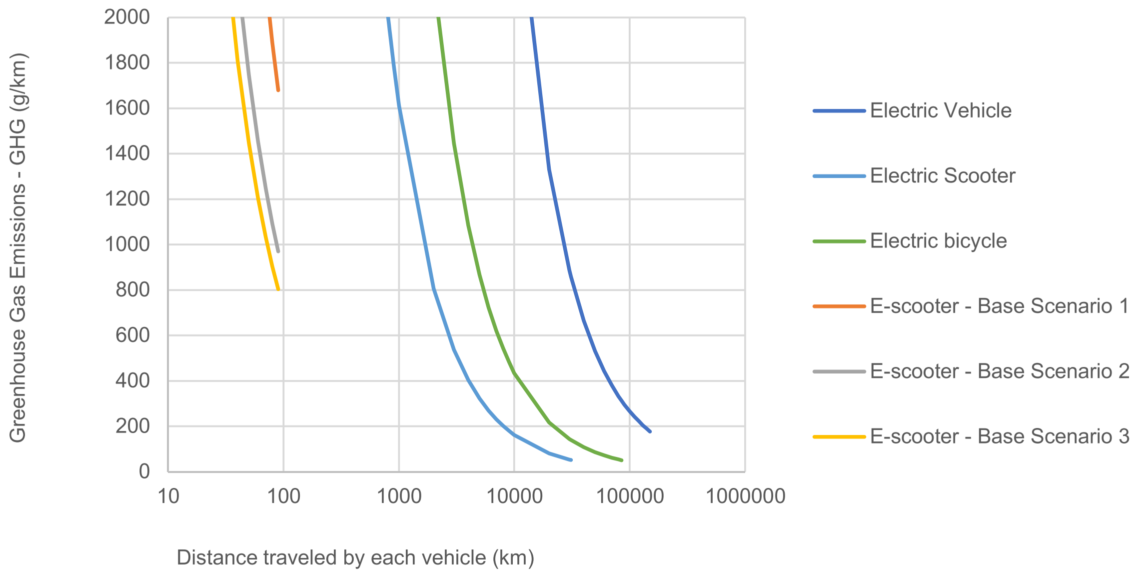

Fig. 4. - Emissions of CO_2 per kilometer per distance travelled (logarithmic scale) for the electric vehicle, electric scooter, electric bicycle, and e-scooter.

Table 13
– Required e-scooter distance travelled in lifetime to match the CO_2 emissions per kilometer of the electric vehicle and bicycle.

Recycling scenario	Required distance travelled in lifetime for e-scooters Electric vehicle (177 g CO_{2eq}/km)	Electric Bicycle (51 g CO_{2eq}/km)
E-scooter Scenario 1	855	2950
E-scooter Scenario 2	494	1700
E-scooter Scenario 3	409	1410

months (approximately 4 years) considering daily trips of 2 km. If the e-scooter was used for the same lifetime as an electric bicycle, it would emit about 2 g CO_{2eq}/km in the worst case and 1 g CO_{2eq}/km in the best case.

5. Conclusions

In the context of X-Minute Cities, the sustainability assessment of these flexible transport modes that induce behavioral change must be measured and evaluated in order to guarantee its contribution to advancing the current climate crisis (Tsavachidis & Petit, 2022). This study makes its contribution by quantifying the life cycle impacts of shared e-scooters, concluding that Climate Change impacts vary from 804 to 1679 g CO_{2eq}/km, for the Base Scenario, based on the extreme operation conditions and deregulated riding conditions of the city of Lisbon, Portugal. These impacts strive mainly from the materials extraction and production stage of the vehicles' lifecycle, which corresponds to approximately 76% of the total emissions of CO_{2eq}. The use and operation of collection/distribution correspond to 23% of the final impacts. However, recycling strategies for end-of-life materials can significantly reduce those impacts, up to 50% cut on CO_{2eq} emissions.

These results represent the realty of Lisbon (Portugal), but are representative of a situation with extreme driving conditions, low usage patterns and reduced e-scooters lifespans, either due to vandalism or the quality of the vehicles. Lifespans between 1 and 6 months are lower when compared to previous studies, for instance, Hollingsworth et al. (6 months to 2 years) (Hollingsworth et al., 2019), Voi (2 years) (Holm Moller et al., 2020), and Chester (16 to 17 months) (Chester, 2019). Also, the American reality indicates that e-scooters are used more often (Hollingsworth et al., 2019). In Lisbon, impacts relate mostly to the production stage of e-scooters due to the vehicles' short life span. As the e-scooter travels fewer kilometers throughout its life, the production impacts are not spread throughout longer lifetimes. The more kilometers travelled by the collection vehicle, the collection phase would have a greater environmental impact, reducing the environmental impacts from the remaining parcels (production and use). In addition, the lower the use of an e-scooter, the lower the energy required, and fewer times is collected and re-distributed. However, the optimization of collection and distribution operations should not be underestimated.

Additionally, there is a wide variation of emissions between scenarios, ranging from 112 to 5325 g CO_{2eq} /km. These results are highly sensitive to the vehicle's mileage, since increasing the number of kilometers driven per day could reduce impacts by 50% to 80%. A less frequent collection also reduces environmental impacts by between 7% and 42%, and increasing the e-scooters' lifespan could reduce impacts by 26% to 47%. Furthermore, replacing ICEV to collect and redistribute e-scooters by an EV could reduce impacts by 5% to 23%.

As for the use of shared transport modes in the urban environment, we conclude that shared e-scooters pollute more than an electric bicycle, an electric motorcycle, and even has greater impacts than an EV, under the same operating circumstances. Only in the most optimistic scenario is it possible to compete with an EV. In order for e-scooters to have a place in the competitive urban environment with other vehicles, it is necessary to define strategies and best-practices that guarantee the following **operation standards of a shared e-scooter**:

- Based on the low usage patterns, it is essential to ensure that they make more trips per day and operate longer distances per day;
- Considering the e-scooters shot lifetime, it is necessary to ensure that the physical structure and materials of e-scooters are stronger and more resistant to vandalism and to pavement characteristics, including its degradation; and
- Since logistics operations are essential to the performance of these e-scooter shared systems, operators must guarantee that these operations are electrified and maximize the penetration of renewable energy resources in electricity generation. For example, the Voi

e-scooter collection system has electrified its entire fleet, implemented replaceable batteries and optimized its collection routes. The use of replaceable batteries enables their collection by bicycle-trailers; and
- In line with the important role of logistics operations, these should optimized to reduce their frequency of collection in order to mitigate the respective environmental impacts.

To enable this, other **complementary policies** should be promoted by municipalities, namely:

- Strengthen anti-vandalism laws to reduce the misuse of e-scooters, which results in a shorter lifespan, therefore, resulting in high CO_{2eq} emissions associated with the production and materials phase;
- Promote personal e-scooters since they are not vandalized and tend to last longer than sharing systems; and
- Promote the deployment of conditions for the circulation of active modes, namely through the expansion of cycle lane networks that also serves e-scooters (taking them out of the road network with worse pavement conditions), thus allowing the improvement of comfort and safety conditions.

Given the current situation of the world pandemic COVID19, e-scooters may be attractive as an alternative to public transport for shorter trips or intermodality (since scooters are more accessible to carry on), as highlighted in the literature (Benita, 2021). As for bicycles, they allow social distance, thus increasing the flexibility of the system.

Further research includes disassembling an e-scooter and performing a life cycle analysis for the constituent materials with the respective real weights. It is also fundamental that operators of shared e-scooters collaborate and provide operational data to improve the performance analysis and corresponding results.

Finally, this study can serve all those involved in the transport sector, whether they are e-scooter manufacturers trying to reduce environmental impacts in the production of their technology or even consumers who are more aware of sustainability that want to make a more informed and environmental choice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.urbmob.2022.100044.

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Modeling of intra-city transport choice behaviour in Budapest, Hungary

Jamil Hamadneh[a], Ahmed Jaber[b,*]

[a] Department of Buildings, Roads, and Space Engineering, Faculty of Engineering and Technology, Palestine Technical University -Kadoorie, Tulkarm, Palestine
[b] Department of Transport Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary

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ABSTRACT

The discrete choice modeling and decisions-tree technique are used to understand the travel behavior of people in Budapest. The discrete choice modeling is applied to develop transport mode choice that mimics the travel behavior of people using their personal and travel characteristics. A revealed preference (RP) survey was conducted by the Hungarian Census Bureau which contains information about the households in Budapest in 2014, is used. Understanding the daily main trips of people is firstly analyzed using decisions-tree technique, where the impact of each variable is presented based on its importance in affecting the travel choice mode. In random utility theory, travelers choose one option out of certain available options to them to maximize their utility. The Multinomial Logit (MNL) model is used to examine the relationship between various variables connected to travelers in order to understand the travel behavior pattern. The result of the analysis shows a clear pattern between car ownership and each of family size, and age, and trip cost variables. The result of decision tree analysis demonstrates that travelers' trip duration is the most important factor that has impact on their transport mode choice, which is mainly distributed within private cars, public transportation, and walking. The developed multinomial transport mode choice model includes sociodemographic, economic, and travel characteristics. The trip time, trip cost, age, car ownership index, trip purpose, gender, employment, and income are the main determinants the impact the transport choice mode. The developed models (i.e., decision tree and the multinomial transport logit choice) are beneficial for the decision-makers who can used it in predicting the travel demand.

1. Introduction

Transport models are needed to study the travel behavior of people as well as the impact of occurred changes on one or more of the components of the transport system, such as tariffs, and the introduction of new transport modes (Hamadneh & Esztergár-Kiss, 2022). Transport models are used to predict the future demand for a particular transport mode based on the characteristics of individuals and the trip environment. In addition, transport choice models play vital roles as a decision-support tool by providing substantial information to planning and decision-making workers. Therefore, transport models are used to support policymakers and decision-makers in cities in their decisions regarding future transport policies and implications.

Travelers take decisions to maximize their utilities by selecting choices that fulfill their needs based on their preferences (Cascetta, 2009; Hamadneh & Esztergár-Kiss, 2021). In daily travel, people usually take decisions on which transport mode they choose to get to their trip purposes (Aloulou, 2018; Ding & Zhang, 2016). Transport modeling includes developing transport mode choice models that can be used in understanding the behavior of travelers in different time periods as well as based on different relevant factors, such as traveling to work, shopping, leisure, education, health, and others. In transport modeling, different factors are considered which characterize the environment of the travel and the individuals. Travel time, travel cost, route, departure time, sociodemographic, and economic variables are factors that impact choosing a transport mode (Mehdizadeh, Nordfjaern & Mamdoohi, 2018; Ruiz-Pérez & Seguí-Pons, 2020; Ye & Titheridge, 2017).

Transport mode choice models are covered in the literature, where a common objective is revealed as studying the travel behavior of people in a specific geographic area. For example, (T Tushara, Rajalakshmi & Koshy, 2013) focus on studying commuter trips (i.e., work trips) in the city of Calicut, while (Miskeen, Alhodairi and Rahmat Manssour A. Abdulsalam Bin, 2013) study all kinds of trips in Libya (i.e., the trip purpose is considered as an independent variable in the developed model). (Jaber, Baker & Csonka, 2022) studied the spatial travel behavior for bike-sharing users. The analysis involved thier trips that influenced by public transportioan network. Findings indicated buses attract more bike-sharing users than trams and rails network. Other scholars study the behavior of travelers when other transport modes enter the transport system, such as (Hamadneh & Esztergár-Kiss, 2021) who

* Corresponding author.
E-mail address: ahjaber6@edu.bme.hu (A. Jaber).

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study the travel behavior of people concerning conventional transport modes and autonomous vehicles using multi-agent transport simulation, (Andrade, Uchida & Kagaya, 2006) study the travel behavior of shoppers' preferences considering public transport (i.e., subway, bus, and automobile) using a hybrid model combining multinomial logit mode and neuro-fuzzy inference system, and (Jánošíková, Slavík & Koháni, 2014) study the route choice for public transport using the taken data from a smart card, such as in-vehicle time and transfer time, where multinomial route choice is developed; the mixed-logit model is developed to find the travel mode behavior of urban residents in catchment areas of rail stations. (Luan et al., 2020). (Paredes et al., 2017) demonstrate that the discrete choice modeling approach is superior in modeling transport mode choice over machine learning models, based on the result of a modeling transport choice model of Singapore.

In this research, two methods of modeling are applied. People choose an option based on their preferences that are connected to their characteristics and the characteristics of the available options (Cascetta, 2009). The decision-tree technique is a predictive modeling approach using a flowchart-like structure in interpreting the output of models based on involved factors. In this paper, the two methods are applied where the MNL uses a fit line for the data while the decision-tree technique divides the data to small reigns. Both methods are used to study the travel behavior of people and the impact of the different trips and travelers' characteristics on choosing a transport mode. The decision-tree technique is also applied to understand the transport mode choice process. The discrete choice models explain, interpret, and predict choices between two or more distinct options (e.g., transport modes). The principle of discrete choice modeling is taken from the random utility theory and the economic theory where people choose an option to maximize their utilities (i.e., profits) (LIU, 2007). In this study, the Multinomial Logit (MNL) model is applied.

The contribution of this research is to interpret the behavior of Budapest's people in choosing a transport mode based on a large sample using two methods. Other relevant studies in Budapest show models of smaller sample size or for a specific group of travelers, such as (Al-Salih & Esztergár-Kiss, 2021) who use around 1900 travelers, and (Mahdi, Hamadneh & Esztergár-Kiss, 2022) who study only leisure travelers. Moreover, those studies use MNL models and none of them used the decision tree technique. In this research, the decision-tree model and the MNL model are applied to a larger sample to interpret the behavior of traveler in choosing a transport mode by estimating the impact of each variable on the utility of a traveler. Moreover, it helps the policymakers and urban planners to decide to manage the demand using the influential variables using charts and probabilities. The sample is taken from a revealed preferences (RP) survey that represents the households in Budapest in 2014. The usefulness of this paper is summarized in predicting the travel demand on transport modes in Budapest, Hungary using two methods of modeling. The output of the decision tree method is easy to be interpreted and new transport modes are easily added.

The paper is structured as follows: the introduction is presented in Section 1, the literature review is presented in Section 2, and the methodological approach is found in Section 3. The results and discussion are presented in Section 4, and finally, Section 4 contains the conclusion, recommendations, and future works of this study.

2. Literature review

The discrete choice models are applied to trains, buses, cars, and airplanes (Levin, 2004). (Levin, 2004) states that wider applications of discrete choice modeling are followed, such as the route choice model, and trip purpose model. In random utility theory (RUT), people make decisions based on their preferences aiming to maximize their benefits, for example selecting a transport mode. According to the theory, a variety of factors influencing people's decisions are linked to the people themselves as well as the issue characteristics. (Fischer, 2010) states that individuals (i.e., travelers as decision-makers) select one option from a finite set to maximize their utilities. (Hauber et al., 2016) show the components of discrete choice modeling are decision-maker, options, characteristics, and rules. In the literature, several studies are conducted to examine the impact of various factors on travel behavior using several techniques. It is worth mentioning that the discrete choice modeling approach is dominant in the conducted studies due to its power in prediction, as demonstrated for example by Paredes et al. (2017).

(Um & Crompton, 1990) show that travelers' choice depends on internal and external factors, such internal factors are the socioeconomic characteristics, and such external factors are travel time and travel cost. (Wedagama, 2009) develop the MNL model for motorcycle ownership in Bali, where the influential household factors are examined. (T Tushara, Rajalakshmi & Koshy, 2013) study work trips using the MNL model to analyze the mode choice behavior in Calicut city. (Miskeen, Alhodairi and Rahmat T, 2013) develop an MNL model based on 1300 travelers taken from both an RP survey and a stated preference (SP) survey in Libya. They developed a transport mode choice model that includes bus, car, auto, walking, and two-wheel modes. (Schwanen, Dijst & Dieleman, 2003) develop an MNL model to study the leisure journeys of old residents. The findings demonstrate that a private car is preferred by old people, and the environment of residential areas impacts the selection of transport modes by people without private cars. (Rastogi & Praveen, 2012) develop an MNL model to predict the travel demand for leisure activities, where people choose a destination and travel mode, where household factors are included in the model, such as car ownership, income, age, travel time, and travel cost. (Spinney, Maoh & Millward, 2018) study the impact of home-elementary school travelers on the transport mode choice. They apply the MNL model and mixed logit model to estimate the impact of environmental characteristics on travel choice decisions. The results demonstrate the distance between home and school has the most significant impact on the transport mode choice, while students' characteristics, weather characteristics, and the neighborhood properties affect the transport mode choice. (Ao et al., 2020) demonstrate the relationship between the rural built environment and the transport mode choice. The MNL model is applied to find the relationship between travelers who live in rural areas and travel mode choice. They find that as density increases the use of private cars increases. Besides, as road traffic congestion increases, the modal shares of electric bicycles and motorcycles increase. (Obaid & Hamad, 2019) show the variables that impact the transport mode choice in Sharjah university city. They find that trip time, and sociodemographic (e.g., sex, car ownership, cars per household, car sharing, travel environment (e.g., weather, and quality of transport system)) are the major variables that impact the transport mode choice. (Du et al., 2020) examine the characteristics of elderly people's travel mode choices for healthcare activities in the city and suburbs, as well as the variables that impact their decisions. It was found that elderly people are more likely to utilize cars to obtain high-quality medical resources. On the other hand, (Li, Zhang & Du, 2018) study similar elements under different temporal and spatial constraints. The results of their study reveal that medical trips of the elderly have become an essential part of city transportation and affects family activities to a certain extent. It is demonstrated that travel time, distance, bus station distance, and walking accessibility influence the strong constraint, whereas family internal factors such as car pick-up, family accompany, and the number household of driver's licenses influence the weak constraint. Table 1 summaries some related studies from literature where author/s, location of the study, main attributes/variables in the developed model/s, and description showing the aim of each study.

This research uses two methods, firstly, the decision-tree technique (non-parametric approach) is a decision-making technique that employs a tree-like model of decisions and their potential outcomes, such as probability occurrence outcomes, resource costs, and utility. This technique applies an algorithm that is similarly applicable in transportation engineering fields; such as transit quality of service (Oña & de Oña, 2015), road accident forecasting (Sangare et al., 2020), and road accident de-

Table 1
Summary of selected similar studies.

Reference	Location	Sample size	Main variables	Description
(Wedagama, 2009)	Bali	313	Income, number of family members, and car ownership.	The study focuses on motorcycle ownership factors.
(T Tushara, Rajalakshmi & Koshy, 2013)	Calicut	514	Time, cost, waiting time, gender, income, and two-wheel ownership.	The study focuses on workers.
(Miskeen, Alhodairi and Rahmat Manssour A. Abdulsalam Bin, 2013)	Libya	1300	Gender, income, education level, travel distance, travel cost, privacy, comfort, reliability, safety, and weather	The study is conducted to predict demand for transport systems based on several variables.
(Schwanen, Dijst & Dieleman, 2003)	Netherlands	Population	Car ownership, households, job, education level, gender, age, and location	The study focuses on the leisure journeys of old residents are studies.
(Rastogi & Praveen, 2012)	India (6 cities)	1689	Car ownership, income, age, travel time, and travel cost.	Prediction of the travel demand for leisure activities.
(Spinney, Maoh & Millward, 2018)	Canada	1971	Age, income, car ownership, location, weather, household size, and population density.	The impact of home-elementary school travelers on the transport mode choice.
(Ao et al., 2020)	Chine	1242	Density, road traffic congestion, age, education level, income, car ownership, safety, proximity to public transport, and accessibility.	The relationship between the rural built environment and the transport mode choice.
(Obaid & Hamad, 2019)	UAE	4000	Gender, car ownership, cars per household, car sharing, weather, trip distance, and quality of transport system	Estimation of the differences among the various groups of travelers to Sharjah University City.
(Du et al., 2020)	China	1358	Gender, age, education level, income, car ownership, travel time, convenience level,	Examination of the characteristics of elderly people's travel mode choices for healthcare activities in the city and suburbs.
(Li, Zhang & Du, 2018)	China	625	Travel time, distance, bus station distance, and walking accessibility influence the strong constraint, car pick-up, family accompany, and the umber household of driver's licenses.	study different temporal and spatial constraints.
(Mahdi, Hamadneh & Esztergár-Kiss, 2022)	Hungary	1101	Time, cost, age, gender, family, job, income, and car ownership.	A transport mode choice for leisure travelers is developed.
(Al-Salih & Esztergár-Kiss, 2021)	Hungary	1889	Age, gender, family size, trip time, trip cost, activity, income, education level, job, and trip distance.	The study found a linkage between mode choice and travel behavior based on the utility function.

tection (Figueira et al., 2017). This approach takes into account the preferences and characteristics of mode choice (Zhan et al., 2016). Secondly, the discrete choice modeling approach is common in developing a transport choice model to find the relationship between choosing a transport mode and the household factors. Budapest is taken as a case study to examine the developed model, where this model has not been done for Budapest using a large sample size collected by the Budapest transportation center, as well as, involving more transport modes such as bicycles and motorcycles. The usefulness of this study is developing prediction models for travel demand using the daily activity plans and the household data (main destination/activity is examined) using two methods of transport modeling.

3. Methodology

The principles of utility theory are based on the preferences of individuals. The utility is an economics theory that aims to explain individual behavior by assuming that people can reliably rank order their choices based on their preferences (Cascetta, 2009). Each individual has different preferences in choosing a transport mode. Random utility theory (RUT) is based on the premise that each individual is a rational decision-maker who seeks to maximize utility based on his or her choices (Ghosh et al., 2013) . In this section, the methodology is divided into two parts which cover the analysis methods. First, a non-parametric analysis to find the variables that have more impact on daily mode choice, and secondly, the MNL model to understand the traveler's choices depending on maximizing their utilities, as follows:

(1) Non-Parametric Analysis

The decision tree technique supports discovering relationships between variables and the presentation of categorical results with more thoroughly outlined explanations. This technique applies an algorithm, which is used in predictive models with high accuracy, consistency, and interpretation. It consists of several methods; the most popular methods are Chi-Squared Automatic Interaction Detection (CHAID), Classification & Regression Tree (CART), and Quick Unbiased Efficient Statistical Tree (QUEST). The basic concept is to divide a data set into homogeneous subsets, where the resulting branches are pure and belong to the same target node/ class. The algorithm measures the homogeneity of multiple split nodes, to find a child node with maximum purity (Bukhsh et al., 2019). CART is chosen in this study for its better representation and predictions. It was presented firstly by Breiman et al. (1984). The algorithm mechanism is based on two pillars of "Purity" and "Balance". Purity is designated by Gini (Index of equality; its score ranges from 0 to 1, 0 indicates perfect equality and 1 maximum inequality) and balance is indicated by the same population distribution among the two sides of the decision tree. For each set of records, the splitting criterion is induced by Gini as shown in Eq. (1). This measure (i.e., Gini Index) is calculated as the sum of class proportions for classes existing at the node; the Gini index is equal to zero if all records in a node belong to the same class.

$$\mathrm{Gini}(X) = \sum_{j\in N} AP_{j,X}\left(1 - P_{j,X}\right) = 1 - \sum_{j\in N} AP^2_{j,X} \quad (1)$$

Where N is a set of classes, X is a set of categories, $P_{j,X}$ is the probability of category X having class j.

(1) Multinomial Logit (MNL) model

Developing a transport choice model to understand the travel behavior of people is conducted through a discrete choice modeling approach. In the random utility theory, each traveler chooses an option that maximizes his/her utility (Hauber et al., 2016). Different methods of analysis are used in the literature to find the relationship between exploratory variables and dependent variables. The characteristics of the previously collected data (i.e., RP) determine the type of discrete choice model. One model of the classical discrete choice models, which is applied to this paper is the MNL model. The characteristics of the MNL model are independent of irrelevant alternatives (IIA), which means that the ratio between two options relies on the characteristics of the two alternatives without impact from other options. Moreover, the MNL model provides a choice model based on the characteristics of individuals rather than the alternatives (Aloulou, 2018; Hauber et al., 2016)

The utility (U) that individual (m) gets from choosing an alternative (j) in the choice set (C) is given by Eqs. (2) and (3).

$$U_{mj} > U_{mk} \ \forall \ j \neq k \tag{2}$$

$$U_i = V(\beta / X_i) + \varepsilon_i \tag{3}$$

where U_i stands for the utility of using a transport mode, V means variables vector (systematic part), which is to be found based on the data. ε_i is a random error (stochastic term), X_i is the explanatory variable, and β is the marginal utility of the estimated coefficients. In the MNL model, the stochastic term (ε) is assumed to be an independent and identically distributed random variable (IID-Gumbel distribution).

The result of a random utility model is the probability of an individual choosing each option. The probability of an individual choosing an option (j) out of a set of options (m) from the choice set (C) is given by Eq. (4).

$$\mathbf{P(cj \backslash C)} = \left(\frac{\exp(\mathbf{V(j)})}{\sum_{\mathbf{j=1}}^{\mathbf{m}} \exp(\mathbf{V(j)})} \right) = \left(\frac{\exp(\mathbf{X_i}\boldsymbol{\beta})}{\sum_{\mathbf{j=1}}^{\mathbf{m}} \exp(\mathbf{X_i}\boldsymbol{\beta})} \right) \tag{4}$$

where P stands for the probability of selecting an option (j) in a choice set (c), where c ∈ C. V(j) = xiβ is the utility of option (j) (linear function of the attributes). β is the vector of unknown parameters, and X_i is a vector of option attributes (e.g., travel time, travel cost, etc.). It is shown that the probability takes exponential form. The probability of choosing option (j) equals the probability of choosing option (j) divided by the summation of the exponential utilities of choosing other options in choice set ©. Based on the economic theory, the utility is transferred to money, for example, the travel time of people has a cost, which is translated in Eq. (5).

$$VOT = \frac{\beta_{tt}}{\beta_{tc}} \tag{5}$$

Where VOT means the value of travel time, β_{tt} stands for the marginal utility of travel time (tt), and β_{tt} is the marginal utility of travel cost (tc).

The two models use different techniques in modeling the data as well as in the final presentation, for example, the MNL is developed where utilities of certain values (e.g., probability) are presented. CART is used to rank the variables in their importance. CART is a rather quick and schematic way, while the MNL is more numerical. For policy and decision makers, CART is easier to read and build on future steps. The variable importance could be obtained by both models, but in our study we prefer using the CART model as, per our knowledge, it is more accurate in line with other tree techniques than the MNL. This finding can be found in several studies such as (Zhao et al., 2020; Xie, Lu & Parkany, 2003; Zhang & Xie, 2008; Lhéritier et al., 2019)

4. Results and discussion

Descriptive statistics are reported about the sample size as shown in the subsection "Descriptive statistics", where modal share with some variables is presented. Additionally, the travel behavior of travelers is modeled using the MNL model using SPSS software. The developed transport choice model includes trip characteristics, sociodemographic variables, and economic variables, as presented and discussed in subsection "Model development."

4.1. Travelers data analysis (i.e., main daily trips)

In Hungary, the Budapest transportation center (BKK, in Hungarian: *Budapesti Közlekedési Központ*) conducts a survey every 10 years. The data in this research is taken from the BKK, which represents the data for 2014. The data include information about the households in Budapest

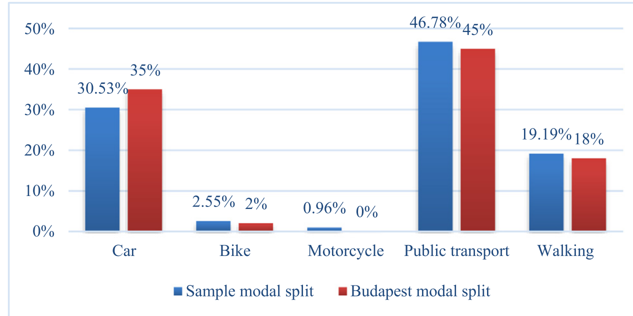

Fig. 1. The modal split in the sample and the actual modal split.

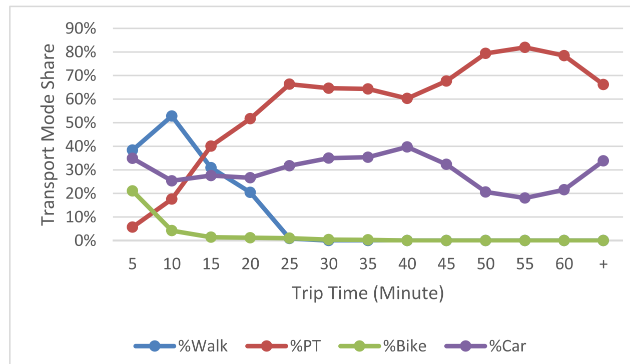

Fig. 2. The transport mode use pattern with trip time.

as well as their travel behavior for one day. The data contains 8505 households, where a traveler per household has provided the information about his/her trip characteristics, and other related information to the households, such as sociodemographic, economic, and trip characteristics. The used data in this study after filtering and cleaning is 7537 travelers (i.e., main daily trips). The sampling rate is nearly 1% of the total 908,247 households in Budapest City (KSH, 2022). It is worth mentioning that Budapest is the capital of Hungary, which has 23 districts. Budapest contains around 18% of the country's population, and it is the largest city in the country (Hamadneh & Esztergár-Kiss, 2021).

4.1.1. Descriptive statistics

Fig. 1 depicts bar charts of the modal split of the sample. It is shown that public transport users occupy the highest share among other modes, while motorcycle users are the lowest share. Car users are 30.53% of the sample, 19.19% of the sample are walking users, and finally, bicycle users are 2.55% of the sample. It is worth mentioning the modal share in Budapest is 35% for the car, 2% for bicycles, 18% for walking, and 45% for public transport (EPOMM, 2019, Jaber and Juhász, Measuring and Forecasting of Passengers Modal Split Through Road Accidents Statistical Data 2021). The sample size is closely representing the population of Budapest. Additionally, based on (KSH 2019), the ratio between males and females is 91:100. In this study, the data represent a ratio of 93.5:100, which is acceptable. In addition, the average age in Budapest is 44.9 years, and in this study, it is 43.3 (KSH 2019). Additionally, Table 2 presents descriptive statistics for the data.

Fig. 2 shows the pattern of mode choice selection with travel time. The figure depicts the modal share of travelers when they travel to their main activities, with the trip length (time). The percentage of travelers who use walking to reach their main activities are decreased when travel time is increased. For example, a trip time of 10 min has the highest percentage among travelers, while no traveler uses walking mode for a trip time higher than 25 min, as shown in Fig. 2. The percentage of travelers who use public transport increases as trip time increases. For

Table 2
Descriptive Statistics for the data.

Variable	Mean		
Trip cost (Ft)	388.3		
Trip time (min)	21		
Age	44.9		
Car ownership Index	0.27		
Variable		**Frequency**	**Percentage**
Trip purpose	Educational	1174	15.6%
	Work	4118	54.6%
	Leisure	230	3.1%
	Shopping	1070	14.2%
	Others	945	12.5%
Gender	Male	3645	48.4%
	Female	3892	51.6%
Income	High (>300,000 Ft)	3464	46.0%
	Medium (150,000–300,000 Ft)	2268	30.1%
	Low (<150,000 Ft)	1805	23.9%
Employment	Yes	5375	71.3%
	No	2162	28.7%

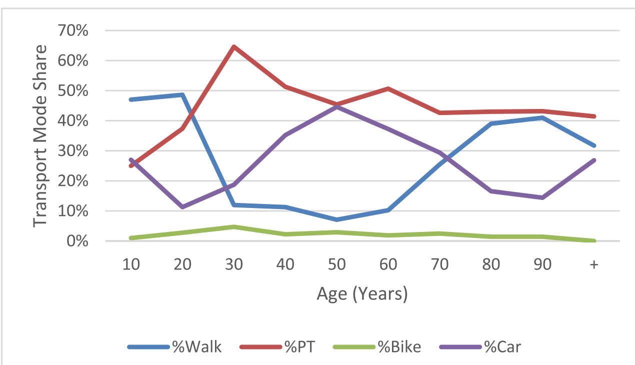

Fig. 3. The transport mode use pattern with age.

example, a large change is shown when travel time increases from 5 min to 25 min, a slight change is noticed when trip time increases from 25 to 45 min, and for a trip time from 45 to 55, the transport mode share is increased. Moreover, it is shown in the graph that for a trip time longer than 55 min, the proportion of people who use public transportation has declined. Bike users at the time of the survey have a low modal share compared to other modes of transport. It is shown that as trip time increases by more than 20 min by bike, the number of travelers who use their bicycles to reach their main daily activities is decreased. The modal share of the car is fluctuating because it is connected to car ownership, as shown in the graph. Trip time of more than 40 min shows a decrease in the modal share, while shorter than 40 min show a slight increase in the modal share. The relationship between the modal split and the trip time is demonstrated in Fig. 2. Each modal share is explained based as follows: walking is preferable for a distance of fewer than 15 min when conditions are allowed (i.e., weather, suitable pedestrian facilities), and some individual preferences, such as health, and cost of travel. The bike is not common at the time of the survey, and the people do not prefer to use the bike for main activities, and they prefer it for leisure activities. Car owners are addicted to using their cars even for short distances.

Fig. 2 provides intersection points, for example, at 7.5 min, bike and public transport are intersected which leads to the shifting in the mode to others. Moreover, at 13 min, walking mode share intersects with public transport mode share. From the figure, it is shown that travelers on bicycles and walking are mainly switched to public transport when trip time is less than 40 min. When the trip time exceeds 40 min, there is a reciprocal change between car and public transport, which means no specific pattern is noticed.

Fig. 3 illustrates the relationship between transport mode use and age. It is shown in the figure that the modal share in people's age fluctuates. People who are less than 20 years and more than 80 years old are more likely to use walking mode, the age class of 20–30 years old shows a decrease in the use of walking mode. Moreover, the age class of 30–60 years old demonstrates the lowest percentage of using walking mode. This is explained by the higher probability of owning vehicles of middle-aged people, while young and old people are limited to using their own vehicles as drivers. In addition, children mainly go to nearby schools on foot.

Table 3 presents the individual trip characteristics concerning car ownership, where the number of owned cars per household is presented. It is shown that as family size is increased, the number of cars owned by households is increased. The average trip time per household is 21 min for different types of car ownerships except those who own 3 cars have 24 min trip time. This is explained by the homogeneity of the sample in the study. The interval of 21 min is based on car ownership categories. The trip time represents the average trip of travelers, not the journey time. This means that the three categories are having the same behavior on the average trip time. The trip cost of people who do not own a car is the lowest compared to others. It is shown in Table 1 that as the number of cars per household increases, the trip cost increases, and as the average age decreases, the number of cars per household increases. This is explicated as follows: increasing the number of cars in a household means more stable salaries and life quality. This leads to the fact of more own car dependency rather than using public transportation, micro-mobility, or walking. In addition, increasing the car ownership index means more family size, which leads to the fact less average age in this sample category.

The above descriptive analysis shows that the modal share is influenced mainly by the trip time, while less influence is noticed across age classes. The locations of activities concerning the origins of travelers, impact transport mode choice, while age is more connected to owning car ownership rather than the use of transport mode, as demonstrated in Table 3.

4.2. *Decision tree analysis*

To have a comprehensive mode choice analysis, the decision tree uses all data sets as shown in Fig. 4. The five classifications of modes are cars, public transportation, motorcycles, bicycles, and walking (see Fig. 1). The decision tree consists of seven independent variables, such as car ownership per household, income, trip time, trip purpose, age, gender, and employment. The number of nodes is 31, with a depth of 5 levels. The interpretation of the results is straightforward. The analy-

Table 3
Relationship between car ownership per household, family size, trip time, trip cost, and age.

Number of owned cars per household (Car ownership)	Family Size	Trip time (minute)	Trip cost (Ft)	Average Age (year)
0	2.6	21	215	47
1	3.1	21	460	44
2	3.7	21	601	43
3	4.3	24	688	42.5

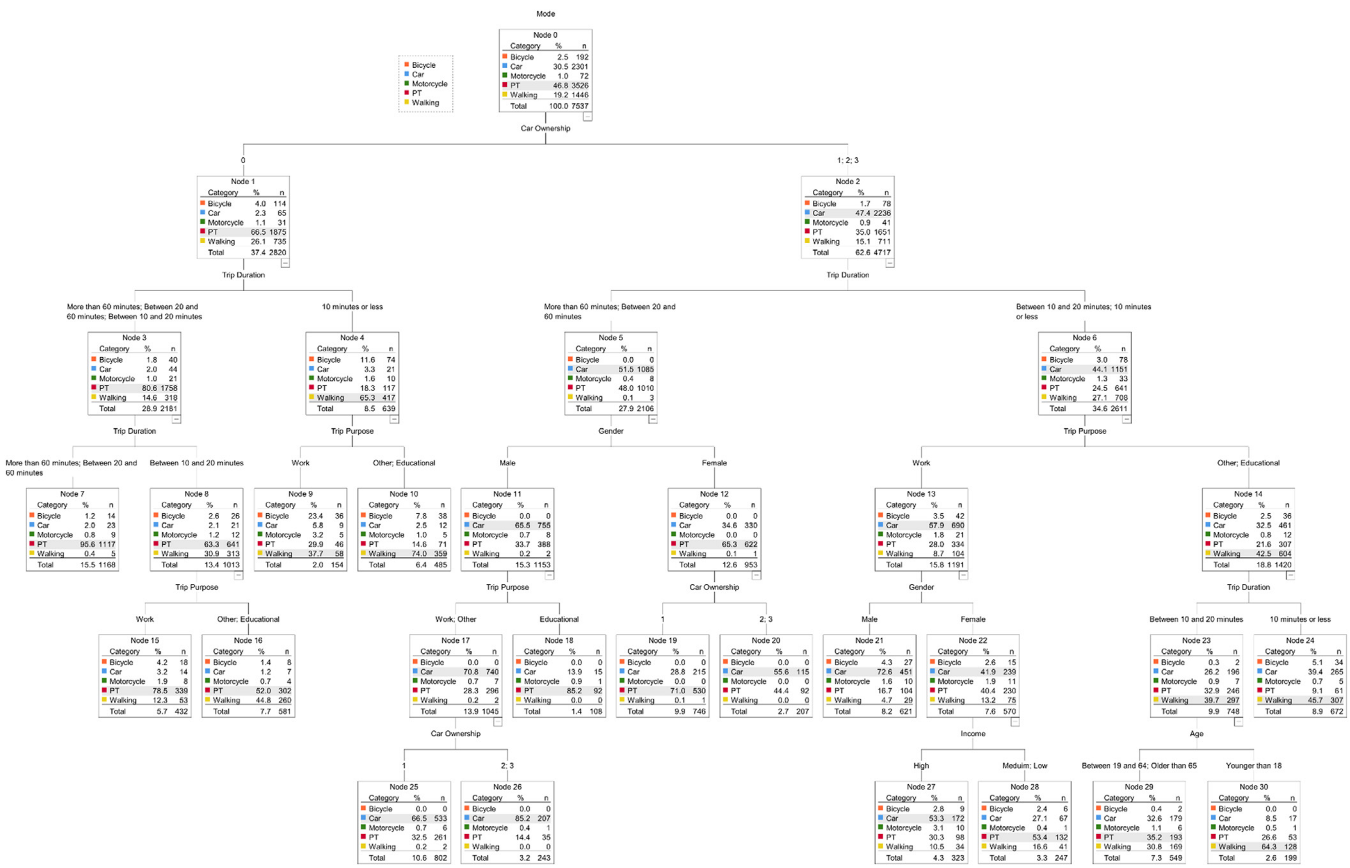

Fig. 4. Decision tree model.

sis is conducted in which each transport mode is studied based on two questions:

1 What are the characteristics of commuters in aspects of gender, car ownership per household, age, and income?
2 What are the trip attributes regarding duration, and purpose?

The first node of the data set is split into two sides based on the most important factor among all variables, which is the car ownership index, as it has the highest Gini index calculated through Eq. (1). On the left side nodes of the zero-owned cars (Node 1), the second-highest Gini index is trip time, which is divided into two branches of less or more than 10 min (Nodes 3, and 4). CART continues splitting the data set based on the independent variables, where the most important variable on each side is considered first. For example, on the left side, the most important variable is trip time, while it is a trip purpose on the right side.

The following points highlight the main characteristics of choosing cars, noting that there is a condition of owning at least one car per household:

- Car trips' characteristics for male travelers are either:
  - ○ Work-based trip (Nodes 17 and 21), or
  - ○ Non-Educational trip with a duration of more than 20 min (Node 17).
- Car trips' characteristics for female travelers have two conditions:
  - ○ If the trip duration is 20 min or less and a work-based trip, with high income (Node 27), or
  - ○ If the trip duration is more than 20 min and the household owns more than one car (Node 20).

For public transportation choices: the nodes are distributed on the two sides of the outputted tree. Thus, the conditions and characteristics are wider, as follows:

- For households that do not own cars, travelers use public transportation choice, if the trip duration is more than 10 min regardless of any other aspects (Node 3 and its branches).
- For a household that owns cars, public transportation is a major choice:
  - ○ If the trip duration is more than 20 min, educational, and male commuters (Node 18).
  - ○ If the trip duration is more than 20 min, for any trip purpose, female commuters, and the household owns only one car Female (Node 19).

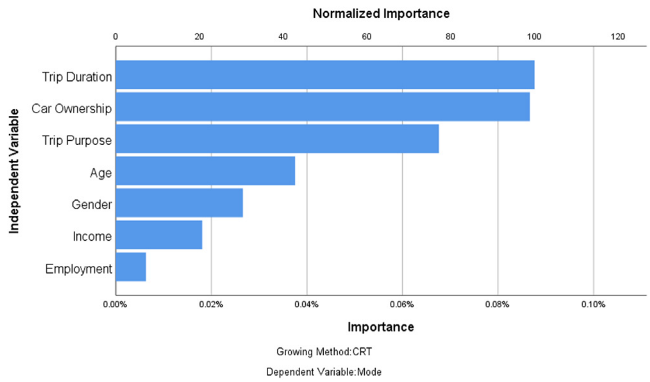

Fig. 5. Ranking of independent variables (Method: CART).

- ○ If the trip duration is 20 min or less, work-based, female commuters, and non-high income (Node 28).

For the walking option, the nodes also are distributed on both sides, mainly with short distances. The detailed situations are:

- For not-owning cars in the household, walking is the crucial travel choice if the trip duration is 10 min or less (Node 4) with 65.3% of users.
- For a household that owns at least one car, walking is a significant choice if the trip duration is less than 20 min, for non-work-based trips. Specifically, for people who are younger than 18 years old (Node 30).

Finally, some remarks are noticed:

- Walking, public transport, and cars are competitive in cases of the trip is between 10 and 20 min, for non-work-based trips, and for commuters who are middle-aged (Node 29).
- Bicycles and motorcycles are not significant choices in all of their characteristics.

Hence the aim is to find key factors for mode preferences, CART algorithm namely the Variable Importance Measure (VIM) is used. VIM measures the ranking of the independent variables according to their association with the dependent variable – mode choice. The case study in Budapest shows that the most important variable is trip duration. Next are consequently as follows: car ownership index per household, trip purposes, gender, income, and employment. Fig. 5 shows the ranking from the most important factors to the least according to the CART model, depending on the normalized importance.

4.3. Mode choice model development

In this subsection, traveler preferences are modeled towards choosing a transport mode, in which each traveler maximizes his/her utility. A discrete choice model through MNL model, where a transport choice model is developed which combines the characteristics of individuals. The explanatory variables in the developed model are trip cost, trip time, age, trip purpose, car ownership, employment, income, and gender.

Eq. (5) shows the general form of the developed model based on Eq. (2). The utility (u) of using a transport mode (i) is givenby

$$U_i = \beta_{o\,(i)} + \beta_{trip\ cost\ (i)} * Trip\ cost * Dummy_i + \beta_{trip\ time\ (i)} * Trip\ time * Dummy_i + \beta_{age(i)} * Age * Dummy_i + \beta_{trip\ purpose(i)} * Trip\ purpose\ (dummy) * Dummy_i + \beta_{car\ ownership\ index\ (i)} * Car\ ownership\ index\ (dummy) * Dummy_i + \beta_{employment(i)} * Employment\ (dummy) * Dummy_i + \beta_{income}(i) * Income\ (dummy) * Dummy_i + \beta_{gender(i)} * Gender\ (dummy) * Dummy_i + \varepsilon \quad (5)$$

where ε represents the random error. Noting that the residuals of the model are normally distributed. β_0, $\beta_{trip\ cost}$, $\beta_{trip\ time}$, β_{age}, $\beta_{trip\ purpose}$, $\beta_{car\ ownership}$, $\beta_{employment}$, β_{income}, and β_{gender} are parameters to be found from the data. $Dummy_i$ is used because the results are

Table 4
Model fitting information.

Model	Model Fitting Criteria −2 Log-Likelihood	Likelihood Ratio Tests Chi-Square	df	Sig.
Intercept Only	17,671.109	–	–	–
Final	5281.607	12,389.502	40	<0.001

explained based on the reference category (i.e., car). These parameters are called marginal utilities of variables (X_i). The scale variables are trip time, trip cost, and age. On the other hand, trip purpose, car ownership, employment, income, and gender are categorical variables (dummy). Trip purpose has work, home, shopping, education, leisure, and other values. The car ownership index is the ratio of the number of cars to the family size (number of owned cars divided by the family size). The employed and unemployed are the two values of the employment variable. Income is divided into three levels, high, middle, and low. Finally, gender has male and female values.

Table 4 presents the model fitting. The model shows significant results, at the confidence level of 95%, and the fitting information demonstrates that including the variables is better than excluding them. The model with the variables shows enhancements in the power of prediction of the model as demonstrated by the fitting information results of the model as well as the McFadden R2 value which is based on the Chi-Square test. Moreover, McFadden demonstrates that the produced model is strong in prediction (i.e., McFadden R2 is 0.701) (McFadden 1974). The degree of freedom is 40, and it is significant which stands for the significant value. It is worth mentioning that we have checked the correlation matrix, and all the variables have a spearman's correlation lower than 0.50 which indicate weak correlations (Kollmorgen et al. 2019; He & Csiszár 2022). Thus, this roughly justifies using the independent variables shown in Tables 5 and 6.

Table 5 presents the likelihood ratio tests of every variable's effect on the developed model. Trip cost, trip time, age, car ownership index, trip purpose, gender, employment, and income, demonstrate significant results at a confidence interval of 95%.

The parameters of the developed model are shown in Table 6, where each parameter coefficient per transport mode is estimated. The reference mode is car mode. The second column is the parameter name, while estimate means the parameter's coefficient (estimate). The standard error (Std. Error) is in the fourth column. Wald is in the fifth column, which is the chi-square value, while the df refers to the degree of freedom. Sig. stands for the significant value (i.e., p-value). The Exp(Estimate) is the exponentiation of the parameter's coefficient, which is an odds ratio (Koppelman & Bhat 2006).

In the case of intercept only (i.e., without considering the independent variables), the developed model shows that the probability of people selecting a bicycle is 9.924 more than the car, the probability of people selecting a motorcycle is 5.688 more than the car, the probability of people to select public transport is 5.138 more than the car, the probability of people to select walking is 12.386 more than the car. Generally, choosing the cheap transport mode is preferred by people.

In the developed model, the independent variables have different impacts on transport modes. Both travel time and travel cost have a negative impact on choosing a transport mode because traveling means paying money rather than gaining money as demonstrated in the economic theory (DeSerpa 1971). Bicycle mode shows 0.025 marginal utility of cost less than the marginal utility of cost using car mode, while motorcycle shows 0.017 marginal utility of cost less than the car (e.g., the increase in the travel cost by one unit means there is a probability of using walking transport mode by −0.017, relative to car mode (reference mode)), public transport mode shows 0.009 marginal utility of cost less than car mode, and walking modes shows 135.627 less than car mode. The cheap transport mode reveals the low marginal utility of travel cost. As a result, the impact of the travel cost on choosing a

Table 5
Likelihood ratio tests.

Effect	Model Fitting Criteria −2 Log-Likelihood of Reduced Model	Likelihood Ratio Tests Chi-Square	df	p>|z|
Intercept	5281.607	0.000	0	.
Trip cost	11,779.298	6497.692	4	<0.001
Trip time	6135.041	853.434	4	<0.001
Age	5336.714	55.107	4	<0.001
Car ownership Index	5615.626	334.020	4	<0.001
Trip purpose	5325.675	44.068	8	<0.001
Gender	5394.223	112.617	4	<0.001
Employment	5326.810	45.203	4	<0.001
Income	5302.090	20.484	8	0.009

Table 6
Model parameter estimates.

Transport mode	Parameter	Estimate	Std. Error	Wald	df	p>|z|	Exp (Estimate)
Bicycle[b]	Intercept	9.924	0.559	314.907	1	–	
	Trip cost	−0.025	0.002	265.156	1	<0.001	0.975
	Trip time	−0.197	0.02	101.698	1	<0.001	0.821
	Age	−0.03	0.008	13.956	1	<0.001	0.971
	Car ownership index	−4.919	0.641	58.867	1	<0.001	0.007
	Trip purpose: Education	−1.082	0.415	6.8	1	0.009	0.339
	Trip purpose: Others	0.005	0.309	0	1	0.986	1.005
	Gender: Female	−0.145	0.248	0.344	1	0.558	0.865
	Employment: No	−0.908	0.3	9.151	1	0.002	0.403
	Income: High-income	0.63	0.303	4.325	1	0.038	1.877
	Income: Low-income	0.183	0.349	0.275	1	0.6	1.201
Motorcycle [b]	Intercept	5.688	0.657	75.001	1		
	Trip cost	−0.017	0.001	317.673	1	<0.001	0.984
	Trip time	−0.039	0.014	7.173	1	0.007	0.962
	Age	−0.029	0.01	8.717	1	0.003	0.971
	Car ownership index	−1.839	0.595	9.548	1	0.002	0.159
	Trip purpose: Education	−0.693	0.451	2.359	1	0.095	0.5
	Trip purpose: Others	0.021	0.383	0.003	1	0.956	1.021
	Gender: Female	−0.676	0.307	4.849	1	0.028	0.509
	Employment: No	−1.037	0.434	5.703	1	0.017	0.354
	Income: High-income	1.045	0.373	7.832	1	0.005	2.842
	Income: Low-income	1.048	0.427	6.03	1	0.014	2.851
Public trans- port [b]	Intercept	5.138	0.248	430.168	1	–	
	Trip cost	−0.009	0	1337.885	1	<0.001	0.991
	Trip time	−0.023	0.004	39.222	1	<0.001	1.023
	Age	0.001	0	0.137	1	0.071	1.001
	Car ownership index	−3.857	0.238	261.547	1	<0.001	0.021
	Trip purpose: Education	0.307	0.182	2.846	1	0.092	1.36
	Trip purpose: Others	0.567	0.132	18.484	1	<0.001	1.763
	Gender: Female	0.815	0.1	66.24	1	<0.001	2.258
	Employment: No	0.243	0.124	3.843	1	0.05	1.275
	Income: High-income	0.167	0.111	2.278	1	0.131	1.182
	Income: Low-income	0.374	0.148	6.412	1	0.011	1.453
Walking [b]	Intercept	12.386	0.476	677.779	1	<0.001	
	Trip cost	−135.627	0	.	1	.	.
	Trip time	−0.243	0.014	284.281	1	<0.001	0.784
	Age	−0.031	0.006	26.705	1	<0.001	0.97
	Car ownership index	−2.714	0.441	37.842	1	<0.001	0.066
	Trip purpose: Education	0.363	0.101	1.066	1	0.302	1.437
	Trip purpose: Others	0.736	0.267	7.614	1	0.006	2.088
	Gender: Female	0.887	0.181	24.147	1	<0.001	2.429
	Employment: No	−0.651	0.21	9.61	1	0.002	0.522
	Income: High-income	0.115	0.217	0.283	1	0.595	1.122
	Income: Low-income	0.226	0.237	0.908	1	0.341	1.253

[a]The reference category is car.
[b]Reference category: Trip purpose: Work, Gender: Male, Employment: Yes, Income: Middle-income.

transport mode is presented as follows from the highest impact to the lowest impact: car, public transport, motorcycle, bicycle, and walking. The marginal utility of travel time per transport mode is 0.197, 0.039, 0.023, and 0.243 for bicycle, motorcycle, public transport, and walking, respectively. The confidence interval that is used in this study is 95%. The model shows significant results at a confidence interval of 95% and insignificant results as shown in Table 6. The insignificant results are kept for comparison, as described later.

The value of travel time for travelers using a particular transport mode is given by Eq. (4). The VOT of travelers when they use bicycles, motorcycles, public transport, and walking is 472Ft./hr., 137Ft./hr., 153Ft/hr., and 0.1Ft/hr. less than car mode, respectively (Hungarian Forint (Ft.) is used in the data, where 1 euro is around 350 Ft).

Age and car ownership index are used as scales in the model, where an increase in one unit of each of them impacts the transport mode choice probability. In case of the bicycle, an increase of age by one year is associated with a −0.03 probability of choosing the bicycle compared to car mode. Thus, a negative impact of age on the bicycle mode share is found. The car ownership index shows a negative impact on using bicycles compared to car mode because having a car negatively impacts using another transport mode. Moreover, as family size increases, the probability of choosing the bicycle as a transport mode decreases. The increase in the car ownership index by one unit leads to a reduction in the probability of choosing the bicycle by 4.919 less than choosing a car. In case of the motorcycle, an increase of age by one year is associated with a −0.029 probability of choosing the motorcycle compared to car mode. Thus, a negative impact of age on the motorcycle mode share is found. The car ownership index shows less negative impact on using the motorcycle compared to the bicycle. The probability of choosing the motorcycle as a transport mode is decreased when family size is increased. The increase in the car ownership index by one unit leads to a reduction in the probability of choosing the motorcycle by 1.839 less than choosing a car. It is shown that the impact of age and car ownership index on the motorcycle are larger than their impacts on the bicycle. In case of public transport, on the contrary of motorcycles and bicycles, an increase in age by one year is associated with a 0.001 probability of choosing public transport compared to car mode. Thus, a positive impact of age on the public transport mode share is found. The car ownership index shows a more negative impact on using public transport. The probability of choosing public transport as a transport mode is decreased when the car ownership index is increased. The increase in the car ownership index by one unit leads to a reduction in the probability of choosing public transport by 3.857 less than choosing a car. It is shown that the impact of the car ownership index on public transport is larger than their impact on the motorcycle and the bicycle. As a result, people can use bicycles or motorcycles more likely than using public transport mode, when the car ownership index is increased. In case of walking, an increase of age by one year is associated with a −0.031 probability of choosing walking compared to car mode. Thus, a negative impact of age on the walking mode share is found. Car ownership index show more negative impact on using walking compared to bicycle and motorcycle, and less negative impact than public transport. The increase in the car ownership index by one unit leads to a reduction in the probability of choosing walking by 2.714 less than choosing a car.

As a result, older people are more likely to walk, bicycle, motorcycle, car, and public transport. Additionally, people are more likely to use cars, motorcycles, walking, public transport, and bicycle, respectively, when the car ownership index is increased.

Trip purpose, gender, employment, and income variables are included in the model, where each one of them has a different impact on transport modes. In case of the bicycle, the probability of choosing the bicycle for travelers who travel to education activities is 1.082 less than those who travel to work activities. In case of the motorcycle, the probability of choosing the motorcycle for travelers who travel to education activities is 0.693 less than those who travel to work activities. In case of public transport, the probability of choosing public transport for travelers who travel to education activities is 0.307 more than those who travel to work activities, and the probability of choosing public transport for travelers who travel to other activities is 0.567 more than those who travel to work activities. In case of walking, the probability of choosing walking for travelers who travel to other activities is 0.736 more than those who travel to work activities. It is worth mentioning only significant results are discussed based on at least a confidence level of 95%.

Gender is significant in all transport modes except the bicycle. The probability of females using public transport and walking (0.815, and 0.887, respectively) is more than males, while the probability of females using the motorcycle is less than the probability of males using the motorcycle.

Employment has an impact on the transport mode choice. The probability of unemployed people choosing a bicycle to travel to main activities is 0.908 less than employed travelers. The probability of unemployed people choosing the motorcycle to travel to main activities is 1.037 less than employed travelers. The probability of unemployed people choosing public transport to travel to main activities is 0.243 more than employed travelers. The probability of unemployed people choosing to travel to main activities is 0.651 less than employed travelers. As a result, unemployed people are more likely to use public transport, car, walking, bicycle, and motorcycle, respectively.

Income influences the transport mode choice of people. People with high income have a higher probability than low income to use bicycles, while low-income people have a higher probability than middle-income people to use the bicycle. The estimates show that people with high income have a lower probability than low-income to using public transport, motorcycle, and walking. Moreover, high-income people have a higher probability to use public transport, motorcycle, and walking than middle-income people.

Thus, high-income people are more likely to use the motorcycle, bicycles, public transport, walking, and car, respectively. Low-income people are more likely to use the motorcycle, public transport, walking, bicycle, and car, respectively. Middle-income people are more likely to use walking, public transport, bicycle, motorcycle, and car, respectively.

The travel behavior of people in Budapest, Hungary is analyzed and modeled using the decision tree technique and a discrete choice modeling approach. The developed multinomial transport logit model demonstrates good accuracy based on Table 4. The travel time and travel cost are negative in all modes of transport, which complies with economic theory (Johnson 1966; A.Small 2012). Other variables show varied impacts on the travel mode choice. The importance of the developed model can be used in predicting the travel demand in the city and the changes that can be occurred because of policy changes in the transport system. For example. the implication of trip cost and trip time are used in controlling the modal split of transport modes.

It is shown from the result of this work and Table 1 that the results of this study present similar variables with significant results and a larger sample size compared to the study of (Al-Salih & Esztergár-Kiss 2021). While the purpose of this study adds a contribution to the literature since the prediction power of the developed model is strong and it presents two types of analysis methods. Moreover, as per our knowledge, none of these studies has outputs that describe the importance ranking of the variables using non-parametric analysis such as the tree-decision techniques.

5. Conclusion

The travel behavior of people is important for policymakers to manage the transport systems and ease people's movements. This research applies two methods of modeling: the discrete choice modeling and the decision-tree technique. Daily activity plans of 7537 travelers are obtained from an RP survey conducted in 2014. Transport mode choice models are developed to help decision-makers in understanding the existing travelers' behavior as well as predict the future travel demand based on the characteristics of the population and travel environment. The decision tree analysis demonstrates that trip time is the most important variable that influences travel choice. The modes of cars, public transportation, and walking are more significant than bicycles and motorcycles. Moreover, the discrete choice modeling is applied, where the MNL model is used. The model shows high strength in prediction and fitting the data, the developed model explains more than 70% of the variance in the mode choice. The developed model includes travel time, travel cost, age, car ownership index, gender, trip purpose, employment, and income variables. The probability of choosing a transport mode is predicted using the previously mentioned variables.

The findings show a negative impact of travel time and travel cost on the travel mode, and each variable has varied impacts on transport modes. The result of the analysis reveals a clear pattern between car ownership and several variables, such as family size, age, and trip cost. The result of decision tree analysis demonstrates that trip duration is the most important factor that affects transport mode choice. The developed MNL model shows that trip time, trip cost, age, car ownership index, trip purpose, gender, employment, and income impact choosing a transport mode by different values. The utility of each variable is presented and explained in the paper. For example, travel time and travel cost demonstrate negative utilities, while other variables show varied utilities. The developed models (i.e., decision-tree and MNL models) are beneficial for the decision-makers who can use them in predicting the travel demand. Future research could consider the number of working members per household.

The limitations of this study are summarized in the absence of new transport modes, such as car-sharing, bike-sharing, and other transport modes with new technology that were not available in 2014 (data age). Moreover, the accuracy of the data recorded by participants/households. It is recommended to study the travel behavior of people based on updated data that includes the current transport modes in Budapest, such as e-scooter, car-sharing, motorcycle sharing, and bike-sharing which have become popular nowadays in Budapest.

Data availability

Data are included in the manuscript and further data are provided as requested

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ridesharing in all its forms – Comparing the characteristics of three ridesharing practices in France

Eléonore Pigalle, Anne Aguiléra*

LVMT, Univ. Gustave Eiffel and Ecole des Ponts, 6-8 Avenue Blaise Pascal, Champs-sur-Marne 77420 France

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A B S T R A C T

While existing literature has primarily focused on carpooling, i.e. ridesharing to work, this article seeks to contribute to the comparison of three non-household ridesharing practices in terms of the profile of the people involved, and the characteristics of each practice regarding cost sharing, the ways ridesharers are connected and their main motivations. We differentiate between ridesharing practices for commuting trips, other (non-work) everyday trips, and long-distance trips. In addition to the usual determinants of ridesharing highlighted by previous literature, this study also investigates the links with collaborative consumption in general. Data come from an online survey conducted in 2016 with a sample of 2,000 French adults. They make it possible to compare ridesharers and non-ridesharers for each of the three categories of ridesharing practices, and also the three categories of ridesharers between them. Results show, on the one hand, that regardless the category of ridesharing, ridesharers differ primarily from non-ridesharers in their practices of the sharing economy, and in the fact that they have people who practice ridesharing in their entourage. Moreover, and secondly, we show differences in terms of the profile of the three categories of ridesharers, the use of online platforms and apps versus off-line methods to connect divers and passenger, and the sharing of travel costs. These result suggest that it is necessary to better distinguish between forms of ridesharing in research in order to improve our understanding of the processes at work in ridesharing, and to propose appropriate policies.

Introduction

Ridesharing refers to a huge variety of short or long-distance, shared rides by car (or van) between people with similar origin-destination pairings (Cui et al., 2020; Furuhata et al., 2013; Mitropoulos et al., 2021; Morency, 2007; Shaheen & Cohen, 2019). It is different from ridehailing services that connect riders to drivers for-profit and through smartphone applications (Brown, 2020; Gehrke et al., 2021; Tirachini et al., 2020; Xu et al., 2021; Yan et al., 2021). Ridesharing includes different categories according to the nature of the ridesharers (family members or not), the purpose of the trip and the connection methods: fampools (sharing of rides between family and friends), carpooling (shared rides between home and work, often arranged by the employer), informal ridesharing (between neighbours, or members of the same association, etc.) and IT-based ridesharing (when drivers and passengers use an online platform or an app (Shaheen & Cohen, 2019; Shoshany Tavory et al., 2020).

In this article, we use the term ridesharing in a more restricted definition. It refers only to the sharing of rides by car, and between people who are not members of the same household. In other words, in the remaining of the text, ridesharing refers to the sharing of a trip (or a part of a trip) between non-household members, already scheduled by the driver, for work or non-work purpose, and not for the purposes of profit (although travel costs may be entirely or partially shared). Moreover, it encompasses practices based on IT, on an institution (such as an employer) and also informal practices (between neighbours, for instance).

Originally, ridesharing was a practical and economical solution mainly adopted by the young and not very well-off (Shaheen et al., 2017). Nowadays, it is seen by many public, private and civil society actors as an everyday solution to a number of individual and collective problems associated with mobility, especially in cities (Kuwahara et al., 2022; Wicki et al., 2019). The intention is to improve sustainability, i.e. to help solve environmental and health problems (reduce the number of cars on the roads, congestion, atmospheric and noise pollution), economic problems (sharing of travel costs, which are the biggest cost item in household budgets in many countries across the world, including France), but also social problems (social inclusion, facilitating access to jobs, connecting low-density areas and by creating social bonds between drivers and passengers).

However, in France as in many developed countries, ridesharing is historically in decline, in particular for commuting trips, which are re-

* Corresponding author.
E-mail address: anne.aguilera@univ-eiffel.fr (A. Aguiléra).

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sponsible for peak hour congestion and a significant proportion of emissions (Chan & Shaheen, 2012; Delaunay & Baron, 2019; DeLoach & Tiemann, 2012; Ferguson, 1997; Galizzi, 2004; Morency, 2007; Neoh et al., 2018; Olsson et al., 2019; Shaheen, 2018; Shaheen & Cohen, 2019). Nonetheless, with the growth of online platforms and apps that connect passengers with drivers and which have proliferated with the spread of Internet and the smartphone, many believe that ridesharing could gain a second wind (Nicoll & Armstrong, 2016; Olsson et al., 2019; Tahmasseby et al., 2016), especially for long-distance trips given the success of the BlaBlacar platform in France (Shaheen et al., 2017).

Understanding the variety of the practices of ridesharing is crucial in order to implement more appropriate measures to encourage its development and ensure that it meets environmental and social goals (Aguiléra & Pigalle, 2021; Pigalle et al., 2020). However, while numerous studies have analysed the profiles of ridesharers (or people expressing a willingness to rideshare) and their main motivations (Bulteau et al., 2019; Delhomme & Gheorghiu, 2016; Gheorghiu & Delhomme, 2018; Morency, 2007; Neoh et al., 2017; Shaheen et al., 2017; Teal, 1987; Vincent, 2008), most of them did not differentiate between the different practices of ridesharing, such as in terms of trip purposes, cost sharing or ways used to connect drivers and passengers (Amirkiaee & Evangelopoulos, 2018; Olsson et al., 2019). Moreover, this literature, both old and more recent, has focused heavily on shared rides between the homeplace and the workplace (or the place of study), often called carpooling, and much less on other trips, although the success of the BlaBlacar platform has recently turned the spotlight on long-distance ridesharers (Beria & Bertolin, 2019; Debroux, 2018; Shaheen et al., 2017).

This article seeks to contribute to the understanding of the practice of ridesharing by (1) comparing non-ridesharing practices with three categories of ridesharing practices and (2) investigating the links with collaborative consumption. For this purpose, we differentiate between three categories of ridesharing practices involving specific timeframes and organisational constraints: commuting trips, everyday mobility (for non-commuting purposes) and long-distance trips (Jacquot, 2018). Ridesharing practices are compared in terms of the profile of the ridesharers, the characteristics of the practice of ridesharing (in terms of cost sharing and the ways ridesharers are connected: digitally, informally or organized by an institution) and the main motivations to rideshare. In addition to the usual determinants of ridesharing highlighted by previous literature, which are sociodemographic, economic, spatial but also psychological (Amirkiaee & Evangelopoulos, 2018; Böcker & Meelen, 2017; Bulteau et al., 2019; Ciasullo et al., 2018; Gheorghiu & Delhomme, 2018; Hartl et al., 2020; Neoh et al., 2018; Olsson et al., 2019; Shaheen et al., 2016), this study also analyses the links with collaborative consumption in general, which have been rarely considered (Amirkiaee & Evangelopoulos, 2018). Data come from an online survey on the sharing economy and collaborative consumption (in general), conducted in 2016 with a sample of 2000 French adults representative of the population in terms of gender, age, professional status and region of residence, and including a dozen questions on each of the three forms of ridesharing defined above.

The rest of the article is divided into four sections. Section 2 is a literature review on the determinants, characteristics and motivations of ridesharing. Section 3 presents the online survey and the methodology. Section 4 discusses the main results. Finally, section 5 sets out the main lessons and limitations of this study, and proposes some new avenues for research.

Literature review

The literature on ridesharing is primarily focused on the comparison between people who rideshare (or express ridesharing participation intention) and non-ridesharers, with an over-representation of carpooling (i.e. home-to-work ridesharing) as shown by several studies (Malichová et al., 2020; Neoh et al., 2017; Olsson et al., 2019). The main findings concern the limited influence of sociodemographic and economic variables, the unclear influence of spatial variables, the huge impact of various psychological dimensions such as trust in other people, environmentalist identity, transportation anxiety, altruism and the role of the family circle and peer group. Moreover, existing literature suggests that the main motivations to rideshare are economic and practical (such as time benefits), and not, or not directly, environmental (Gheorghiu & Delhomme, 2018).

Sociodemographic and economic variables

The literature mainly deals with the links between ridesharing (and especially carpooling, i.e. home to workplace ridesharing) and the usual variables of gender, age, income, professional category or marital status and household composition that influence travel behaviour and especially car use. The results are quite heterogeneous, even contradictory. In particular, they seem to depend on the type of journey in terms of distance and trip purpose of shared rides (Malichová et al., 2020).

While the meta-analysis conducted by Neoh et al. (2017) concludes that women have a higher propensity to carpool than men, the one conducted a few years later by L.E. Olsson et al. do not who any significant impact. In France, however, the survey by Delhomme and Gheorghiu (2016) on ridesharing for everyday work and also non-work purposes (accompanying children, leisure and shopping) identifies gender as one of the main determinants, with women almost three times more likely to rideshare than men, due in particular to the importance of ridesharing organised between parents and linked to accompanying children. The same authors also find that being a woman reduces the frequency of carpooling, while Belz and Lee (2012) reach the opposite conclusion for the United States. However, for Neoh et al. (2018), the link between gender and carpooling is indirect, and actually reflects gender differences in driving motivations. Finally, a survey conducted in 2015 in France shows an over-representation of men in the driver and passenger population of carpoolers (ADEME, 2015).

The influence of age is more consensual, with most studies concluding that the practice of ridesharing, as a passenger or a driver, decreases with age. This is what the ObSoCo survey (Observatory Society and Consumption, ADEME, 2017) in France shows in particular. Another study on BlaBlacar, a long-distance ridesharing platform, also highlights an over-representation of young people, which is however more pronounced amongst passengers than amongst drivers (Shaheen et al., 2017, p. 17). P. Delhomme and A. Gheorghiu also find that the probability of practising ridesharing as a passenger or driver for everyday work or non-work trips decreases with age in France. However, the effect is small compared to other variables, in particular gender. Furthermore, by disaggregating the data according to the type of ridesharing, the authors confirm that, amongst ridesharers, the frequency of ridesharing decreases with age, but only for home-to-work (or home-to-study) journeys and also for those involving the accompaniment of children.

The other socio-demographic and economic variables, such as income, professional category, level of education, marital status and household size, seem to explain ridesharing more weakly (Olsson et al., 2019). Delhomme and Gheorghiu (2016) find that household size increases the probability of ridesharing for both work and non-work trips in France, but also the frequency of this practice, particularly for trips involving the accompaniment of children. However, they do not mention any link with income or marital status. For long-distance journeys *via* the BlaBlacar application, Shaheen et al. (2017) do not find any difference in income level between ridesharers and the adult French population. On the other hand, they show an inverse link between ridesharing frequency and income level, and highlight that passengers have on average a lower income than those who propose a seat in their car. Furthermore, BlaBlacar users have a higher level of education than the French population, linked to the over-representation of students as well as executives and employees. On the other hand, retired people are underrepresented. Finally, in the United States, where this type of statistic is available unlike in other countries such as France, Blumenberg and Smart (2014) find for Southern California and on the basis of Census and Travel Surveys data dating from 2000 to 2001, respectively, that immigrants have a higher propensity to carpool than people born in the USA, a result which they attribute to the importance of social networks in certain immigrant communities. However, Shaheen et al. (2016), based on a survey of informal carpooling, find the opposite, i.e. an over-representation of US-born workers.

Spatial variables

Two main categories of spatial variables are of interest in the literature on ridesharing practices. The first concerns the characteristics of the place of residence, with authors mainly studying the effect of the size of the agglomeration in which the municipality of residence is located and/or its density. The second category focuses on mobility practices, according to various factors such as the distance to work or the distance travelled annually (for all trip purposes). However, the results are often difficult contradictory, or difficult to interpret.

Despite the few studies available, it seems that carpooling increases with the urban (as opposed to rural) character, density and population size of the territory of residence. Thus, in France, the ObSoCo survey (ADEME, 2017) finds that the share of people who have carpooled in the last 12 months is slightly higher in agglomerations with more than 100,000 inhabitants, but the difference with other territories is small. In the same direction, with the case of the Lille Metropolitan Area in France, E. Castex shows that the lower the density, the weaker or even non-existent the carpooling offer (Castex, 2015). In contrast, Belz and Lee (2012) find no effect of density of residence on the propensity to carpool in the United States, although they note that density at the place of employment favours trip sharing. The explanation put forward for the links between carpooling and density is mainly that it is easier to form crews but also to reach a carpooling meeting point in dense urban areas (Olsson et al., 2019), but this has not been tested. Another hypothesis, which merits further investigation, concerns the role of the accessibility of the place of residence to public transport (Delhomme & Gheorghiu, 2016). Finally, to our knowledge, even if previous research underlined the use of carpooling by low-income household in suburban areas (Belton-Chevallier et al., 2018), the influence of the living standard of the place of residence has not been considered by the literature, although the practice of ridesharing could be more important in the least wealthy regions.

Regarding the links between ridesharing and mobility, Delhomme and Gheorghiu (2016) find no difference between ridesharers and non-ridesharers in terms of access to a car, a motorised two-wheeler or a bicycle. However, they show that while the distance to the place of work (or study) and the total number of kilometres travelled per year are identical for French ridesharers and non-ridesharers, this variable contributes to explain the frequency of carpooling and, to a lesser extent, the frequency of ridesharing for accompanying children (but not for leisure and shopping reasons). Other research concludes, however, that the propensity to carpool increases with the distance (or time) between the homeplace and the workplace (Olsson et al., 2019; Park et al., 2018). Gheorghiu and Delhomme (2018) also show that the frequency of carpooling but also ridesharing for childcare trips increases with the distance to the workplace (or place of study). However, the literature review by Neoh et al. (2017) concludes that the links between distance travelled (for all trips) and carpooling remain unclear.

Psychological variables

Like any human decision, choices of transport mode(s), and therefore the practice of ridesharing, also depend on psychological factors: character traits (such as trust to other people and altruism), adherence to certain values (e.g. in terms of ecology), peer influence, *etc*. (Lanzini & Khan, 2017). For some authors, these factors even explain ridesharing better than sociodemographic, economic and spatial variables, while others come to the opposite conclusion (Neoh et al., 2018; Olsson et al., 2019). In any case, taking psychological dimensions into account opens up new perspectives for action such as ridesharing promotion campaigns tailored to specific populations (Bachmann et al., 2018; Wang & Chen, 2012). The main results highlighted by the recent literature concern sensitivity to ecological issues, the attitudes towards transport modes, the influence of friends and family (Bulteau et al., 2019) and the relationship with others (particularly in terms to trust to other). However, the influence of the collaborative economy as an alternative practice and value system has not been studied (Amirkiaee & Evangelopoulos, 2018), although it has been in other areas such as the practice of home and car sharing (Hartl et al., 2020).

Ecological sensitivity

Ridesharers, even very occasional ones, declare themselves to be more sensitive to ecological issues, and in particular to the environmental impacts of current travel behaviour, than non-ridesharers (Delhomme & Gheorghiu, 2016; Neoh et al., 2017; Olsson et al., 2019). However, while there is a large consensus on this result, the causal links between this finding and the choice to rideshare are controversial (Hartl et al., 2020; Olsson et al., 2019). The same debate can be found in other areas of the collaborative economy, such as home sharing or car sharing between individuals, where it has been demonstrated that the ecological dimension plays only a moderate and rather indirect role (Böcker & Meelen, 2017; Hamari et al., 2016). Similarly, most surveys agree that the 'ecological' dimension of ridesharing, i.e. the willingness of reducing the carbon footprint of travel, plays a quite secondary role in the decision-making of both drivers and passengers (ADEME, 2017; Gheorghiu & Delhomme, 2018; Setiffi & Lazzer, 2018).

Attitudes towards transport modes

Logically, ridesharers have a more positive opinion of ridesharing than non-ridesharers (Wang & Chen, 2012). They also perceive less difficulty in practising it, and in particular in finding a passenger or a driver (Olsson et al., 2019). Collective and active modes are also subject to differences in appreciation between ridesharers and non-ridesharers. More precisely, ridesharers declare a better appreciation of public transport and active modes (Delhomme & Gheorghiu, 2016). However, they also value the car in terms of comfort, safety and independence, even if they have a less positive overall assessment of the car than those who never practice ridesharing (Gheorghiu & Delhomme, 2018). However, the degree of appreciation of the car tends to increase with the practice of ridesharing according to the results of the survey conducted by Gheorghiu and Delhomme (2018) in France. Finally, Amirkiaee and Evangelopoulos (2018) demonstrate that transport anxiety (for instance regarding congestion or the availability of parking spaces at destination) influences ridesharing participation intention of car drivers. Ridesharing seems thus to be a kind of acceptable compromise for individuals wishing to reconcile most of the advantages of the car (such as flexibility) with a reduction un the burden of driving and a decrease in the ecological footprint of their mobility practices. In particular, people value in ridesharing the gain in accessibility, transport conditions (e.g. compared to a crowded bus or driving alone) and travel time compared to public transport (Pinto et al., 2019).

Influence of the entourage, trust in other people and altruism

Some studies emphasise the role of family, friends or professional environment: for instance, Gheorghiu and Delhomme (2018) show that the frequency of ridesharing, both for work and non-work purposes, increases if people know other people practicing ridesharing. This result is in line with that obtained by Bachmann et al. (2018) who, however, were not interested in ridesharing practices but in intentions.

These same authors also emphasise the role played by trust in others, but consider that the relationship is not direct: thus, trust in others influences the perception that individuals have of their own ability to rideshare (the more they trust others, the more they consider themselves capable of ridesharing), which in turn influences ridesharing practices. In the Paris Region, Bulteau et al. (2019) also highlight that the entourage is of prime importance in the adoption of carpooling. Finally, using the example of BlaBlacar, Setiffi and Lazzer (2018), like also Lemoine et al. (2017), note that users of the long-distance ridesharing platform gradually develop a feeling of trust in other users and also of belonging to a community, which tends to reinforce their use of ridesharing. Finally, several studies emphasise that socialisation and mutual aid are important motivations for ridesharing (Olsson et al., 2019), the influence of which is also reinforced over time, as has been observed in particular amongst users of the BlaBlacar platform (Setiffi & Lazzer, 2018). Other research confirm that altruism is positively associated with ridesharing intentions (Amirkiaee & Evangelopoulos, 2018).

Characteristics of ridesharing practices

In the majority, literature considers separately self-organized ridesharing, which does not generally involve cost sharing, from ridesharing organized by an institution and ridesharing organized by a digital platform (Chan & Shaheen, 2012). Therefore, we do not know if the ways ridesharers are connected varies across ridesharing carpooling, everyday non-work ridesharing and long-distance ridesharing, especially regarding the use of digital platforms.

Moreover, if the literature on the motivations to rideshare is more extensive, it is primarily focused on carpooling. If ridesharers (both passengers and drivers) seek economic gains, the latter do not seem to be the main nor a higher motivation than environmental, social and practical dimensions of ridesharing (Arteaga-Sánchez et al., 2020; Setiffi & Lazzer, 2018). Indeed, and in line with the influence of psychological variables, socialisation and mutual aid seem to be important motivations for ridesharing (Olsson et al., 2019), and their influence seems to increase over time, as has been observed in particular amongst users of the BlaBlacar platform (Setiffi & Lazzer, 2018). The 'practicality' of ridesharing also regularly appears as a justification given by the respondents in the surveys. While some of the later do not detail what this aspect precisely means for the respondents (Neoh et al., 2017), others mention different dimensions such as time benefit (compared to public transport) and schedule reliability. Finally, ridesharers are, on average, more sensitive to environmental issues than non-ridesharers, and most surveys agree that the 'ecological' dimension of ridesharing, linked to the prospect of reducing the carbon footprint of journeys, plays a role in the decision-making of drivers and passengers alike (ADEME, 2017; Gheorghiu & Delhomme, 2018; Setiffi & Lazzer, 2018). However, the real influence of ecological motivations remains disputed by the literature (Amirkiaee & Evangelopoulos, 2018). Gheorghiu and Delhomme (2018) recently highlighted that environmental motivations were more important for people practising ridesharing for more than two trip purposes, compared to people ridesharing for only one or two purposes.

Purpose of the study

From this literature review, two main limitations appear and justify our study. Firstly, ridesharing practises other than carpooling are rarely considered in terms of profile of the rideshares and characteristics of the practice: methods of connection between drivers and passengers, sharing of the costs and motivations. Secondly, we lack understanding about the influence of the sharing economy (in general) on ridesharing practices, as noted by some authors (Neoh et al., 2018). An exception is the recent research by Mattia et al. (2022) that highlighted how the attitude towards sharing economy impacted the perception of the economic and environmental benefits of ridesharing services for non-users in Italia.

Data and method

Survey

The survey was conducted online in 2016 over a sample of 2000 French adults representative in terms of gender, age, professional status and region of residence. The general objective was to study collaborative consumption in France, both in terms of practices and representations since collaborative consumption had been shown to reflect forms of adherence to alternative values relating to the organisation of the economy and social relations (Hamari et al., 2016).

The questionnaire included a specific part on ridesharing practices, which distinguished between three categories: everyday ridesharing (i.e. for short distance non-work trips, such as shopping trips), carpooling defined as ridesharing for commuting trips, and long-distance ridesharing, i.e. for trips over 80 km from the homeplace according to the usual definition of long-distance used in French national household travel surveys. For each of the three categories, the question asked was as follows: "Do you sometimes share a car ride (as a driver or passenger) with someone outside your household (friend, neighbour, colleague, person met through an online ridesharing platform, etc.)?" The possible answers were: never, occasionally or regularly. Those who answered "regularly" are called the regular ridesharers in the remaining of the paper.

Variables

According to the literature review section, several categories of variables were tested in statistical analysis (see below). They are summarized in Table 1.

Regarding the methods of connection, for each of the three categories of ridesharing practices, the questionnaire distinguished between, on the one hand, digital ridesharing i.e. the use of online platforms or apps, and, on the other hand, non-digital ridesharing, based on personal or professional networks. More precisely, the respondents were offered three possible answers: arrangement with acquaintances, contact organised by an institution (school, organisation, company, etc.) or IT-based solution. Moreover, the respondents were asked, for each of the three categories of ridesharing practices, if they shared the cost or not.

Regarding the motivations to practice ridesharing, six motivations were extracted from the literature, and the respondents were asked to choose and rank the three most important: for mutual help; to save money; to make the trip more sociable; to reduce pollution; for another reason (to be specified); for no other reason. The "practical" dimension referred to in a number of studies was not considered here, because of the difficulties of interpretation mentioned in the above literature review. The question of the main motivations concerned ridesharing practices in general, and were not asked for each category. Only the first of the three main motivations were included in the analysis (Table 1).

In addition, the questionnaire included classical socio-demographic (gender, age, household size, etc.), economic (income) and usual characteristics of the place of residence (population density, standard of living and region; Fig. 1). The data used for the calculation of both the population density and the standard of living of households come from the INSEE statistical database of French municipalities in 2016. Since the literature underlines the links between ridesharing and relationship with others, the respondents were also asked general questions about their level of trust to strangers and their practice of volunteering.

The questionnaire also included quantitative and qualitative questions related to transport and mobility: the number of cars in the household, the frequency of use of the car and public transport for commuting trips, everyday trips and long-distance trips, the accessibility of the homeplace by public transport and also some questions about the representations of the car and public transport in general. The respondents were also asked if people of their private or professional entourage practiced ridesharing.

Table 1
Variables included in the models.

Variables	Calculation
Characteristics linked with ridesharing practice*	
Main motivation	Categorical with 5 modalities (to reduce pollution; to save money; to make the trip more sociable; for mutual help; for another reason)
Cost sharing	Ordered categorical (0=never; +1=rarely; +2=often; +3=very often)
Connection between driver and passenger(s)	Categorical with 3 modalities (organised by an institution [school, organisation, company, *etc.*]; arrangement with acquaintances; contact organised by website [blablacar, klaxit, *etc.*])
Sociodemographic and economic characteristics	
Gender	Binary (0=female; 1=male)
Age	Numeric
Household composition	Categorical with 5 modalities (couple with child; couple; alone with child; alone; other cases [with your parents, family members, friends, roommates…])
Number of children in the household (−18 years)	Numeric
Education	Ordered categorical (−1=bellow baccalaureate; 0= baccalaureate; +1=higher baccalaureate)
Socio-professional categories	Categorical with 8 modalities (self-employed; executive; employee; student; worker; intermediate occupation; retired; without activity)
Perception of income	Ordered categorical (−2=very difficult; −1=difficult; 0=well; +1=comfortable; +2=very comfortable)
Spatial characteristics of the municipality of residence	
Population density (in inhabitants per square km)	Numeric
Standard of living (in euros)**	Numeric
Sub-territory (Fig. 1)	Categorical with 5 modalities (northeast; northwest; paris region; southeast; southwest)
Mobility	
Number of cars in the household	Numeric
Representations of the car	Ordered categorical (−1=disadvantages; 0= equal benefits and disadvantages; +1=benefits)
Representations of the public transport	Ordered categorical (−1=disadvantages; 0= equal benefits and disadvantages; +1=benefits)
Perception of the quality of public transport provision near the place of residence	Ordered categorical (−2=very bad; −1=bad; +1=good; +2=very good)
Relation to others	
Being trusting of other people	Binary (0=no; 1=yes)
Being involved in volunteering activities	Binary (0=no; 1=yes)
Having a personal circle that uses ridesharing	Composite score between 3 items. Ordered categorical (0=no, none; +1=yes, but very little; +2=yes, in part; +3=yes, most of the people in my circle)
Opinions about the sharing economy	Composite score between 11 items. Ordered categorical (−2=highly disagree; −1= disagree; 0=neither agree nor disagree; +1= agree; +2=highly agree)
Uses of peer-to-peer services	
Via an online platform	Ordered categorical (0=no; 0.5=occasionally; 1=regularly)
Off-line peer-to-peer exchanges	Ordered categorical (0=no; 0.5=occasionally; 1=regularly)

*Variables included only in the models comparing ridesharers.
** The standard of living (in euros) is equal to the disposable income of the household divided by the number of consumer units (French national institute for statistical and economic studies).

Finally, the respondents were asked about their online and off-line practices of collaborative consumption. They were also asked about their opinions regarding these practices through a series of 11 questions such as “Do you think that collaborative consumption is a way to give meaning to life in society”, or “Do you think that collaborative consumption is a way to become more independent from large companies?” A composite score was calculated in order to reflect the global opinion on collaborative consumption (Table 1).

Fig. 1: France divided into 5 regions

Population studied

Since our objective was to analyse and compare the different categories of ridesharing, the respondents were split into four groups: one in which people did not practice any category of ridesharing, and three in which people practiced only one of the three categories of ridesharing regularly. We chose to focus only on regular ridesharers in order to eliminate very infrequent practices. Additionally, we chose to focus on exclusive ridesharers, i.e. who practiced only one form of ridesharing, since the purpose of our study is to analyse whether there are differences between the three categories of ridesharing practices.

In the end, about the half of the initial sample of 2000 adults were removed from the analysed data set (Supplementary Table 1). The population studied involved 1022 participants: 74.5% who practised none of the three forms of ridesharing (n = 761), 14.3% who regularly practised only long-distance ridesharing (n = 146), 5.2% only carpooling (n = 53), and 6.1% only ridesharing for daily trips other than commuting (n = 62). If we only consider the 261 regular and exclusive ridesharers, 20.3% practiced commuter ridesharing, 23.7% everyday ridesharing and 55.9% long-distance ridesharing.

Statistical analysis

Data analyses were undertaken using the free software R in three separate steps each based on generalised binomial models (so-called “generalised linear regression” on binomial data or “logistic regression”), for which the general formula is:

$$g(\mu) = \log\left(\frac{\mu}{1-\mu}\right)$$

First, we performed three models, each including one form of ridesharing against the group of non-ridesharers. The ridesharing group was coding with “1″ while the non-ridesharing group was coding as “0″. We included as explanatory variables both numerical and categorical variables presented in Table 1. Basic descriptive analyses are available in Supplementary Table 1. The objective was to identify the determinants of the practice of each category of ridesharing.

Second, we achieved models between each form of ridesharing (coded “1″) against the two others groups of ridesharers merged together (coded “0″) with the same variables used during the first step. This second step highlighted the specificities of each form of ridesharing.

Third, we performed models between each form of ridesharing (coded “1″) against the two others groups of ridesharers merged to-

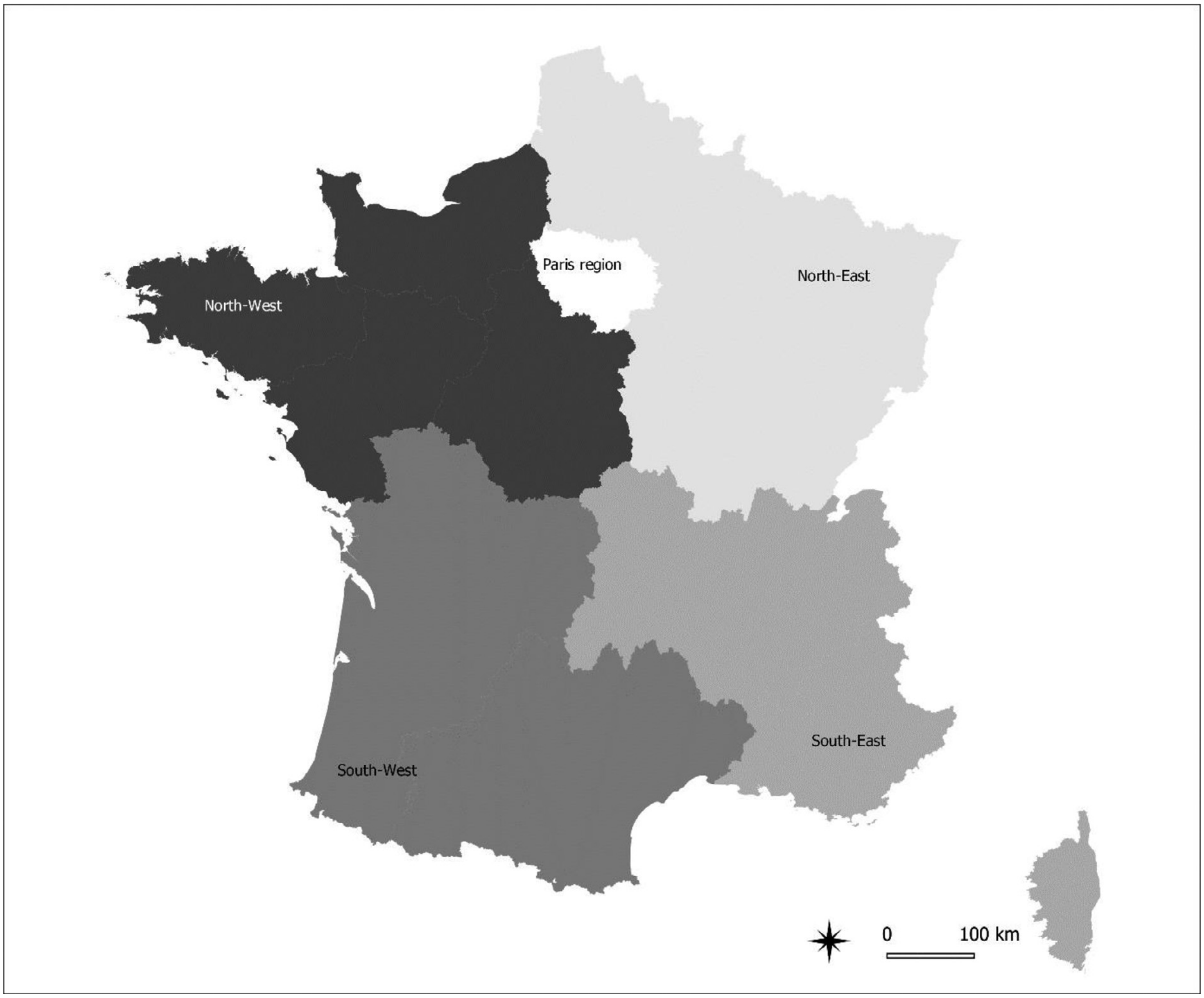

Fig. 1. Graphics program: QGIS; Data (OpenStreetMap contributors under ODbL license).

gether (coded "0″) but on the characteristics of ridesharing practices: main motivations, cost sharing and methods of connection used.

For each model, results are presented in a specific table as follows:

- For numerical predictors, the coefficients were reported. They correspond to the slope modification (increase if coefficient higher than 0, decrease if coefficient bellow 0) by an increase of 1 of the numerical predictor on the probability to practice a specific form of ridesharing against the non-ridesharing (step 1), against the other forms of ridesharing (step 2) or on the characteristics of ridesharing (step 3). For example, if the predictor "Age" is associated with a coefficient of 0.05 for one of the models of step 1, it means that if age increases by one year, the probability to practice ridesharing is increased by 0.05 (or 5%).

- For categorical predictors, the estimated marginal means were reported (so-called least-squares means; Harvey, 2018; Searle et al., 1980). They were calculated with the packages "lsmeans" and "emmeans" and correspond to the probability to practice a form of ridesharing (for step 1) by controlling for any other predictors included in the models. For example, if the categorical predictor "Gender" is significant for the step 1, this means that the probability to practice ridesharing is different between female and male.

- To assess the whole model performance, we reported the sensitivity (i.e., probability to detect members of a specific group) and the specificity (i.e., probability to not detect members of another group) to identify correctly the ridesharers, as well as the balanced accuracy (i.e., the mean between sensitivity and specificity).

Results and discussion

Tables 2 to 4 show firstly that, regardless the category of ridesharing, ridesharers differ primarily from non-ridesharers in their practices of the sharing economy, and in the fact that they know people who practice ridesharing in their entourage. Moreover, and secondly, we also highlight differences across the three categories of ridesharing (carpooling to work, ridesharing for non-work everyday purposes, and long-distance ridesharing) in terms of the profile of the ridesharers and the characteristics of ridesharing practices.

To rideshare or not to rideshare: influence of collaborative consumption and the entourage

From all our variables, only two systematically discriminate ridesharers from non-ridesharers (Table 2). They do not concern socio-demographic, economic or spatial variables, which agrees with a recent meta-analysis (Olsson et al., 2019). They concern the use of peer-to-peer services ("Uses of peer-to-peer services" variables, $p<0.05$) and the fact of having people in the private or professional entourage who also practise ridesharing ("Having a personal circle that uses ridesharing" variable, $p<0.05$).

Ridesharers have a greater tendency to practise collaborative consumption in general (Böcker & Meelen, 2017; Malardé & Pénard, 2019). This finding suggests that collaborative mobility (i.e. the practice of

Table 2
Results for the comparisons between each category of ridesharers and non ridesharers.

	Commuter ridesharing ($n = 53$)	Everyday ridesharing ($n = 62$)	Long-distance ridesharing ($n = 146$)
Sociodemographic and economic characteristics			
Gender			
Female	3.6%	7.1%	13.2%
Male	5.9%	6%	11.9%
Age	−0.042	0.02	−0.016
Household composition			
Couple with child	7%	4%	5.5%
Couple	2.3%	4.8%	12.1%
Alone with child	7.2%	9.8%	14%
Alone	3.8%	6%	19.3%
Other cases [with your parents, family members, friends, roommates…]	3.4%	8.2%	11.8%
Number of children in the household (−18 years)	−0.957*	0.389	0.111
Education	−0.294	−0.106	0.093
Socio-professional categories			
Self-employed	0%	14.4%	24.1%
Executive	7.7%	5.5%	12.2%
Employee	3.6%	2.1%	9%
Student	3.9%	8.7%	18.1%
Worker	9%	2.5%	13.6%
Intermediate occupation	4.3%	5.9%	8.9%
Retired	–	7.8%	8%
Without activity	–	5.7%	6.5%
Perception of income	−0.143	−0.519**	−0.052
Spatial characteristics of the municipality of residence			
Population density (in inhabitants per square km)	-2.25^{-5}	-5.56^{-5}	3.29^{-6}
Standard of living (in euros)	-5.89^{-5}	-4.68^{-5}	-4.23^{-5}
Sub-territory			
Northeast	6.7%	8.4%	14.3%
Northwest	4.9%	4.6%	7.5%
Paris region	3.1%	8.3%	12.8%
Southeast	5.2%	8.4%	15.2%
Southwest	3.9%	3.1%	12.3%
Mobility			
Number of cars in the household	−0.099	−0.085	0.572**
Representations of the car	−0.227	0.156	0.271
Representations of the public transport	−0.106	−0.105	0.095
Perception of the quality of public transport provision near the place of residence	0.221	0.025	0.264*
Relation to others			
Being trusting of other people	−0.174	0.111	0.527
Being involved in volunteering activities	−0.257	0.139	0.579*
Having a personal circle that uses ridesharing	0.624*	0.586*	0.947***
Opinions about the sharing economy	0.147	0.335	0.214
Uses of peer-to-peer services			
Via an online platform	2.525***	1.65**	2.008***
Off-line peer-to-peer exchanges	2.598***	1.927***	1.057*
Sensitivity	45.3%	22.6%	52.7%
Specificity	99.1%	99.2%	97.1%
Balanced Accuracy	72.2%	60.9%	74.9%

*$p<0.05$, **$p<0.01$, ***$p<0.001$; for each ordered categorical variable and numerical variable, the coefficients are reported; for each categorical variables the probability to practice the specific form of ridesharing are reported. For example, for ordered categorical variables: when individuals have a personal circle that uses ridesharing, they have a probability to practice commuting ridesharing that increases of 62.4% (coefficient = 0.624). For example, for categorical variables: when an individual is a female, she has a probability to practice long-distance ridesharing of 13.2%, which is not different of those of a male (11.9%).

ridesharing) is part of a lifestyle that values alternative consumption practices based on IT or not ("*Via* an online platform" variable, $p<0.01$; "Off-line peer-to-peer exchanges" variable, $p<0.05$) (Belk, 2014; Katrini, 2018; Schor, 2016). Moreover, collaborative mobility seems to be embedded in practices that are shared by within the user's social environment ("Having a personal circle that uses ridesharing" variable, $p<0.05$). Indeed, the presence of people in the private or professional entourage who practise ridesharing has a major influence, a fact that has already been reported in previous research (Bachmann et al., 2018; Bulteau et al., 2019; Eriksson & Forward, 2011; Gardner & Abraham, 2008; Gheorghiu & Delhomme, 2018; Hartl et al., 2020; Lanzini & Khan, 2017). Altogether, these points suggest that ridesharing is not only a simple travel choice, but is part of a lifestyle that is favourable to the sharing of goods and services.

Conversely, the results regarding non-ridesharers could also be interpreted, not so much as an expression of resistance to ridesharing, but more likely as a combination of several contrary factors such as unfamiliarity with the practice (both individual and in the personal circle) and also less adherence and use of the sharing economy. In other words, for non-ridesharers, ridesharing, and more broadly the sharing economy, are not part of the familiar environment. Consequently, informing and educating this population could help to develop ridesharing practices (Bulteau et al., 2019; Delhomme & Gheorghiu, 2016; Gheorghiu & Delhomme, 2018; Olsson et al., 2019).

Specificities of long-distance ridesharing

Three main points characterize people practising long-distance ridesharing compared to the two other categories of ridesharers (Tables 3 and 4). The first is their good perception of the quality of public transport near their place of residence ("Perception of the quality of public transport provision near the place of residence" variable, $p<0.05$;

Table 3
Results for the comparisons between each category of ridesharers.

	Commuter ridesharing (n = 53)	Everyday ridesharing (n = 62)	Long-distance ridesharing (n = 146)
Sociodemographic and economic characteristics			
Gender			
Female	15.1%	26.1%	58.6%
Male	22.1%	22.6%	52.6%
Age	−0.026	0.031	0.004
Household composition			
Couple with child	31.4%	20.3%	44%
Couple	11.9%	19.2%	66.7%
Alone with child	23.8%	31.1%	43.5%
Alone	15%	22%	63.2%
Other cases [with your parents, family members, friends, roommates…]	11.1%	29%	60.4%
Number of children in the household (−18 years)	-0.878^{*}	0.498	0.139
Education	0.228	−0.249	0.164
Socio-professional categories	***	**	
Self-employed	0%	42.8%	74.2%
Executive	28.4%	12.9%	50.3%
Employee	26.8%	11.6%	58%
Student	15.9%	12.5%	73.6%
Worker	64%	3.1%	39.3%
Intermediate occupation	14%	23.1%	59.4%
Retired	–	38.3%	38.4%
Without activity	–	50.4%	51.5%
Perception of income	0.118	−0.236	0.096
Spatial characteristics of the municipality of residence			
Population density (in inhabitants per square km)	-2.19^{-5}	-6.59^{-5}	5.09^{-5}
Standard of living (in euros)	-1.06^{-5}	-2.45^{-5}	3.65^{-5}
Sub-territory			
Northeast	23.4%	20.4%	54.4%
Northwest	17.5%	29.9%	48.6%
Paris region	16.9%	33.9%	50.4%
Southeast	19.2%	22.5%	55%
Southwest	16.2%	15%	69.6%
Mobility			
Number of cars in the household	−0.206	−0.358	0.409
Representations of the car	−0.197	0.077	0.053
Representations of the public transport	0.152	−0.087	−0.075
Perception of the quality of public transport provision near the place of residence	−0.215	−0.261	0.273^{*}
Relation to others			
Being trusting of other people	-1.153^{*}	−0.44	0.93^{**}
Being involved in volunteering activities	-1.049^{*}	−0.17	0.647
Having a personal circle that uses ridesharing	−0.26	-0.616^{*}	0.465^{*}
Opinions about the sharing economy	0.299	−0.142	0.001
Uses of peer-to-peer services			
Via an online platform	−0.079	0.312	−0.212
Off-line peer-to-peer exchanges	2.172^{***}	0.624	-1.779^{***}
Sensitivity	43.4%	48.4%	76%
Specificity	93.7%	93.9%	65.2%
Balanced Accuracy	68.6%	71.2%	70.6%

$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$; for each ordered categorical variable and numerical variable, the coefficients are reported; for each categorical variables the probability to practice the specific form of ridesharing are reported. For example, for ordered categorical variables: when individuals have a good perception of the quality of public transport, they have a 27.3% more chance to practice long-distance ridesharing rather than the two others forms (coefficients = 0.273). For example, for categorical variables: when an individual is a worker, he has a 64% probability to practice commuter ridesharing (64%) rather than the two others forms of ridesharing which is higher than the other socio-professional categories.

Table 3). Previous studies have already suggested that long-distance ridesharing is practised not so much because public transport is lacking but with the aim to avoid it (Castex, 2017; Delaunay & Baron, 2019). Ridesharing would seem to constitute an alternative to the existing options, and thus a substitute for public transport, as is indeed observed for occasional long-distance ridesharing (Minett & Pearce, 2011). Under these circumstances, the environmental benefit of ridesharing is questionable, since it has the effect of increasing access by car of major urban areas that already enjoy good public transport provision (Castex, 2017; Monchambert, 2020).

The second point is that long-distance ridesharers rely more on platforms and apps, and less on institutional and informal ridesharing than other ridesharers (“Connection between driver and passenger(s)” variable, $p<0.001$, Table 4). In other words, by facilitating the matching between drivers and passengers, online platforms and apps seem to encourage the development of long-distance ridesharing, which is consistent with the success of Blablacar in France. Moreover, long-distance ridesharers share travel costs associated to ridesharing more frequently than the two other categories (“Cost sharing” variable, $p<0.01$; Table 4 and Fig. 2). This result is probably related on the one hand to the higher use of IT to connect drivers and passengers, and, on the other hand, to the fact that long-distance travel costs are higher than for short distance trips.

The third interesting result concerns the high level of trust in other people manifested by long-distance ridesharers compared to the other two categories of ridesharers (“Being trusting of other people” variable, $p<0.01$; Table 3). Previous studies have explained that trust in other people influences individuals’ perceptions of their own capacity to rideshare (i.e., higher the trust to other people, higher they consider themselves as capable of ridesharing), which itself affects ridesharing

Table 4
Results for the comparisons between each form of ridesharing regarding ridesharing characteristics.

	Commuter ridesharing (n = 53)	Everyday ridesharing (n = 62)	Long-distance ridesharing (n = 146)
Main motivation			
To reduce pollution	21.5%	18.5%	59.5%
To save money	28.7%	22.6%	48.1%
To make the trip more sociable	20.6%	21.2%	57.4%
For mutual help	14.7%	26.9%	57.3%
For another reason	29%	7.8%	65.6%
Cost sharing	−0.351*	−0.137	0.387**
Connection between driver and passenger(s)		***	***
Organised by an institution (school, organisation, company, etc.)	32.1%	26.8%	40.2%
Arrangement with acquaintances	22.8%	28.2%	48.3%
Contact organised by IT (BlaBlaCar, Klaxit, etc.)	13.7%	3.2%	84.3%
Sensitivity	1.9%	0%	69.2%
Specificity	99.5%	100%	67.8%
Balanced Accuracy	50.7%	50%	68.5%

*$p<0.05$, **$p<0.01$, ***$p<0.001$; for the ordered categorical variable, the coefficients are reported; for each categorical variables the probability to practice the specific form of ridesharing are reported. For example, for ordered categorical variable: when individuals declared to share cost, they have a probability to practice commuter ridesharing which decreases by 35.1% (coefficient = −0.351). For example, for categorical variables: when an individual declares to be connected with other driver/passenger through IT, he/she has a probability of 3.2% to practice everyday ridesharing compared to 84.3% to practice long-distance ridesharing.

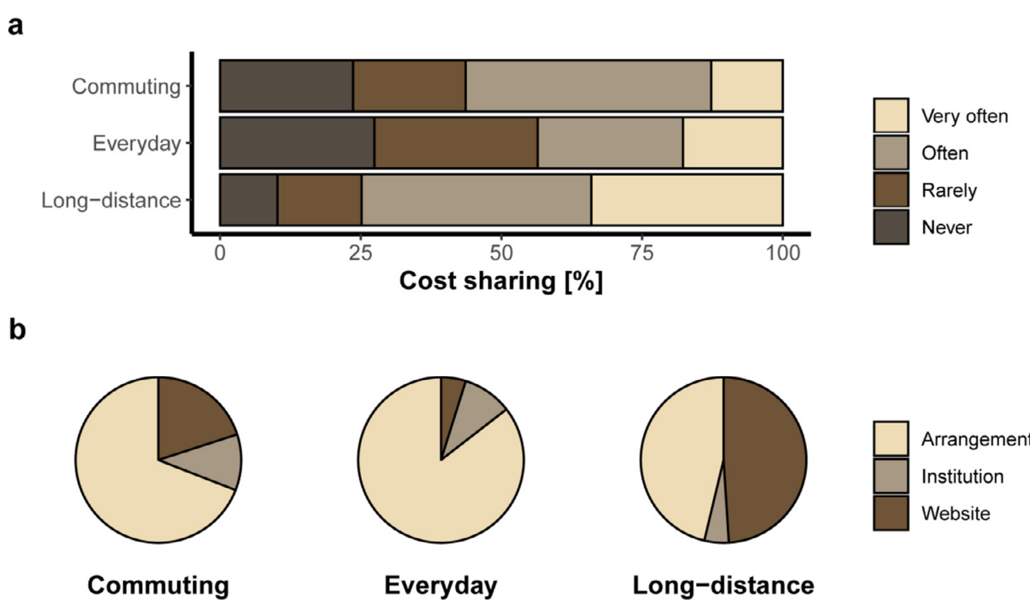

Fig. 2. Significant variables distinguishing forms of ridesharing. Graphics program: R.

practices (Bachmann et al., 2018; Bulteau et al., 2019; Gheorghiu & Delhomme, 2018). However, our results show high levels of trust amongst long-distance ridesharers that are much higher than in all the other groups. This could be explained by the fact that long-distance ridesharers make greater use of digital platforms and apps (“Connection between driver and passenger(s)” variable, $p<0.001$, Table 4), since studies have shown a link between trust in other people and the use of dedicated online ridesharing platforms (Anaya-Sánchez et al., 2020; Belk, 2014; Chan & Shaheen, 2012; Lemoine et al., 2017; Malardé & Pénard, 2019; Saxena et al., 2020; Setiffi & Lazzer, 2018). Indeed, user ratings and feedback (Tadelis, 2016) create a sense of trust (Setiffi & Lazzer, 2018), which can be reinforced by a sense of security based on the feedback provided on both drivers and passengers. In other words, this rating system is probably perceived as a way of weeding out “bad” ridesharers. Conversely, the lack of information on other ridesharers has already been reported as an obstacle to the practice of ridesharing when it is arranged *via* online platforms (Abrahamse & Keall, 2012). These previous results suggest that the use of digital platforms is, for long-distance ridesharers, the source of a new and more reassuring social currency than informal ridesharing, like a safety guarantee. Equivalent findings have already been reported for other digital sharing platforms (Malardé & Pénard, 2019).

Fig. 2: Ridesharing practice differs according to cost sharing and connection methods

Specificities of commuter ridesharing (carpooling)

Compared to the two other forms of ridesharing, carpoolers show the highest proportion of workers (“Socio-professional categories” variable, $p<0.001$; Table 3), a professional group that is yet under-studied in the literature about ridesharing, apart from a recent study that mentioned the significant involvement of workers living in the same geographical area in carpooling practices (Belton-Chevallier et al., 2018; Buliung et al., 2010). In addition, carpoolers tend to live in households with less children than the other ridesharers (“Number of children in the household (−18 years)” variable, $p<0.05$; Table 3) and non-ridesharers (“Number of children in the household (−18 years)” variable, $p<0.05$; Table 2). They are more likely to use peer-to-peer services, but without using an online platform or an app (“Off-line peer-to-peer exchanges” variable, $p<0.001$; Table 3). Finally, the travel costs of ridesharing are generally not shared between the passengers for this category of ridesharing (“Cost sharing” variable, $p<0.05$; Table 4 and Fig. 2). Therefore, carpooling seems then to be more related to a system of mutual help between people with a car and who are alternatively drivers and passengers.

Specificities of everyday ridesharing (for non-work-related purposes)

By contrast with carpoolers and long-distance ridesharers, everyday ridesharing practices have received little scholarly attention (Gheorghiu & Delhomme, 2018). Yet, our findings show that the profile of everyday ridesharers is quite specific. They are more likely to be without activity, self-employed and retired than other ridesharers (“Socio-professional categories” variable, $p<0.01$; Table 3). They are also the ones, out of the four groups (ridesharers and non-ridesharers), who most often admit to being in serious or even very serious financial difficulties (“Perception of income” variable, $p<0.01$; Table 2). Finally, these ridesharers mainly organise their ridesharing informally with people they know, and not through an online platform or an app (“Connection between driver and passenger(s)” variable, $p<0.001$; Table 4 and Fig. 2). Everyday ridesharing mainly seems to form part of a system of mutual help intended to resolve mobility problems. Other authors have already observed such forms of arrangement, of collaborative solidarity (Coutard et al., 2004; Néchet, 2016), especially in suburban areas, where ridesharing was shown to be largely organised between near neighbours (Pradel et al., 2014; Thébert et al., 2016). Thus, the practice of everyday ridesharing corresponds to an exchange of services between people living close to each other in order to optimise day-to-day organisation, probably including school and extracurricular activities as shown by previous studies (Arbour-Nicitopoulos et al., 2012; Gheorghiu & Delhomme, 2018).

Conclusion

To our knowledge, this study represents one of the first attempts to characterize and compare different forms of regular non-household ridesharing, in a literature dominated by research on carpooling (i.e. home-to-work ridesharing). Based on an original survey on a representative sample of the French population, our work shows that, firstly, whatever the type of ridesharing, people practising ridesharing have specific characteristics compared to non-ridesharers. They are primarily related to psychological aspects (level of trust to other people and influence of the entourage) but also to collaborative consumption in general, a point that has received little attention so far. By contrast, as already demonstrated for carpoolers, socio-demographic and spatial variables are not influential to differentiate ridesharers from non-ridesharers. Secondly, we demonstrate that ridesharing differs according to the type of trip considered (work, non-work or long-distance) in terms of the profile of the ridesharers, the sharing of the costs and the methods of connection used.

This work underlines that the diversity of ridesharing practices deserves more attention in research, in order to improve our understanding of the processes at work, and to propose appropriate policies. In particular, our results suggest that long-distance ridesharing is boosted by the development of platforms and apps, while more classical forms of methods of connection are still at work for carpooling and everyday non-work ridesharing. Even if our data are quite old, the current very measured success of ridesharing apps for short distance trips (Malardé & Pénard, 2022) suggests that our results are still valid. Therefore, public authorities that wish to develop everyday ridesharing should not rely entirely on digital technology, but must also encourage the development of social links at a local level. Regular ridesharing should become a solution for low-income people, or people who do not wish to drive each day to get to work or to accompany children due to fuel prices, stress, fatigue, etc., especially in low-density areas where car dependency is the highest. Additionally, our results underline the importance of the entourage and also collaborative practices in other domains than mobility. It suggests that the diffusion of ridesharing should benefit from the development of the sharing economy. Finally, our work suggests that it is necessary to distinguish between ridesharers in the communication strategies of transport authorities.

Of course, our work has a number of limitations, such as being based on data that are already somewhat old, failing to distinguish between passengers and drivers (Bulteau et al., 2021), and considering only exclusive and regular ridesharers. In addition, our typology of ridesharing practices in three categories is questionable. Finally, this work opens new avenues for research in this topical area. Firstly, future work should consider the people who practise ridesharing non regularly, and those who practise two or three forms of ridesharing. Secondly, certain variables are missing or would merit more in-depth analyses in the future. In particular, the links between everyday ridesharing and family organisation, the diversity and complexity of which have been demonstrated in numerous studies (Ho & Mulley, 2015; Ibrahim, 2003; Kaufmann & Widmer, 2005, 2006), need further investigation. The influence of working conditions, such as the places and hours of work (fixed or variable; (Abrahamse & Keall, 2012; Neoh et al., 2017; Habib et al., 2011), the size of the company (Charles & Kline, 2006; Neoh et al., 2017; Teal, 1987; Vanoutrive et al., 2012), are also potentially interesting avenues to a better understanding of carpooling and, in particular, the use of platforms, institutions or self-organisation to match drivers and passengers. From a methodological point of view, the approach based on mobility biographies, which situates travel practices and changes within longer individual and household timescales (Rau & Manton, 2016) seems to us a particularly interesting perspective in this respect, opening up new forms of targeted public action based on household lifecycles (Ho & Mulley, 2015). Thirdly, a research effort is needed on the impacts of the current health crisis (Hensher, 2020; Molina et al., 2020), the development of telework and the increase in fuel prices on the different forms of ridesharing (Aguiléra & Pigalle, 2021). Finally, and fourthly, more research is also needed regarding the environmental but also social impacts of each category of ridesharing practice. Even if our data do not allow for detailed results on the topic, our findings suggest that some forms of ridesharing compete more with public transport than others, especially ridesharing for long-distance trips. This coincides with the conclusions of previous studies (Castex, 2015; Delaunay & Baron, 2019; Morency, 2007), which noted that not all forms of ridesharing are desirable in sustainability terms. More recently, some authors have questioned the environmental benefits of ridesharing and flag warnings about its numerous rebound effects (Coulombel et al., 2019; Yin et al., 2018): significant growth in ridesharing would reduce the use of public transport or active modes in favour of the car. On the other hand, our work also highlights that ridesharing brings social benefits in terms of accessibility for low-income people, but also in terms of the development of social ties. Moreover, this work shows that ridesharing practices, whatever the category, seem to be part of specific lifestyles that value the relationships with other, including the practice of collaborative consumption for financial but also social motivations. These findings plead for a better consideration of the social impacts of each form of ridesharing, in a literature where environmental concerns dominate (Pigalle & Baron, 2020; Reigner & Brenac, 2019).

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Availability of data and material

The data and material that support the findings of this study are available from the corresponding authors upon reasonable request.

Code availability

The code that supports the findings of this study is available from the corresponding authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Eléonore Pigalle: Investigation, Writing – original draft, Writing – review & editing, Formal analysis. **Anne Aguiléra:** Investigation, Writing – original draft, Writing – review & editing.

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Supplementary materials

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The local socio-economic impact of improved waterborne public transportation. The case of the New York City ferry service

Gitte Schreurs*, Kris Scheerlinck, Maarten Gheysen

KU Leuven, Faculty and Department of Architecture, Hoogstraat 51, 9000 Ghent, Belgium

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ABSTRACT

This paper looks into the recent actions of the New York City government to connect its five boroughs over water and the consequential impact on the socio-economic conditions of local coastal neighborhoods. The predictions from the Comprehensive Citywide Ferry Study (CFS2013) are contrasted with actual data and observations of the transformations that have taken place in the direct surroundings of a selection of ferry terminals, both in terms of spatial changes, as well as economic growth or decline.

The paper starts with an illustration of how different modes of waterborne transportation steered urban transformation processes and coastal land uses over time. Next, the paper explains the rise of the NYC ferry network as a contemporary answer to a growing demand for public transportation that connects coastal neighborhoods. A comparative analysis between a selection of ferry landings reflects upon the impact that improved accessibility has on neighborhoods' spatial, social, economic, and environmental conditions. The paper studies several parameters, including the neighborhoods' property prices, employment rates, daily commutes, development interest, demographics, and tourism.

What distinguishes this paper from other studies is the direct link between the quantitative data and the social, economic and environmental characteristics of the surroundings of the ferry landings. Instead of providing a mere technical analysis, the paper studies the transformation of neighborhoods in proximity to the ferry stops and reflects upon hypothetical future impact of new ferry stops. A link is made between the quantitative results of existing studies to a case analysis of the concerned neighborhoods. Whereas the methodology used in this paper is a combination of both a theoretical and an empirical analysis of New York City's waterfront, the main goal is to provide a theoretical contribution by notion of a case study approach.

1. Introduction

1.1. Introduction to the paper

Cities are increasingly looking at ways of how to expand their public transportation facilities. Introducing a ferry network is a popular contemporary option for coastal cities (Cheemakurthy et al., 2017). By introducing a ferry as a new form of public transportation, strategic waterfront locations are connected by a pleasant form of traveling. While the construction of a ferry terminal can be managed with only limited spatial impact on the waterfront, the socio-economic impact on its surrounding neighborhoods can be extensive. Enhanced accessibility to an area can trigger better maintenance of public space, increase property prices, create more commercial facilities, etc. This paper investigates the impact of the reinstatement of water as an important transportation infrastructure on the ferry terminals' surrounding neighborhoods. The question is raised whether there is a causal relationship between increased waterborne transportation and coastal socio-economic transformation, displacement, and gentrification. Using New York City as a case study, this paper investigates the impact of a ferry network on two neighborhoods: Red Hook and Brooklyn Heights/Cobble Hill, both located in Brooklyn. To gain insights on these matters, several elements are explored, including property prices, employment rates, median household income, commuting times, development interest, demographics, and tourism. To increase the probability that the ferry landing is the source of impact, the data that are gathered are of a radius of maximum 1.6 kilometers (1 mile) around the ferry landings. By comparing the predictions of the Comprehensive Citywide Ferrystudies (a study by the New York City government that predicts the impact of ferry networks and landings) with the recent data and ongoing transformation processes of those two neighborhoods, the aforementioned potential causal relationships are investigated. The paper ends by exploring

* Corresponding author at: Groenewandeling 39, 9031 Ghent, Belgium
E-mail address: gitte.schreurs@kuleuven.be (G. Schreurs).

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the hypothetical impact of the planned ferry route to Coney Island, New York, on the social, spatial, and economic configuration of Coney Island Creek.

The methodology used in this paper is a combination of both a theoretical and an empirical analysis of New York City's ferry network and waterfront transformation, but the main goal is to provide a theoretical contribution by notion of a case study approach.

1.2. Accessibility versus Gentrification

In an effort to replace the use of cars by a more efficient and sustainable form of commuting, new and expanded forms of public transit are implemented in cities worldwide. Whereas the intentions are to enhance a neighborhood's livability and to add comfort for the local stakeholder, enhancing accessibility entails other consequences for the neighborhoods in question as well, especially when they have thus far been rather secluded from the city center. Neighborhoods that are less accessible often remain under the radar for larger redevelopment projects or private investments. They are not as appealing for residents with strong financial capital, or for young families who commute to work. When accessibility to these neighborhoods suddenly increases, it will attract new types of stakeholders, changing the identity of these neighborhoods drastically (Schreurs, 2022). Noorlander saw this happening in a formerly remote neighborhood in Amsterdam, where, after the introduction of a new bridge " [s]ocial tensions are emerging between the new social, cultural and economic stronger and dominant new residents and the 'old' social economic lower class residents" (Noorlander, 2018). In New York, the same is happening. In Williamsburg (Curran, 2007), for instance, every time a shift in accessibility took place (e.g. the construction of the Williamsburg Bridge in the early 20th century, the announcement of the closure of the L-train for maintenance after Super Strom Sandy, the introduction of a shared bike system, and the arrival of two ferry terminals), the neighborhood drastically changed as well.

Plenty of research has been done on how enhanced accessibility triggers the increase of property prices, displacement of lower-income inhabitants, and consequentially causes gentrification. Revington states that improvements in transit for people without cars can affect land values, because it provides accessibility to places that are valued by developers and investors (Revington, 2015). Similarly, Dawkins and Moekel argue that accessibility is one of the most dominant features that trigger gentrification (Dawkins and Moeckel, 2016). It is a difficult excersize to find a balance between adding value and livability to a secluded neighborhood, and the extent of socio-economic changes that it triggers.

Because of their industrial history, waterfront neighborhoods in a city like New York are generally more accessible by vehicle, and less by existing public transportation networks such as the subway or the bus. Since 2017, New York has therefore significantly expanded its ferry network, to serve strategic areas on its 930 kilometers of coastline. According to Walker's research (Walker, 2012), successful ferry transit needs to answer to seven preconditions: the ferry has to (1) operate with a high frequency, (2) have its landings located in very high density neighborhoods, (3) have quality landside access and be part of a larger network of public transportation, (4) be free from competition from nearby bridges or tunnels, (5) navigate over a direct path, (6) have few major terminals instead of many little ones, and (7) operate with affordable pricing. Walker specifies that New York's Staten Island Ferry answers to all of these preconditions. However, as the New York City ferry network continuously expands, more and more small terminals are implemented, some of which are no longer located in high density neighborhoods or are less connected to the existing subway and bus services. The question that arises is how the implementation of a ferry terminal, and the increased accessibility by waterborne transportation affects these formerly secluded neighborhoods and their ongoing social and economic processes.

2. New York City's waterfront

2.1. New York City's waterfront: a history

Over history, waterfronts have played a crucial role in coastal cities' spatial, social and economic transformation. Because of complex interplays of unique spatial conditions, development (dis)interest, complicated landownerships, (in)accessibility, and several other factors, waterfront neighborhoods have often transformed at a different pace and at a different scale compared to the inner city. New York is one of those cities with a vibrant history of coastal transformation processes, defining its overall social and economic processes.

New York's unique coastal transformation already started with its initial inhabitants. The Lenape tribe lived predominantly in proximity to the water to fish, for the oyster reefs, and to travel or transport goods by boat. After the first Dutch explorers discovered the land in 1626, multiple European settlements established along the coastline and were quickly connected by a first ferry service (Bone et al., 1997). The water surrounding New York has continuously been used for transporting both goods and people. Manhattan's first wharf was already completed before 1650, which is realtively early compared to other important port cities on the East Coast, such as Boston (U.S. National Park Service n.d.) and Charleston (Butler, 2020). At a later stage, New York's waterfront has functioned as a strategic location for war effort as a military base. Around 1810, the arrival of steam ships and the importance of the cotton industry made New York a most important port city (Tremante, 2000).

To connect the city to more inland agricultural areas, the Erie canal was dug in 1825, making New York the trading capital of the nation (New York State gov n.d.). Waterborne transportation was the predominant mean of conveyance at the beginning of the 19th century, with all the significant industries developing in proximity to the coastline. During these centuries of significant economic development, the spatial and economic transformation of the land was based on the possibilities of waterborne transportation.

During the course of the 20th century, transportation methods for industries have gradually shifted from ships to trains and trucks, making a prime waterfront location no longer essential for industrial growth. This has resulted in a decline of waterfront land value and a rapid abandonment of the industries' coastal locations. Many cities in America have known a similar significant industrial decline over the course of the 20th century (Levinson, 2006). During the ongoing industrial decline, transportation by vehicle has been rising. A combination of severe industrial decline and the construction of large infrastructures along the coastline (Caro, 1975) has largely disconnected urban life from the water, which created a stagnation in urban transformation on New York's waterfront between the 1950s and the 2000s.

While in other large American cities - like Boston and Baltimore - post-industrial waterfronts at this time were completely redeveloped into popular centers of commerce and tourism by large investments (del Rio, 2018), New York's waterfront remained in a state of limbo (Silber, 1996). Where before, the city's waterfront and its multiple forms of transportation has continuously functioned as a pioneer in urban development, innovation, and economy, 20th century New York largely developed as if it were a non-coastal city. Hosted by building vacancy, the waterfront gradually became home to artists, immigrants, homeless people, and other marginalized social groups (Cotter, 2019). At this time, "notions like personality, authenticity and spontaneity made their appearance in the domain of public life" (Sennett, 1978).

Today, in the 21st century, a new episode in waterfront development is written. The vast amount of available and rather cheap post-industrial land has provoked a renewed interest of real-estate developers, which currently defines the transformation of the waterfront of New York City. Large investment projects are replacing significant portions of the former industrial waterfront and repurpose them for (often high-end) residential and recreational land uses.

2.2. New York City's waterfront: the future

Additional to the affordability of post-industrial land and a pressing housing demand, the shift in waterfront development was partially triggered by Mayor Bloomberg's effort to reclaim the water for the city's benefit. In 2011, Bloomberg introduced his Vision 2020: Comprehensive Waterfront Plan for New York (NYCgov 2011). In this plan, he repeatedly referred to the water as New York's '*sixth borough*', and he stated that he wanted to make New York "again […] known as one of the world's premier waterfront cities" (Rovzar, 2011). In the decade after the publication of this Comprehensive Waterfront Plan, a significant change has taken place regarding waterfront development, coastal planning, and waterborne transportation. After several private ferry initiatives in the 2010s, the city's own NYC Ferry Service initiated in May 2017 to solve the waterfront's inaccessibility by public transport. The ferry is a rather affordable, luxurious, and convenient mode of transport between neighborhoods (often located in different boroughs) that were thus far separated by water.

Since the introduction of the NYC Ferry Service, connecting strategic waterfront locations, a huge impact is visible on the surrounding urban fabric. The property values in close proximity to a ferry landing rose instantly, while a trend of new recreational developments and commercial activities is visible at the newly accessible neighborhoods. The following chapters investigate the impact that is posed on the adjacent coastal urban land when waterborne public transportation is ameliorated, and if there is a causal relationship between the construction of a ferry terminal and changes in the socio-economic conditions of its surroundings.

3. NYC Ferry network

3.1. Comprehensive Citywide Ferry Study (CFS)

The New York Government (both of city and state) invests a lot of means and workforce into studies, looking at how to enhance spatial, social, economic and environmental development. Regarding transportation, studies have been conducted over the past decade on the impact of car-based transportation and parking (NYCplanning 2013), bus rapid transit (NYC Department of Transportation 2013), light and heavy rail transit (Hochul, 2022) (on New York State level), transit accessibility (NYCplanning 2021), and mobility in general (NYC Department of Transportation 2018). Regarding the recent increase in coastal developments, several studies are done regarding resilient architecture and adaptive strategies in flood areas (NYCplanning 2013) and studies on coastal climate resiliency (NYCEDC and NYC Mayor's Office of Resiliency 2019). But additionally, in terms of waterborne transportation the city has invested in feasibility studies, since increased coastal accessibility is indispensable in light of the contemporary high-end waterfront investment plans. In 2011, the New York City Economic Development Corporation (NYCEDC) introduced the Comprehensive Citywide Ferry Study (CFS2011) (Berry et al., 2011), a feasibility study for the implementation of ferry services throughout New York. The study consisted of the analysis of areas eligible for a ferry landing, focusing on their demographics, workforce, commute and water conditions, and suggested possible ferry routes and predicted their impact on the selected areas. This study highlighted that introducing waterborne transportation between the boroughs would lower fuel consumption and congestion rates, meaning reductions in both travel time and cost for commuters, an expansion of the labor market, and less traffic accidents.

With the publication of the 2011 Comprehensive Citywide Ferry Study, the already operative East River Ferry (Fig. 1) – operated by NY Waterway - was analyzed, looking into its popularity and its effect on the neighborhoods surrounding its ferry stops. The East River Ferry makes a loop between Manhattan, upper Brooklyn and Queens, with stops at Wall Street/Pier 11, Dumbo, South Williamsburg, North Williamsburg, Green Point, Hunters Point and East 34th street. This early project of the ferry as an alternative mode of transportation and commuting proved to be a success during the first years of its operation. To respond to this positive result, the NYCEDC had a team of experts update the study in 2013 (CFS2013, 2013) (Berry et al., 2013) to anticipate a future expansion of the ferry network. In the report of the Comprehensive Citywide Ferry Study of 2013, the remaining eligible sites of the CFS2011 are compared with the average results of the stops on the East River Ferry route during its operation over the preceding two years. The CFS2013 report starts with an illustration of the socio-economic impact of the East River Ferry between 2011 and 2013, highlighting its success.

Since the introduction of the East River Ferry, property values within 1.6 kilometers (1 mile) of a ferry landing increased with an average of 1.2%; while property values within 200 meters ($1/8^{th}$ of a mile) of a ferry landing increased with a whopping average of 8%. In 2013, a total increase of 0.5 billion dollar of residential property value could be noted within a 200-meter radius of the seven East River Ferry stops. Additional to the rise in property value, a remarkable growth in residential and commercial building surface was established. Within a 400-meter radius ($1/4^{th}$ of a mile) of a ferry terminal, the surface of residential floorspace increased with an average of 7%. Also, the surface of retail space within that same radius increased by 4.2% between 2011 and 2013 (Berry et al., 2013). This outcome of both increased property value and the development of new projects and land uses convinced the city government to initiate more ferry routes, the first of which have been opened in May 2017.

After the pilot project of the East River Route, a second important route is the South Brooklyn Route. Implemented in 2017 as a first extension of the pilot project, this new route connects Wall Street to five additional stops to its south, all located in Brooklyn. The first stop after Wall Street is the landing in Dumbo, followed by Pier 6, Red Hook, Sunset Park, and Bay Ridge. The stops were selected following the recommendations of the 2013 Comprehensive Citywide Ferry Study.

The next two paragraphs illustrate the two stops on the South Brooklyn Route after Dumbo: The Pier 6 and Red Hook terminals. Although these two stops are on the same route, they exist of very different conditions, which allows to contrast different spatial, social and economic notions. To investigate whether a ferry terminal indeed triggers socio-economic growth, a comparison is made between Pier 6 and Red Hook's initial analyses in the CFS2013 report, and their actual impact on the surrounding urban environment after implementation.

3.2. Pier 6/Atlantic stop, Brooklyn

Following the predictions of the CFS2013 report, terminal BBP Pier 6/Atlantic (nowadays named Atlantic Avenue) became a permanent ferry stop on the South Brooklyn Route (Fig. 2). On this route, Pier 6 is located between Dumbo to its north (which is also part of the East River Route) and Red Hook/Atlantic Basin to its south.

The CFS2013 report highlighted that, in terms of demographics at that time, the direct environment of Pier 6 was already home to an extremely wealthy population. In the decade between 2000 and 2010, the annual median income doubled to $128.405 per household, compared to the average of $51.270 for all of New York City. A clear shift is also visible in ethnicity of the inhabitants. In 2000, people living in Brooklyn Heights (the neighborhood adjacent to the ferry landing) were predominantly Black (41.8%), compared to 31.1% White people. In 2020, however, the percentage of Black inhabitants has decreased to 20.3%, compared to 52.1% of White inhabitants (NYU Furman Center 2019). With almost no unemployment in 2010, the area around Pier 6 is a most valuable neighborhood for New York's economy and welfare. The 6.348 people who commute to Manhattan on a daily basis, might seem to indicate a large number of potential users for a ferry service. However, public transportation by subway and bus was already well-established in the area before the arrival of the ferry, providing commuting times that barely exceed traveling by car. Moreover, commutes to Manhattan by ferry add three to eight minutes to the journey, compared to traveling by bus or subway.

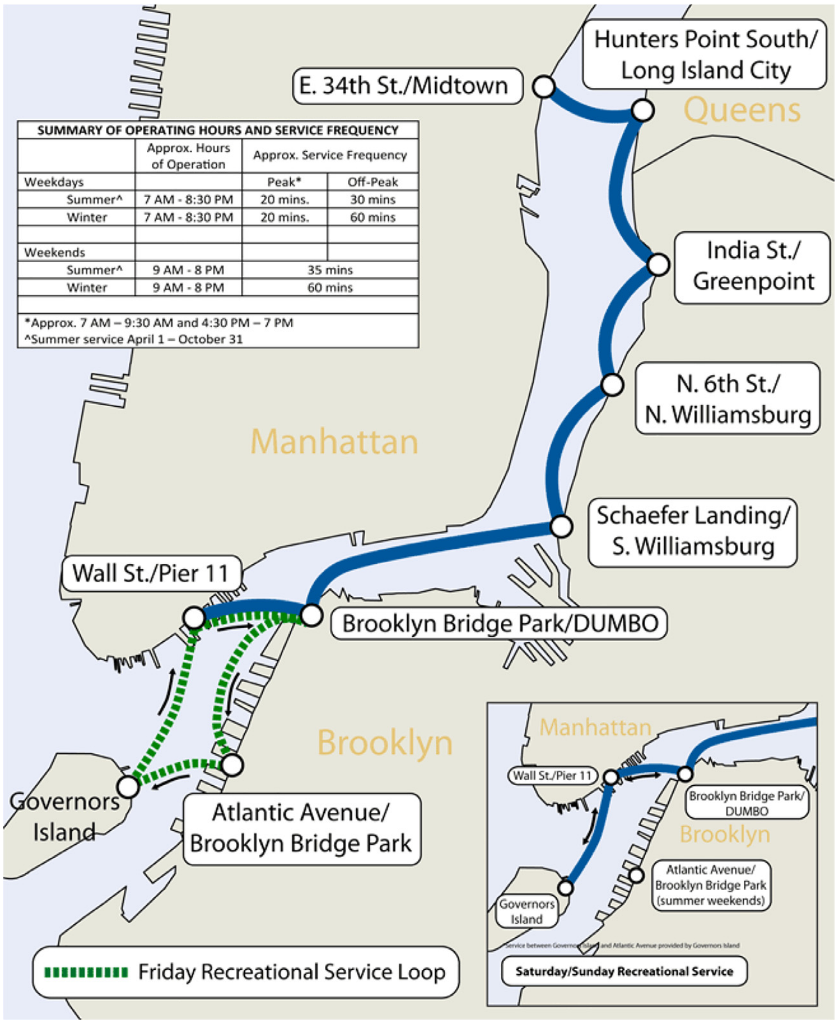

Figure 1. 2011 East River Route, operated by NY Waterway and studied in the CFS2013.
Source: Image courtesy of NY Waterway (NYWaterway.com).

Figure 2. (left): South Brooklyn Route as initiated in May 2017.
(right): South Brooklyn Route as operative in July 2022.
Source: NYC EDC (website: www.nycedc.com/nyc-ferry-south-brooklyn-route).

Figure 3. The Piers of Brooklyn Bridge Park (Pier 6 Ferry Terminal at the bottom of the image).
Source (web): www.moso-studio.com.
Source (web): www.moso-studio.com.

When the first route, the East River Ferry Route, was initiated in 2011, a stop was already implemented at Pier 6, named the Atlantic Avenue/Brooklyn Bridge Park Ferry Terminal. However, the Atlantic Avenue Terminal only operated in summer weekends as a recreational stop, providing a connection between Manhattan and Brooklyn Bridge Park. As part of the East River Ferry Route, the terminal at Pier 6 aimed to attract an inflow of people from other neighborhoods for leisure and recreational purposes, instead of an outflow of commuters. In other words, the main initial stakeholders for this ferry stop were tourists and visitors, not local inhabitants.

This becomes visible in the actual landing's spatial implementation: the terminal mainly focuses on the redeveloped recreational and commercial facilities at Brooklyn Bridge Park at its north (Fig. 3). After the redevelopment of Pier 1 and Pier 6 for recreation in 2010, Brooklyn Bridge Park gradually expanded over the following years, adding Pier 2 (2014), Pier 5 (2017) and Pier 3 (2018) to the park. Since 2017, the large recreational stretch of waterfront is bordered on both north and south side by a ferry terminal. Before entering the Pier 6 ferry terminal from the mainland, you are obliged to cross a section of the Brooklyn Bridge Park. The design of the public space directly adjacent to the landing is in function of the ferry. The added benches and commercial facilities anticipate the waiting time for travelers and provide a pleasant experience.

Based on Walker's conditions for a successful ferry network (Walker, 2012), the Pier 6 terminal answers to all of the local elements that are required. It is operated at a high frequency, is located in a very high density neighborhood, has other forms of public transport within walking distance, has limited competition of car accessibility, and navigates over a direct path to the favorable ferry terminal in lower Manhattan.

Comparing the statistics of average daily riderships in the third quarter of 2017 (NYC Ferry 2017) (start of operation) and 2019 (NYC Ferry 2019) (last year before Covid-19), we see that the stop is somewhat increasing in popularity, with a daily average of 322 riders in 2017 and 429 riders in 2019. In both years, weekend days have between 51% and 54% more travelers than weekdays, which can be explained by its recreational intent.

During the decade after the initial 2011 Comprehensive Citywide Ferry Study, annual median household income in the area around Pier 6 has risen even further. The rent prices in the neighborhood have increased more intensively than in the rest of Brooklyn, going from an average of $1600/month in 2011, to $2260/month in 2020 (NYU Furman Center 2019). Community and action groups in Cobble Hill, one of the neighborhoods next to the Pier 6 landing, were already fighting the construction of high-rise residential towers to counter ongoing gentrification and obstruction of views and greenery before the ferry terminal became a permanent part of the South Brooklyn Route (Gould and Lewis, 2016). Since the local property values were already exceeding New York's average before the introduction of the ferry, and other means of public transit in the area are excellent; the ferry has most likely not been the cause of a drastic socio-economic shift in the area. However, the ferry terminal makes the southern part of the Brooklyn Bridge Park more accessible for travelers from Manhattan and South Brooklyn, generating a larger inflow of visitors for recreational purposes, which might contribute to a further increase in revenue of tourism. But since these were ongoing processes, we cannot assume a clear causal relationship between the implementation of the ferry terminal at Pier 6 and the area's clear process of gentrification and social displacement.

3.3. Red Hook stop, Brooklyn

Compared to the Pier 6 landing, Red Hook has a different logic. Both in the CFS2011 and in the CFS2013, the area of Red Hook in South Brooklyn has been investigated as a potential site for a ferry landing. On first sight, the statistics of the CFS2013 report do not clearly explain why Red Hook has ultimately been chosen as a preferable location for a ferry terminal. Compared to average East River Ferry landings, Red Hook only had $1/40^{th}$ of the population density within a 400-meter radius from the ferry landing (NYCplanning 2010). While the labor force and actual employment were also extremely low in Red Hook at the time: only 1 person was employed in Red Hook for every 54 people in proximity to the East River Ferry stops. Additionally, only 151 people within the 400-meter radius from Red Hook's stop were employed in Manhattan at the time of the study. Which is 11 times less compared to, for instance, South Williamsburg (a stop on the East River Ferry Route), where 1694 inhabitants commute to Manhattan on a daily basis (Berry et al., 2013). Red Hook neither has significant touristic or recreational activities. Additionally, the main attraction in Red Hook, the IKEA, has already been served by its personal ferry service to Manhattan since 2008.

Based on the available data, we can assume that Red Hook has been selected by two decisive criteria: (1) the prior increase of median household income in the neighborhood, and (2) the planned private real-estate developments in the near future.

When analyzing the median household income in Red Hook, a drastic shift is visible between 2000 and 2010. In 2000, the median annual income within a 400-meter radius around the ferry landing was $34.352 per household, a little below the average New York income of $38.293 per year. In 2010, however, the median income for the same area in Red Hook had almost doubled, reaching $74.219, far above the average for New York, which was $51.270 in that year. Especially the amount of very high incomes increased, with 5 times more families who have an annual income over $100.000. This remarkable increase suggests a recent inflow of wealthier families into Red Hook, which implies the first signs of gentrification for the neighborhood. The second factor that may have contributed to the decision of a ferry landing in Red Hook are the planned redevelopments of multiple warehouses and industrial buildings to expensive lofts and condominiums. In 2013 (at the time of the second CFS study) three large developments – located in close proximity to the ferry stop - were in the design stages and by 2017 (at the time of the implementation of the ferry landing) they were under construction. Following a population-growth in New York City of nearly 20% in 30 years (the population has increased from 7.3 million to 8.8 million inhabitants (U.S. Census Bureau n.d.)), there is more demand for housing, which partially explains the recent trend of densification of the city's waterfront in general. For the real-estate sector, a ferry to Manhattan within walking distance can increase listing prices for these condominiums. The Red Hook condominiums have eventually been sold for prices ranging between 1.5 and 4 million dollars (Elliman 2022).

These two observations - the inflow of wealthier families and a densification of the waterfront - are most likely the decisive factors for the introduction of a ferry stop in Red Hook. The ferry anticipated the growing residential and retail interest in the neighborhood and reduced the commute to the financial district of Manhattan from approximately 75 minutes by bus and subway, to 20-30 minutes by ferry (walking and waiting time included). In reality, however, 2020 statistics show that eventually, the ferry is the least used mean of transportation for Red Hookers. The car remains the most preferred mode of transport for their commutes (NYC Ferry 2020).

Since April 2006, the Atlantic Basin also functions as the Brooklyn Cruise Terminal, the sole location in New York City where large cruise ships can dock. In the CFS2013, no mention was given of the cruise terminal as a motivation for the ferry landing. However, today, the ferry has become an important mode of transportation for the cruise ships' tourists to visit Manhattan.

The spatial impact of the Red Hook ferry landing onto its direct environment is minimal. In the existing Atlantic Basin, no dredging was required and the ferry terminal is constructed as a floating dock (Fig. 4). The basin and its surroundings are an industrial waterfront zone, completely fenced from the neighboring residential area. Minimal interventions have been made to redesign the surrounding area to create a proper and pleasant waiting area, as was done at the Pier 6 terminal. The Red Hook landing is merely inserted into the existing industrial situation, without adding additional commercial facilities, restrooms, or greenery. Few seats and timetables on the floating dock are the only facilities at the terminal. A combination of temporary fences, arrows, and orange cones direct the traveler over a large concrete surface towards the ferry landing.

The limited available numbers show that between the CFS2013 report and the year 2020, the number of inhabitants in Red Hook has decreased, while the median household income has increased. This indicates a form of gentrification, displacement, and shift in demographics. However, statistics simultaneously show that the ferry is a highly underused mean of transportation for the community. Lower-income families in the Red Hook Houses (public housing of the New York City Housing Authority) are located closer to bus and subway stops, while high-income families seem to prefer cars over the ferry, since Red Hook is efficiently connected to lower Manhattan by the Hugh L. Carrey Tunnel.

In terms of Walker's conditions for a successful ferry, Red Hook only answers to the frequency in operation. In contrast, it is not surrounded by a very high density neighborhood, is not close to other means of public transportation, and it is challenged by a highway and tunnel to Manhattan nearby.

It can be assumed that in the case of Red Hook, the ferry neither triggered its ongoing gentrification. The gentrification in Red Hook was already happening in the background (by plans of redevelopment and gradual shifts in inhabitants) and is stimulated by multiple different factors. However, in contrast to the landing on Pier 6, the Red Hook terminal does not have the intention to attract external visitors into the area, but to answer to a growing demand of commuters and new types of residents.

3.4. Conditions and motives for a ferry stop

Comparing the data of the Comprehensive Citywide Ferry Studies with the actual developments of ferry routes and landings shows that the location of the first ferry terminals was mainly decided based on a high level of potential, already present on-site, preferably within a 400-meter radius. This 'potential' can have different meanings, among which: (1) a recent intensive increase in labor force and actual employment in Manhattan and Brooklyn (and therefore a high number of potential commuters), (2) a recent shift in demographics, especially with a remarkable increase of median annual household income, (3) concrete plans for redevelopment and future implementation of residential, retail, commercial, and/or recreational facilities, and (4) existing qualitative recreational and commercial facilities with current low accessibility from and to Manhattan. In the former two examples, the ferry hosts the outflow of people from the area around the terminal, for instance to commute to work. The latter two examples are strategies to improve an inflow of external visitors to increase the area's revenue and popularity. A supplementary condition for a ferry location is the technical feasibility of construction of the ferry terminal. Most of the eligible sites have available bulkheads or existing piers and sufficient water-depth. The application of a floating dock without additional dredging is highly favorable because of its cost-effectiveness.

Based on the first output of the East River Ferry (statistics of 2011-2013), the ferry as new mode of public transportation seemed highly successful. The East River Ferry Route remains the most popular and most used ferry route until this day. In 2017, the route had an average of 7.990 riders per day (third quarter, weekend days) (NYC Ferry 2017), while in 2019, this number had already risen to 13.130 people per day (NYC Ferry 2019). The South Brooklyn Ferry Route went from an average of 2.930 riders per day during the same period in 2017 to 4.289 per day in 2019. The COVID-pandemic has caused a fall in these numbers for 2020 (NYC Ferry 2020), but in 2021, a clear recovery became visible again (NYC Ferry 2021).

Based on the available information, we can state that the initial NYC Ferry Service did not mean to trigger the start of gentrification processes, yet to enhance areas that are already economically, recreationally, and/or residentially qualitative. However, currently, the NYC ferry network is still expanding, and reasonings for ferry locations vary. Ferry landings are still predominantly proposed to increase areas that are already valuable socio-economic destinations, often in an ongoing process of gentrification. However, in some cases, ferry terminals are proposed in smaller neighborhoods, with lower density and with lower-income families who do not necessarily work in Manhattan. This raises

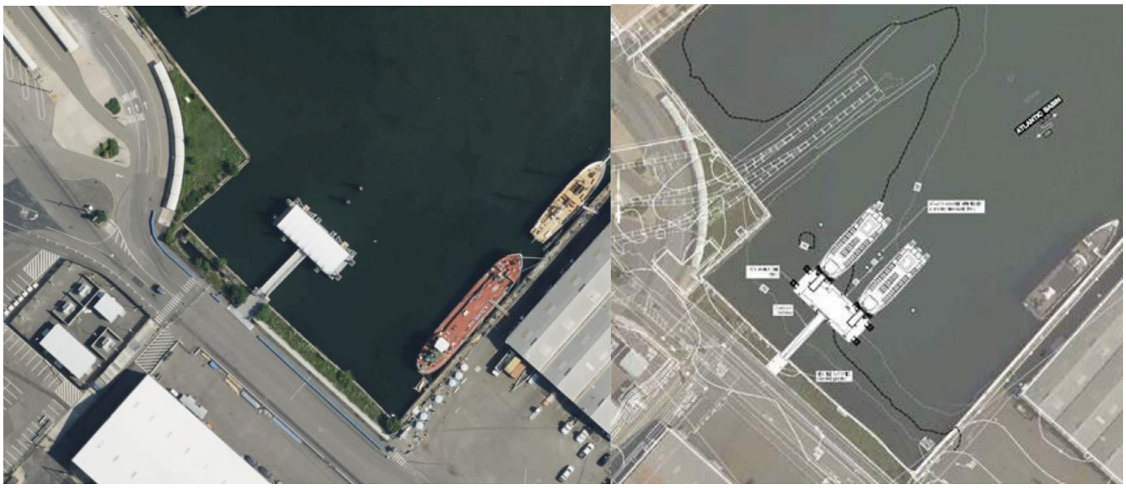

Figure 4. (left): Red Hook, Atlantic Basin landing as proposed in 2017.
(right): Red Hook, Atlantic Basin landing as operative in 2022.
Source: Image courtesy of website Bklyner (website: www.bklyner.com).

the question what will happen to more vulnerable coastal areas as the NYC Ferry Service increases their accessibility. Will the increased accessibility magnify the negative effects of imperative social displacement on the city's waterfronts? Will this generate a boom in property prices, so significant that initial inhabitants and small-scale entrepreneurs are irrevocably out-priced?

The following chapter explores a ferry landing that is planned to open in the year of writing (2022) and has been subject to a lot of backlash: the terminal at Coney Island Creek.

4. The Coney Island Creek ferry stop: A blessing or a curse?

At the time of writing (summer 2022), the New York City Ferry Service has seven operational ferry routes[a]. One additional route is – after a year of delay - planned to open late 2022: the Coney Island Route (Fig. 5). NYC Ferry writes on their website that " [t]he Coney Island route will connect communities in Coney Island and Bay Ridge to Wall Street/Pier 11" (NYCferry 2022). Although this description indicates a focus on the local communities, it is fair to assume that the real ambition is to facilitate the trip to the Coney Island Amusement Park, which the peninsula is most known for.

4.1. Coney Island: a situation

Coney Island is a peninsula in the south of Brooklyn that is famous for its amusement park, beach, and aquarium. For over a century, the entertainment business in this area has attracted millions of visitors per week. As a result, Coney Island has historically functioned as a motive to invest in innovative public transportation to carry the millions of visitors to the far south of the city.

Because of its rather remote location, the island became a vacation resort for the wealthy New Yorker during the 19^{th} and 20^{th} century. Around this time, investors and project developers constructed hotels and resorts in Coney Island to make profit out of holiday facilities. Their business-model was clearly based on the resorts' commercial value, but was simultaneously linked to the first development of railway systems. In order to make the peninsula more easily accessible for their audience, the investors were also in charge of constructing railroads and introducing a connection by steamboat ferry to Manhattan at the end of the 19^{th} century. More attractions were added on the island to stimulate more railway transportation. The destination of entertainment became a stimulation for people to use the public transport system and vice versa. At the turn of the 20^{th} century, Coney Island had the largest amusement park area of the United States. A steamboat ferry and four separate railways entered Coney Island by this time, each constructed by a different developer (Denson, 2011). However, over the course of the 20^{th} century, the amusement business lost a lot of its glamour and large portions were replaced by housing developments. Today, only part of the initial railways is still running to Coney Island and the steamboat ferry disappeared a long time ago. A trip from Manhattan easily takes 1.5 hours. That is why, in terms of accessibility, a ferry connection seems like a viable alternative to reduce the travel time to little over half an hour, and add to the experience of entertainment for the visitors.

Most of the political or investment interest for Coney Island has repeatedly focused on its entertainment business and accompanying facilities. Strengthened by the approval of the 2009 Coney Island Comprehensive Rezoning plan (NYCplanning 2009), real-estate investors regained significant interest in the surroundings of the amusement park to build high-rise residential buildings to sell for profit. The original residential neighborhoods on the Coney Island peninsula - such as the area around Coney Island Creek (Schreurs, 2022) - have been existing in the shadow of the amusement park and its surroundings. These neighborhoods suffer from high unemployment and poverty rates, are badly accessible by public transportation, and are located in vulnerable flood zones (NYU Furman Center 2019).

4.2. Coney Island Ferry Stop

The Coney Island Route has been under construction for several years. As explored earlier in this paper, locations for ferry landings that are selected in the Comprehensive Citywide Ferry Study, are often based on existing potential. In the case of Coney Island, the two main 'potentials' of the area, that might have been a reasoning behind the ferry landing, are the inflow of external people to improve accessibility to the existing commercial and recreational facilities, and to enhance future projects that are currently in the pipeline. Real-estate agents are already using the future ferry route in their public advertisements. To sell

[a] The aforementioned (1) East River Route and (2) South Brooklyn Route, the (3) Rockaway Route, connecting Manhattan with the beaches in the south of Brooklyn, the (4) Astoria Route which connects Manhattan with upper Brooklyn and Queens, the (5) Soundview Route going from Manhattan to The Bronx, the (6) St. George Route, connecting west Manhattan to Staten Island, and the (7) Governors Island Shuttle Route, a recreational weekend connection between Manhattan and Governors Island.

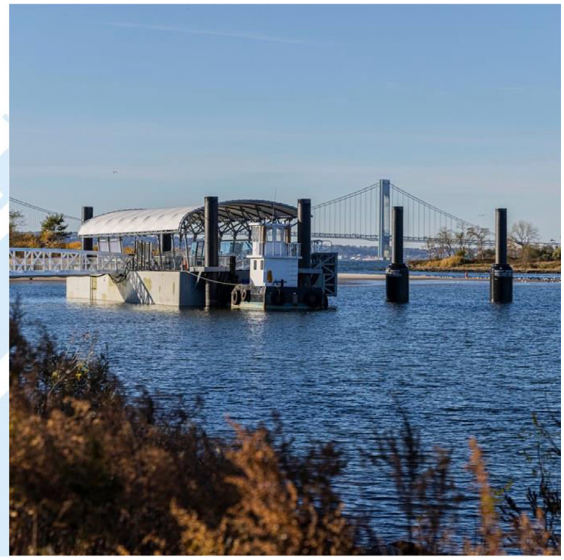

Figure 5. (left): Proposed Coney Island route by NYC Ferry.
(right): Landing constructed at Coney Island Creek.
Source: NYC Ferry (website: https://www.ferry.nyc/routes-and-schedules/route/coney-island-route)Source: Image by Hiroko Masuike for The New York Times.

their new high-end luxury apartments on Coney Island, advertisements state: "Ferry to Manhattan Coming Soon!" (Freytas-Tamura, 2021).

The other stops on the Coney Island line - Bay Ridge and Wall Street Pier 11 - are already part of other ferry routes, making Coney Island the only stop where constructions were needed to add a landing. Remarkably, the landing is constructed on Coney Island's north shore, at Coney Island Creek, and not at the popular touristic beach, boardwalk and amusement park on the south shore. In the reports of the CFS2013, both Beachside and Creekside are initially mentioned as possible locations for the ferry landing. Only the Creekside seemed a viable option, as the beach is too shallow for the ferry to dock and radical dredging was needed to construct the landing at this location. In reality, the north shore of Coney Island Creek neither proved to be a good solution. The dredging, for instance, can only take place in the latter half of the year to protect the natural habitat of winter flounder and horseshoe crabs (Parks, 2021). Additionally, toxic materials were released in the water of the Creek during dredging, infuriating local inhabitants and health organizations. In April 2022, the NYCEDC and its contractors were fined \$70.000 for violating state environmental laws while building the Coney Island ferry terminal (State of New York 2022).

4.3. Predicted socio-economic impact for the Coney Island Creek

General concerns of local inhabitants, organizations and professionals regarding the ferry being located on the Creekside, instead of on the Beachside, are mainly based on environmental arguments. They fear increased pollution of the water and a disruption of biodiversity and wildlife in the Creek.

At the same time, there is a potential social threat as well (Schreurs, 2022), since Coney Island Creek is a rather vulnerable area. The median household income (\$42,780) is 41% under the average for New York City (\$72,930), generating a poverty rate of 25.6% in Coney Island, compared to 16% citywide (NYU Furman Center 2019). The area is simultaneously vulnerable to the rising sea level and climate change, with 86.4% of its properties being at direct risk of flooding (Risk Factor, nd.). The area of Coney Island Creek has remained in the shadow of the amusement park, staying under the radar for large investments, making current gentrification and displacement minimal. This makes the area all the more vulnerable when large top-down interventions are introduced.

Constructing a ferry landing on the Creekside creates a clash between the actual location of the ferry stop and the reason behind it. The Comprehensive Citywide Ferry Study originally focused on the demographics and characteristics of the area that is located within a 400 to 800 meters radius of a landing. However, the walking distance between the Coney Island stop and the amusement park is approximately two kilometers. Compared to Walker's preconditions (Walker, 2012), the Coney Island Creek neighborhood is not of very high density and is not connected to other forms of public transportation. Coney Island is the final destination of the ferry line. Its primary goal is to increase public transport for an inflow of visitors to the popular amusement park and beach, which largely misses its target because of the far distance.

Locating the landing on the north shore of the peninsula will have important socio-economic implications for the neighborhood of Coney Island Creek. A first (minor) impact on Kaiser Park and its local users is the removal of the fishing spot and the disruption of fishing activities because of the noise and turbulence of the catamaran. The ferry will also discourage use of the water for sports and recreation. A more dominant impact will be the increased influx of people. Because of its peninsular nature, the neighborhood of Coney Island Creek only has very limited foot traffic at present. Having the landing located on the north shore and its destination on the south shore will inevitably increase the number of pedestrians in the area. The renewed inflow of visitors will likely generate a market for commercial shops, while Kaiser Park will have an increase of users as a waiting area for passengers. Since accessibility increase is one of the significant features of gentrification (Dawkins and Moeckel, 2016), a serious impact on this already vulnerable neighborhood can be assumed, influencing the prices of the local housing market. Thus far, the neighborhood of Coney Island Creek is not in a significant process of displacement or gentrification, but the increase in market value by the beneficial accessibility to Manhattan and enhanced local economic conditions will have a different impact on the inhabitants. Most of the families in Coney Island Creek are tenants: especially the families living in houses that are rented on the private market are most vulnerable to fluctuations in property prices. Interviews conducted by the author suggest that many of the inhabitants have chosen this area for its affordability. Therefore, an increase in property prices would inevitably cause social displacement. In contrast, many families live in subsidized public housing projects, several of which are located in proximity to the new ferry landing. For them, increased accessibility and pedestrian passage might be beneficial. During interviews, inhabitants of these housing projects often complained about poor mobility, especially concerning the distance to public transportation and their connection to Manhattan. The ferry connection might eliminate these obstacles for them. Additionally, the external maintenance of the public space around the ferry stop will enhance their living conditions without the risk of displacement, since NYCHA[b] houses are rent-stable subsidized housing. For the smaller local businesses, increase in property value is less beneficial. At the moment, businesses around Coney Island Creek are mainly car-oriented, since vehicular accessibility is very high in the area, because of the direct connection to the Belt Parkway. However, residential buildings are of higher value than buildings for manufacturing or industry, meaning an imminent risk to shift a building's land use when the interest in the housing market of Coney Island Creek increases.

The ferry landing at Coney Island Creek has a goal of serving an inflow of visitors to the large amusement park and enhancing the overall accessibility of the remote peninsula. The area of Coney Island Creek is already threatened by multiple other factors, including pollution, flood risks, low education and unemployment. The ferry will, to soms extend, serve the local inhabitants by increasing the accessibility to Manhattan. But by introducting the Manhattan - Bay Ridge - Coney Island ferry line into this low-income neighborhood, it will mostly threaten the stakeholders with a significant inflow of new visitors, in combination with an already emerging investment interests because of a pressing housing demand in the city. The shift from predominantly car-based traffic to public transportation can trigger an increased external interest for the area, both in terms of recreation, as in terms of investment.

5. Conclusions

Studying the initial predictions for the ferry network and several cases of actual implementation of ferry stops in neighborhoods indicates that a ferry connection is not an unequivocal strategy. In the Comprehensive Citywide Ferry Study report of 2011, the initial East River Ferry route is considered a success story, based on the economic growth and increase in income of the neighborhoods adjacent to the terminals in the first operative years of the ferry. In reality, when studying the CFS2013 and the actual implementation of extra ferry lines, it becomes clear that locations for the terminals are largely selected based on the neighborhood's ongoing process of gentrification, a high existing interest for investment, local recreational and touristic qualities, or for redevelopment projects that are already in the pipeline. Therefore, it is questionable if the ferry is indeed the trigger of new socio-economic growth, or the consequence of anticipated growth.

During the past decades, New York City's waterfront has been rapidly redeveloping because of a growing interest in repurposing its post-industrial land for residential or recreational uses. Often, these projects are public-private partnerships, with large financial investments from the private sector. The issue that many of these new waterfront projects struggle with, is their generally low accessibility by public transportation. Because of their former industrial land-use, coastline neighborhoods are mainly accessible by boat and vehicle. Public transportation such as subway lines often do not reach coastal areas. As a result, the contemporary redevelopments of these neighborhoods have largely been dependent on buses and cars. However, following the city's plans to connect its five boroughs over water, the NYC ferry service has gradually been implemented in New York, increasing the accessibility of these coastal areas drastically.

Even though many of the neighborhoods around ferry landings are undergoing a process of gentrification, this is almost never triggered by a sole element. It is argued that increased accessibility is the main feature of gentrification (Dawkins and Moeckel, 2016), but it is most likely a combination of different elements that causes the socio-economic growth in waterfront neighborhoods in New York, since the ferry remains a rather slow and infrequent form of public transport. By the implementation of the ferry, these already desired locations are additionally enhanced in terms of accessibility, and therefore also in terms of property value and amount of residential and commercial building surface. Based on the criteria for selecting these initial locations for ferry stops, a causal relationship between the arrival of a ferry and gentrification cannot be simply claimed. Even if the ferry landings were not introduced in these areas, redevelopment and enhancement of these post-industrial waterfronts would likely have taken place.

At Coney Island Creek, the first large-scale real-estate developments are already popping up. The gentrification that will arise in this area will be triggered by a combinations of this increase in interest by project developers, the affordability and availability of the land in this remote area, the potentials of a location close to the beach, and the prospects of increased accessibility by a ferry service.

However, based on the study of actual implementation of ferry locations, and further expansion of the ferry network, it becomes clear that a landing generates different effects within different contexts, regardless of the initial reason for implementation. At Pier 6, the aim was to increase public transportation to a site, already qualitative in terms of tourism and recreation, a strategy that is applied in numerous other ferry locations as well (e.g. Dumbo, South Williamsburg, and Long Island City). At Red Hook, the strategy was to answer to the ongoing process of local redevelopment and gentrification. At Coney Island, the ferry is introduced to serve the already popular destination area of the amusement park. The decision to locate the ferry landing on the Creekside of Coney Island is circumstantial, based on technical matters, yet the impact on the local conditions will be significantly more drastic than when the terminal would be located on the beachside. While the other observed neighborhoods with ferry stops were already undergoing a strong process of gentrification, the area of Coney Island Creek is only in the primal stages of a growing development interest. A ferry connections will potentially magnify the effect and increase the pace of redevelopment in the area.

The ferry service in New York started with connecting high potential areas over water. The network answered to all conditions that are needed to make it a success story according to Walker, providing terminals at very high density neighborhoods, serving badly accessible post-industrial sites, connecting to the local subway network, with terminals located in strategic locations, mainly at popular destinations in Manhattan and Brooklyn.

In the meantime, the success of the ferry as a pleasant, luxurious, and efficient mode of public transport is clear, and the network is expanding rapidly. This time, however, terminals do not limit to places with high potential or tourist attractions. Smaller or lower-income neighborhoods are included in the ferry's network, which brings along some issues. Not all coasts are suited to host a ferry landing, as they require dredging or significant structural interventions. Dredging the soil at the bottom of the water of post-industrial areas risks the surfacing of industrial pollution. Additionally, the ferry's operating hours are limited to the daytime, making alternative modes of public transportation still necessary. A ferry can have a siginifcant effect by speading up processes of gentrification, changing the socio-economic configuration of a neighborhood.

Because of their historic industrial importance, waterfronts of coastal cities worldwide have often developed with waterborne traffic as an important factor. This translates into waterfronts with piers, bulkheads, and sufficient water depth. In light of the industrial decline of the past decades, a new identity is needed for many metropolitan coastal neighborhoods. Because of densification and city growth, these rather affordable locations are often used for building residential towers or waterfront public parks. The core issue with these new developments is their accessibility. In a city like New York, subway lines do often not reach the coastline. A ferry service is a popular new mode of transportation to make these neighborhoods more easily accessible to the public. In the wake of cities' industrial decline, many post-industrial waterfronts

[b] *NYCHA: New York City Housing Authority*.

(often considered less desirable) have gradually been claimed by lower-income families and small businesses. When these neighborhoods are made more accessible, they fear to become more desired. In that case, what starts as an added value to already popular coastal areas, can turn into a trigger of gentrification for lower income neighborhoods.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The Pedestrian Network Concept: A Systematic Literature Review

Mona Jabbari[a,c,*], Fernando Fonseca[b], Göran Smith[a,g], Elisa Conticelli[d], Simona Tondelli[d], Paulo Ribeiro[b], Zahra Ahmadi[e], George Papageorgiou[f], Rui Ramos[b]

[a] Mobility and Systems, RISE Research Institutes of Sweden, 417 56 Gothenburg, Sweden
[b] Centre for Territory, Environment and Construction (CTAC), University of Minho, 4800-058 Guimarães, Portugal
[c] CitUpia AB, 104 30 Stockholm, Sweden
[d] Department of Architecture, Alma Mater Studiorum – University of Bologna, 40136 Bologna, Italy
[e] Department of Business Administration, Faculty of Education and Business Studies, University of Gävle, 801 76 Gävle, Sweden
[f] Department of Management and Marketing, SYSTEMA Research Centre, European University Cyprus, 2404 Nicosia, Cyprus
[g] Institute of Transport and Logistics Studies, University of Sydney Business School, NSW 2000 Sydney, Australia

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ABSTRACT

The design of urban spaces that foster sustainable practices requires new analytical and structural approaches to spatial planning. An appropriate pedestrian network could significantly contribute to sustainable urban development goals, particularly by promoting sustainable mobility and pedestrian friendliness. With such goals, several attempts have been made to develop suitable models for pedestrian networks. However, something that is missing from the current literature is a framework that incorporates the main findings of the various studies as an integrated concise concept of the pedestrian network. To address this knowledge gap, this paper reviews studies on pedestrian networks and evaluates this concept based on the systematic 3W1H analysis method, which asks where, what, who, and how. In essence, the following questions are thus analyzed: Where is the pedestrian network located, What criteria play a role in the pedestrian network's performance, Who uses the pedestrian network, and How can the pedestrian network be analyzed? In this context, a systematic literature review is carried out by investigating studies conducted during the period 2001 to 2023 that appear in the Scopus database. The paper presents the results of the review of a selection of 67 papers dealing with pedestrian networks. Findings show that different models have been developed based on particular characteristics. Overall, researchers aimed to identify the most suitable network based on specific criteria for optimizing the walking experience in urban areas. By synthesizing the findings reported in these papers, this paper arguably contributes to a more comprehensive understanding of pedestrian networks, provides insights into the prioritization of design phases, facilitates the use of pedestrian network assessment models for future research, and creates a bigger picture for urban planners with a multidimensional view to a new sustainable urban structure.

1. Introduction

Walking is considered to be one of the most important non-motorized modes of transport (Jabbari, Ahmadi, & Ramos, 2022). Pedestrian mobility, or the act of traveling on foot, is indeed the oldest form of mobility. Before the invention of wheeled vehicles, animals for transportation, or even boats, humans had to rely solely on their own two feet to get from one place to another. As civilizations began to evolve, pedestrian mobility remained an important mode of transportation. Ancient Greeks, Persians, and Romans, built networks of roads and footpaths to facilitate travel by foot, and even today, some of these ancient routes are still in use (Amato, 2004; Habibi, 1996; Hodza & Butler, 2022; Lay, 1999). In many parts of the world, a pedestrian network continued to be an essential means of transportation. The primary function of the pedestrian network is to provide mobility for pedestrians, allowing them to travel from one location to another on foot. The pedestrian network in Iranian cities worked as a city skeleton and there were main urban elements and activities included the bazaar complex, school, and neighborhood centers (Farkisch, Ahmadi, & Che-Ani, 2015; Jabbari, Fonseca, & Ramos, 2021). The concept of the pedestrian network originated in 1797 when the French army occupied Venice and attempted to build a structure to connect the island groups by waterways (Vivo, 2016). They worked to transform the amphibious city into a homogeneous pedestrian network by creating canals, building bridges, and creating paths. De Vivo (2016) believes that walking was a daily habit and formed the pedestrian network in sixteenth-century Venice.

* Corresponding author.
E-mail address: mona.jabbari@civil.uminho.pt (M. Jabbari).

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Despite being replaced by faster modes of transport for longer journeys, walking continues to be an essential means of transportation for shorter trips, and for changing between modes. The Personal, social, economic, and environmental benefits of walking are well documented: Walking reduces traffic congestion, air pollution, and noise; it is beneficial for individual health and well-being; it provides economic benefits; it affects property prices; and it improves the sociability and vitality of urban spaces (Bahrainy & Khosravi, 2013; H.-Y. Chan, Xu, Chen, & Liu, 2022; Kim, Park, & Lee, 2014; P. Zhao & Li, 2017). For these reasons, the promotion of walking and walkability has become a focus of various urban policies, especially since the rise of the green mobility debate. Green mobility has gained popularity in recent years due to growing concerns about the impact of transportation on the environment, climate change, and the public health issues associated with air pollution. Green mobility represents a shift towards more sustainable modes of transportation (Delso, Martín, Ortega, & Van De Weghe, 2019; Pamucar et al., 2022; Zamparini, Domènech, Miravet, & Gutiérrez, 2022). In addition, the COVID-19 pandemic has highlighted the importance of pedestrian networks in creating safe and healthy cities. In many cities around the world, there has been a shift toward prioritizing pedestrian infrastructure in response to the pandemic (Sainz-Santamaria et al., 2023).

Accordingly, the quality of the pedestrian network is arguably one of the most important parameters for sustainable urban development and sustainable mobility (Forsyth, Oakes, Lee, & Schmitz, 2009; Lilasathapornkit, Rey, Liu, & Saberi, 2022). A pedestrian network can be understood as a structure within an urban space, which consists of interconnected streets with elements of accessibility and connectivity (Fonseca, Fernandes, & Ramos, 2022; Gaglione, Cottrill, & Gargiulo, 2021; Jabbari et al., 2021; Pearce, Matsunaka, & Oba, 2021). More recently, two well-known pedestrian network projects were implemented in Hong Kong and Toronto. In Hong Kong, the at-grade pedestrian network was created in the 1970s, linking the different outdoor and indoor pedestrian areas into a continuous experience of movement and creating a collective urban identity (Z. Tan & Q.L. Xue, 2014; Z. Tan & Xue, 2015; Zhou, Zhang, & Jf Chiaradia, 2022). Toronto's pedestrian network is a largely underground downtown pedestrian network that spans more than 30 kms of restaurants, shopping, services, and entertainment and opened in 1987 (Bélanger, 2007; Cui, 2021).

Despite the many opportunities to study and implement pedestrian networks, there is limited research, both on technical and practical application issues (Kelly, Tight, Hodgson, & Page, 2011). Much of the work on pedestrian networks has been presented in processes that involve multiple stages with few components that did not consider a unit structure (Gaglione et al., 2021; Mitchell & MacGregor Smith, 2001; Xue X. Yang, Stewart, Fang, & Tang, 2022). To overcome this weakness, Hall and Ram (2018) pioneered the simplification of pedestrian network models using the well-documented Walk Score measure. However, it focused only on individual and independent variables of walking and not on the correlation of these variables in the context of urban planning. The literature review showed that the current models are complex, they are still not very application-oriented, they may be too articulate for urban planning, and they maybe not consider the pedestrian network assessment as an urban structure.

To address these knowledge gaps, the aim of this study is to review and synthesize the extant knowledge on pedestrian networks. To do this, the paper take stock of papers published on PNs between 2001 and 2023 and utilizes the 3W1H method (Malik, Chandra, Rao, & Arora, 2020) to analyze these. As such, it analyzes *where* (W) is the pedestrian network located?, *what* (W) criteria play a role in the pedestrian network's performance?, *who*(W) uses the pedestrian network? and *how*(H) can the pedestrian network be analyzed?

The rest of this paper is structured as follows. After explaining the applied method in Section 2, Section 3 outlines the results from the literature review. The discussion, including a conceptual model that arguably contributes to a more comprehensive understanding of PNs, is then presented in Section 4. Lastly, a few concluding remarks are provided in the fifth and final section.

2. Method

The aim of this study is to review the current pedestrian network models and simplify their processes and components in the context of urban planning using the 3W1H method. This method is a rational thought process and a well-documented method for decision-making (Chi, Lin, & Liu, 2008; Jagarajan et al., 2017; Malik et al., 2020; Y. Tan, Liu, Zhang, Shuai, & Shen, 2018), which has previously been successfully applied in other cases (Jagarajan et al., 2017; Y. Tan et al., 2018; J. Zhao, Sun, & Webster, 2020).The information processed by the 3W1H method identifies the relationship between the purpose and the components of a given model. The method includes three main questions: where, what, who, and how? The method provides a complete perspective for the construction of the assessment model. It consists of a set of concepts, relationships and their scope (Johannessen, Flak, & Sæbø, 2012).

Studying pedestrian networks involves a reflection on the theoretical and practical implications of the concept. This systematic literature review follows a four-step procedure that corresponds to the methodological approach used by Motomura et al. (2022), which is illustrated in Fig. 2. First, in step 1, the so-called identification step, the sources and procedures for the literature search are determined on the basis of the Scopus database. It focused on papers published since 2001 that appeared in the Scopus database. All studies are recent, with one-third of the total papers (24 out of 67) published since 2020. Step 2 is then to define the scope, which includes the objectives and a review protocol for the systematic review. The process consists in searching the expression "pedestrian network" in articles published in journals with more than four occurrences in the title, abstract, text, and keywords. This ensures that "pedestrian network" is a relevant expression used in the searched papers. The following step 3 is about the eligibility and identification of concepts through a focused synthesis of the results according to the 3W1H method. Finally, Step 4 is the evaluation and includes a comprehensive summary of the main processes and components in theory and practice in terms of where, what, who, and how to influence the process of the pedestrian network.

3. Results

According to the described literature review method, 67 papers containing the expression "pedestrian network" were identified (Table 1). From these, 28% are within the scientific field of mathematics, 47% are related with urban planning, and 26% with remote sensing. The majority of these papers come from Asian research centers (Diagram 1). They include mathematical approaches that focus on developing algorithms to automatically identify the geometry of pedestrian routes; urban planning approaches that often focus on identifying and assessing the capacity of urban space for pedestrians including by conducting surveys to target groups; remote sensing approaches, on the other hand, typically focus on tracking the pedestrian environment using high quality imagery by satellite imagery and open data sources to identify patterns of pedestrian behavior.

Based on 677 papers found in the Scopus databases, 31 papers related to urban planning are considered in order to analyze more (Abass & Tucker, 2018; Arroyo, Mars, & T., 2018; Azad, Abdelqader, Taboada, & Cherry, 2021; D'Orso & Migliore, 2020; Delso, Martín, & Ortega, 2018; Fonseca et al., 2020; Garip, Þalgamcýoðlu, & Cimþit Koþ, 2015; Q. Guo, Xu, Pei, Wong, & Yao, 2017; Hajrasouliha & Yin, 2015; J. He et al., 2016; Jabbari et al., 2022 M. Jabbari, Fonseca, & Ramos, 2018; Kwon, Kim, & Lee, 2017; Lunecke & Mora, 2018; Oswald Beiler, McGoff, & McLaughlin, 2017; Özbil, Yeþiltepe, & Argýn, 2015; Pearce et al., 2021; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014; Z. Tan & Xue, 2015; Ujang, 2016; X. Yang, Sun, Huang, & Fang, 2022; Zhou et al., 2022). This paper seeks to answer the following questions: (1) Where is the

Table 1
References and topics of the references containing pedestrian network on Scopus database.

	Authors	Approach	Purpose	Local
1	Zhou et al. (2022)	Urban planning	Estimating wider economic impacts of transport infrastructure Investment: Evidence from accessibility disparity in Hong Kong	Hong Kong
2	Łaszkiewicz et al. (2022)	Mathematical	Valuing access to urban greenspace using non-linear distance decay in hedonic property pricing	Poland
3	Gaglione et al. (2022)	Urban planning	Where can the elderly walk? A spatial multi-criteria method to increase urban pedestrian accessibility	Italy
4	H.-Y. Chan et al. (2022)	Mathematical	Impacts of the walking environment on mode and departure time shifts in response to travel time change: Case study in the multi-layered Hong Kong metropolis	Hong Kong
5	Fonseca et al. (2022)	Urban planning	Walkable Cities: Using the Smart Pedestrian Net Method for Evaluating a Pedestrian Network in Guimarães, Portugal	Portugal
6	X. Yang et al. (2022)	Urban planning	A Framework of Community Pedestrian Network Design Based on Urban Network Analysis	China
7	H.-Y. Chan et al. (2022)	Urban planning	Pedestrian route choice with respect to new lift-only entrances to underground space: Case study of a metro station area in hilly terrain in Hong Kong	Hong Kong
8	Jabbari et al. (2022)	Urban planning	Defining a Digital System for the Pedestrian Network as a Conceptual Implementation Framework	Sweden
9	Gholami, Torreggiani, Tassinari, and Barbaresi (2022)	Remote sensing	Developing a 3D City Digital Twin: Enhancing Walkability through a Green Pedestrian Network (GPN) in the City of Imola, Italy	Italy
10	X. Yang et al. (2022)	Remote sensing	Attributing pedestrian networks with semantic information based on multi-source spatial data	China
11	Azad et al. (2021)	Urban planning	Walk-to-transit demand estimation methods applied at the parcel level to improve pedestrian infrastructure investment	USA
12	Gaglione et al. (2021)	Urban planning	Urban services, pedestrian networks and behaviors to measure elderly accessibility	Italy
13	Cui (2021)	Urban planning	Building three-dimensional pedestrian networks in cities	Australia
14	Georgiou, Skoufas, and Basbas (2021)	Urban planning	Perceived pedestrian level of service in an urban central network: The case of a medium size Greek city	Greece
15	Carroll, Caulfield, and Ahern (2021)	Mathematical	Appraising an incentive only approach to encourage a sustainable reduction in private car trips in Dublin, Ireland	Ireland
16	Moustaid and Flötteröd (2021)	Mathematical	Macroscopic model of multidirectional pedestrian network flows	Sweden
17	Pearce et al. (2021)	Urban planning	Comparing accessibility & connectivity metrics derived from dedicated pedestrian networks and street networks in the context of Asian cities	Japan
18	Zhao et al. (2020)	Remote sensing	Walkability scoring: Why and how does a three-dimensional pedestrian network matter?	Hong Kong
19	Yang et al. (2020)	Remote sensing	Pedestrian network generation based on crowdsourced tracking data	China
20	Vo, Qian, Lam, and Sumalee (2020)	Remote sensing	Modeling joint activity-travel patterns in pedestrian networks with use of Wi-Fi data	Hong Kong
21	D'Orso and Migliore (2020)	Urban planning	A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments	Italy
22	Zuo et al. (2020)	Urban planning	First-and-last mile solution via bicycling to improving transit accessibility and advancing transportation equity	USA
23	Fonseca et al. (2020)	Urban planning	Smart Pedestrian Network: An Integrated Conceptual Model for Improving Walkability	Portugal
24	Sun, Wallace, and Webster (2020)	mathematical	unraveling the impact of street network structure and gated community layout in development-oriented transit design	Hong Kong
25	Higgins (2019)	Mathematical	A 4D spatio-temporal approach to modeling land value uplift from rapid transit in high density and topographically-rich cities	Hong Kong
26	Bhattacharjee, Roy, and Das Bit (2019)	Remote sensing	Constructing digital pedestrian maps of the disaster affected areas	India
27	Lesani and Miranda-Moreno (2019)	Remote sensing	To estimate travel times (speeds), to classify bicycle-pedestrian WiFi signals, and to extrapolate pedestrian MAC counts.	Canada
28	Itu, Cerbu, and Galatanu (2019)	Remote sensing	Modeling and Testing of the Sandwich Composite Manhole Cover Designed for Pedestrian Networks	Romania
29	Oyama and Hato (2018)	Remote sensing	To estimate the route choice parameters with the fewer personal approach	Switzerland
30	M. Jabbari et al. (2018)	Urban planning	Integrated approach to assess a pedestrian network by combining multi-criteria and space syntax.	Portugal
31	Delso et al. (2018)	Urban planning	To provide a procedure to evaluate the impact of obstacles to pedestrian mobility and walkability	Spain
32	Lunecke and Mora (2018)	Urban planning	Understanding the impact of downtown Santiago's three-scale pedestrian network on walkability	USA
33	He et al. (2018)	Urban planning	To explore the influences of various morphological features of non-uniform and orthogonal breezeway networks on pedestrian ventilation in high-density urban environments under Singapore's climatic conditions.	Singapore
34	Arroyo et al. (2018)	Urban planning	To identify factors that influence the decision to walk and cycle.	Spain
35	Yao, Wang, Fang, and Wu (2018)	Remote sensing	To identify Vehicle-Pedestrian Collision Hotspots at the Micro-Level	China
36	Hoogendoorn, Daamen, Knoop, Steenbakkers, and Sarvi (2018)	Mathematical	To analyze relations between density network and speed pedestrian	Netherlands
37	Jung and Hong (2017)	Remote sensing	Guiding network for pedestrian detection	Korea
38	Zhu, Liao, Lei, and Li (2017)	Remote sensing	To predict multiple attributes together in a unified framework	China

(continued on next page)

Table 1 (*continued*)

	Authors	Approach	Purpose	Local
39	Osama and Sayed (2017)	Mathematical	To assess the impact of network connectivity, directness, and topography on pedestrian safety	Canada
40	Ki-Ho and Kang (2017)	Remote sensing	Aggregating Channel Features (ACF) and rich Deep Convolutional Neural Network (DCNN) features for efficient and effective pedestrian detection in complex scenes	China
41	Hänseler, Lam, Bierlaire, Lederrey, and Nikolić (2017)	Mathematical	To describe this interaction, a stream-based pedestrian fundamental diagram	China
42	Guo et al. (2017)	Urban planning	Focused on the role of different road network patterns on the occurrence of crashes involving pedestrians.	China
43	Kwon et al. (2017)	Urban planning	Locating Automated External Defibrillators in a Complicated Urban Environment Considering a Pedestrian-Accessible Network that Focuses on Out-of-Hospital Cardiac Arrests	Korea
44	Zheng and Elefteriadou (2017)	Mathematical	Estimating pedestrian delay at unsignalized intersections in urban networks	USA
45	Oswald Beiler et al. (2017)	Urban planning	Trail network accessibility: Analyzing collector pathways to support pedestrian and cycling mobility	USA
46	Qu and Lim (2016)	Mathematical	Detecting pedestrian using neural network with a weighted fuzzy membership function	South Korea
47	Ujang (2016)	Urban planning	Studying tourists' expectations on the spatial characteristics of walkways in terms of accessibility, connectivity and continuity	Malaysia
48	Xin and Wu (2016)	Mathematical	To improve traffic safety and protect pedestrians	China
49	Dai and Jaworski (2016)	Remote sensing	Investigating the influence of built environment on pedestrian crashes	USA
50	Roshandeh, Li, Zhang, Levinson, and Lu (2016)	Remote sensing	Simultaneously assess the overall impacts of vehicle & pedestrian crashes caused by signal timing optimization in dense urban street networks.	USA
51	Hong, Shankar, and Venkataraman (2016)	Remote sensing	To derive a modeling framework for characterizing the space-time exposure of pedestrians in crosswalks,	USA
52	Rashidi, Parsafard, Medal, and Li (2016)	Mathematical	To minimize the safety hazard for pedestrians and the total transportation cost of the network	USA
53	Z. Tan and Xue (2015)	Urban planning	To track the evolving concept of grade-separated pedestrian networks in Hong Kong, revisiting the critical actions from 1965 to 1997.	Hong Kong
54	Tiplica (2015)	Mathematical	Studying the behavior of drivers interacting with pedestrians and what might be the cause of their decisions of legitimate transgressions	France
55	Yu, Ma, Lo, and Yang (2015)	Remote sensing	Optimizing mid-block pedestrian crossing network with discrete demands	China
56	Hajrasouliha and Yin (2015)	Urban planning	Investigating the impact of street network connectivity on pedestrian volume	USA
57	Garip et al. (2015)	Urban planning	Studying the influence of architectural configuration on the pedestrian network	Turkey
58	Özbil et al. (2015)	Urban planning	Understanding street-level urban design qualities and objectively measured street network configuration are related to pedestrian movement, controlling for land use	Turkey
59	Z. Tan and Q.L. Xue (2014)	Urban planning	Elevating pedestrian systems of Hong Kong in the context of planning regulation and land finance	Hong Kong
60	Zhang and Chang (2014)	Mathematical	Defining model to evacuate pedestrian–vehicle mixed-flow networks	USA
61	Raghuram Kadali, Rathi, and Perumal (2014)	Mathematical	Evaluating the pedestrian mid-block road crossing behavior using artificial neural network	India
62	Kasemsuppakorn and Karimi (2013)	Mathematical	A pedestrian network construction algorithm based on multiple GPS traces	USA
63	Tal and Handy (2012)	Urban planning	Measuring nonmotorized accessibility and connectivity in a robust pedestrian network	USA
64	Chin et al. (2008)	Urban planning	Accessibility and connectivity in physical activity studies: The impact of missing pedestrian data	Australia
65	Bélanger (2007)	Urban planning	Underground landscape: The urbanism and infrastructure of Toronto's downtown pedestrian network	Canada
66	Trépanier, Chapleau, and Allard (2002)	Mathematical	Transit Itinerary Calculation on the Web: Based on a Transit User Information System	USA
67	Mitchell and MacGregor Smith (2001)	Mathematical	Topological network design of pedestrian networks	USA

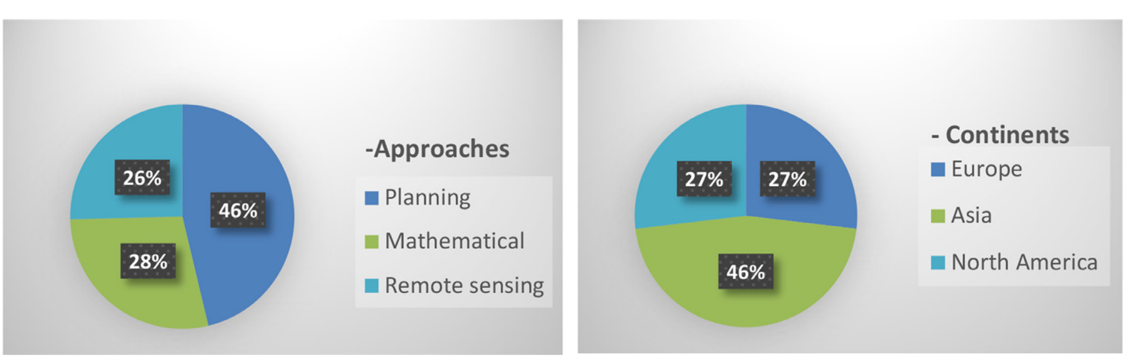

Diagram 1. Division of the papers into approaches and continents.

pedestrian network located? (2) What criteria play a role in the pedestrian network's performance? (3) Who uses the pedestrian network? and (4) How can the pedestrian network be analyzed? Fig. 2 shows the relationship between these questions based on the 3W1H method.

3.1. Where is the pedestrian network located?

The question "Where is the pedestrian network located?" identifies the place for which the model was designed at the site. In fact, the pedestrian network is closely related to the practical context in which the work is carried out. In order to understand the practical context, researchers have pursued a variety of objectives. The main objectives of this research, which addresses the concept of the pedestrian network, are: to promote social interactions at the neighborhood level; to increase urban vitality in the city center; to find the potential urban space for the pedestrian network in the city center; and to improve the conditions for visiting and promoting trade in city centers (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014).

The models analyzed different geographical scales including urban space, street network, and urban structure. As such, the research arguably included micro-scale, macro-scale, and even multi-scale approaches (J. He et al., 2016; M. Jabbari et al., 2018; Kwon et al., 2017; Lunecke & Mora, 2018; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014). Some researchers are currently using the specific scale of the pedestrian network model in the urban planning processes based on limited data (J. He et al., 2016; Tal & Handy, 2012; Z. Tan & Xue, 2015). Indeed, the pedestrian network model is applied at multiple scales based on the spatial hierarchical theory (M. Jabbari et al., 2018; Lunecke & Mora, 2018). This theory contains an integrated dataset at multiple scales and links planning, analysis and data to the hierarchical urban structure (Bereitschaft, 2018; Buckley, Stangl, & Guinn, 2017; Cheng & Masser, 2003; Girling, Zheng, Monti, & Ebneshahidi, 2019).

The COVID-19 pandemic has had a significant impact on the pedestrian network. In many cities around the world, there has been a shift towards prioritizing pedestrian infrastructure in response to the pandemic. This has been driven by the need for physical distancing and the recognition of walking as a safe and healthy mode of transportation during the pandemic to provide safe and accessible routes for people to walk from one point to another. The primary function of pedestrian infrastructure is to provide mobility for pedestrians, allowing them to travel from one location to another on foot. The pandemic has highlighted the importance of the pedestrian network in creating safe and healthy cities. The changes made to the pedestrian infrastructure during the pandemic have the potential to create lasting improvements (Sainz-Santamaria et al., 2023) and redesign pedestrian networks as main urban structure.

3.2. What criteria play a role in the pedestrian network's performance?

Pedestrian network models have a wide range of applications as they not only address physical environmental aspects but also consider some macro-level street network analyses (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014). In order to qualify and evaluate the different dimensions, this paper considers two main contexts. First, some pedestrian network models identified criteria related to the characteristics of each street suitable for walking (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014). Second, some other pedestrian network models assessed the position of the street in the network by using urban structure criteria such as connectivity, integration and distribution (Hajrasouliha & Yin, 2015; J. He et al., 2016; M. Jabbari et al., 2018; Özbil et al., 2015; Tal & Handy, 2012).

The studies on criteria related to the characteristics of streets show that they are very complex. By understanding what a pedestrian considers an attractive route, planners can build more pedestrian-friendly and liveable cities. In the beginning, it focuses on the majority criteria that most influence the definition of the street that the literature review revealed a large number of research findings and related attributes associated with walkability. The main criteria considered can be divided into four groups: built environment, urban function, accessibility, and natural environment.

Built environment includes several perceptual qualities that can affect the walking environment (Bahrainy & Khosravi, 2013; Garcia & Lara, 2015; Kim et al., 2014; Wey & Chiu, 2013). Some researchers have proposed six sub-criteria in this context: image, enclosure, human scale, transparency, complexity, and slope(Ewing & Handy, 2009; Lundberg & Weber, 2014). These criteria have been used to create urban design quality indices to capture aspects of the built environment that are related to people's emotional responses to aesthetics in urban areas (Ferrer, Ruiz, & Mars, 2015; Garip et al., 2015; M. Jabbari et al., 2018; Lunecke & Mora, 2018).

Urban function affects spatial activity. Land use as one of the sub-criteria of urban function affecting pedestrian satisfaction and distribution in urban space (Bahrainy & Khosravi, 2013; Bélanger, 2007; Lamíquiz & López-Domínguez, 2015; Lerman & Omer, 2016). Population density is another sub-criterion most often used in this topic (M. Jabbari, Fonseca, & Ramos, 2018; Tal & Handy, 2012). Above all, population density correlates residential areas with pedestrian movements (Lerman & Omer, 2016; Peiravian, Derrible, & Ijaz, 2014). To be safe in a pedestrian network should consider the traffic condition because pedestrians are especially vulnerable on the roadway in the case of collisions and personal security (Fonseca et al., 2022). In fact, the urban function classifies three sub-criteria, including land use, population density and safety.

Accessibility is another criterion analysed by several authors that can improve pedestrians' quick access to a given location. This includes public transport and intelligent transport systems (ITS) as a sustainable method of urban mobility (Grecu & Morar, 2013). Accessibility is a facilitating criterion that strongly links urban function to the built environment. For example, to connect suburban areas that are largely car-dependent, considering the accessibility criterion can promote the pedestrian network through transport purposes as intermodal transportation (Gilderbloom, Riggs, & Meares, 2015b; Lamíquiz & López-Domínguez, 2015; Oswald Beiler et al., 2017).

Natural environment of streets and urban areas is also an important criterion, influencing walking and making a comfort zone (Panagopoulos, Duque, & Dan, 2016), pleasant conditions, by temperature control with artificial solutions (Peiravian et al., 2014) green spaces, sunlight, shade and wind are important for walking (Koh & Wong, 2013). Some authors have developed approaches to improve the walkability in green spaces of urban areas (Lwin & Murayama, 2011).

Another group of studies assessed the position of the street in the pedestrian network at the macro-level. Some structural criteria were assessed to get a better understanding of the spatial configuration of the streets, the road network and the location of economic activities (Chin, Van Niel, Giles-Corti, & Knuiman, 2008; Gilderbloom et al., 2015b; Kim et al., 2014; Lerman & Omer, 2016; Millward, Spinney, & Scott, 2013; Peiravian et al., 2014). The degree of connectivity in the street network is the most important parameter for any movement in urban space (Carpio-Pinedo, Martínez-Conde, & Daudén, 2014). The connectivity criterion joins places with people and defines how streets are networked (Azmi & Ahmad, 2015; Bahrainy & Khosravi, 2013; Pearce et al., 2021). Furthermore, the urban structure defines how the streets are arranged and interconnected and how they connect the different urban areas with their surroundings. A well-functioning urban structure has coherent neighborhoods where the centers of activities are within easy walking distance. In this context, walking creates economic value and social vibrancy (Gallimore, Brown, & Werner, 2011; Lindelöw, Svensson, Brundell-Freij, & Winslott Hiselius, 2017; Loo, Mahendran, Katagiri, & Lam, 2017). The integration of the road network is also a morphological parameter with implications for pedestrian movement (Carpio-Pinedo et al., 2014; Koh & Wong, 2013). Additionally, Z. Tan and Q.L. Xue (2014) examined the distribution of pedestrian mobility in the street network, as another parameter. He, Tablada, and Wong (2018) consider that the distribution of pedestrian flows characterizes these multi-level pedestrian systems.

3.3. Who uses the pedestrian network?

The organization of the pedestrian network based on the habits, pedestrian behavior and lifestyles of users living in cities has been discussed by many authors (Borst et al., 2009; Stevenson et al., 2017; X. Yang et al., 2022. However, it is only in recent years that attention has been focused on 'vulnerable' populations (children, older people, people with disabilities) in relation to the accessibility (Abass & Tucker, 2018). Gradients, pavement widths, obstacles on sidewalks, sidewalks in poor condition, traffic characteristics, etc. represent barriers for users walking in the city, especially for vulnerable populations. This is particularly important for users who require a wider space, such as pushchair and wheelchair users (H.-Y. Chan, Ip, Mansoor, & Chen, 2022; Fonseca et al., 2022; Gaglione et al., 2021; Šurdonja, Otković, Deluka-Tibljaš, & Campisi, 2023).

In addition, some studies have developed level of service (LOS) measurement to assess and compare the quality of urban services for different user modes (i.e. car, pedestrian, bicycle and transit). Several factors contribute to the LOS: pedestrian satisfaction with the route to the stop, satisfaction of waiting passengers, and satisfaction of passengers using the pedestrian network as part of intermodal transport. Traditional cost-benefit analysis is usually applied in an evaluation context to capture direct benefits to users, such as savings in travel time and improved quality of transport services sought by the municipality (urban manager). In order to realize the potential of systematic use of urban space, it is necessary to learn lessons from existing cases and understand user (pedestrian) behavior and concerns (Azad et al., 2021; Jabbari et al., 2022 Zhou et al., 2022; Zuo, Wei, Chen, & Zhang, 2020).

3.4. How can the pedestrian network be analyzed?

The urban planning process to provide a pedestrian network model is a complex task. The physical structure of the city as well as economic, social and environmental factors of different scales must be taken into account in the planning process. However, 79% of the walk score studies conducted by Hall and Ram (2018) were based on independent variables, only once as a mediating-moderating variable (Abass & Tucker, 2018) and on no occasion as a dependent variable. Also, in a few papers a bivariate correlation model was applied (Duncan et al., 2016; Hall & Ram, 2018; Towne et al., 2016). Therefore, the urban information model about pedestrian network should integrate the multidimensional urban aspects of economy, society, and environment. In fact, bonding among different criteria through different models determine the relationships between the potential of urban space and pedestrian.

Furthermore, pedestrian network, including multifunctional spaces, is used by different users with often conflicting interests and pedestrian network models reflect aspects of the users (Herrmann, 2016). Elderly, children and disabled people are vulnerable users that should not be forgotten in pedestrian network planning in urban public spaces (Šurdonja et al., 2023; Wijayanti & Pandelaki, 2012). Some studies look at pedestrian flows and behavior, while others use surveys to collect pedestrian data(Arroyo et al., 2018; Cui, 2021; Duncan et al., 2016; Hall & Ram, 2018; Towne et al., 2016; Ujang, 2016). However, more work is needed on classifying users and combining the results from their feedback in the pedestrian network model.

An attempt is made to classify urban spaces in order to propose a new typology of public space based on the way public space is managed, the so-called urban space typology (Carmona, 2010). The typology approach was applied in the city center and classified into pedestrian zones based on the characteristics of the public space. These pedestrian zones provided a short design document to manage the PEDESTRIAN NETWORK based on specific characteristics (Z. Tan & Xue, 2015). In the 1960s, pedestrian zones emerged in Europe, especially in city centers, and spread rapidly. For example, in 1966 there were only 63 pedestrian zones in Germany, but by 1972 there were 182 and by 1977 there were 370 pedestrian zones (Kostof, 2004; Lunecke & Mora, 2018). Lunecke and Mora (2018) have shown that the high volume of pedestrians in the street network occurred at specific street sections. These areas were usually located near the pedestrian zones.

The pedestrian network requires full consideration of the spatial continuity of the city (Yücel, 1979). The connectivity of the street network has an important impact on walking and how streets are interconnected (Azmi & Ahmad, 2015; Bahrainy & Khosravi, 2013). Therefore, a convenient design of pedestrian network should be provided to encourage walking and minimize obstacles. The connectivity of the street network can be defined as the number of intersecting streets per unit area (Azmi & Ahmad, 2015; Garcia & Lara, 2015). Space syntax was used to assess street network connectivity because it has several advantages over simpler measures of road network connectivity, such as passive graphical terms. By using axial lines, the space syntax is better suited to calculate movements in networked settlements and functional connectivity in networks (Gilderbloom, Riggs, & Meares, 2015a; M. Jabbari et al., 2018; Lerman & Omer, 2016; Tianxiang, Dong, & Shoubing, 2015).

In turn, the urban configuration is the most important factor in shaping pedestrian movement patterns. Peponis, Ross, and Rashid (1997) presented some findings on the morphology of Greek cities and their patterns of pedestrian movement. In their study, patterns of pedestrian movement and urban configuration were compared using the typological model of urban layouts. Different measures of urban configuration are related to aspects of social life. Accessibility is based on the relationships that each space has with the others in an urban system (Girling et al., 2019; Jabbari et al., 2022 Jeong & Banyn 2016). As a result, the use of integration analysis in urban studies has increased in recent years and the pedestrian network model has been developed (J. He et al., 2016). For instance, Li, Xiao, Ye, Xu, and Law (2016) measured the spatial configuration of street networks in the Chinese city of Gulangyu using integration analysis to guide urban planning and tourism management policies and tourist preferences. Cutini (2016) also used space syntax to analyze the relationship between movement and the urban structure of Florence to examine how movement patterns have changed over time as the metropolitan area has grown and its network has been progressively reshaped. In this sense, this method should be useful for further comparison with another model supporting pedestrian network, as it takes into account both spatial and functional aspects of urban form.

In the urban planning literature, numerous studies have focused on the relationships between walking and all these criteria. These factors are usually composed of multiple criteria and sub-criteria that are interrelated but weighted differently (MiMillward et al., 2013). The multi-criteria analysis (MCA) approach was used in the pedestrian network model to address the complexity of urban mobility issues reflected in the multiplicity of sustainability indicators (M. Jabbari et al., 2018). The MCA enabled through the structured prioritization of a number of nested variables of urban space in relation to pedestrians. These approaches were inspired by the study of Frank, Schmid, Sallis, Chapman, and Saelens (2005) which created a combined walkability index from three urban criteria to analyze their influence on physical activity. The MCA is also a commonly used tool, especially in spatial planning. The MCA evaluates decision problems and different options based on specific criteria or the preferences of decision makers, using a set of qualitative and/or quantitative criteria with different weights (Durmuş & Turk, 2014). Furthermore, H.-Y. Chan et al. (2022) based on a face-to-face questionnaire survey conducted in a new station area of a hilly neighborhood, developed a binary mixed logit model to estimate the effect of route attributes, trip characteristics, socio-demographics, and walking preferences on the decision to use alternative underground walking routes.

Table 2
Models Evaluation for Pedestrian Network.

What: Goal	Where: Place-Scale	Who: User	How: Model Content	Method	Strength Model	Author
To bring more walk-in shop visiting; purchasing opportunities; characteristics of an target group-friendly pedestrian network	Some streets, Urban spaces/Micro-scale	Citizen/ Tourist	Static built environment data, dynamic environmental behavior data and Street network	Survey maps, GIS and Space Syntax software	Considering three main dimensions sociology, economic and urban planning; Improving understanding of service proximity and user behavior	He et al. (2018); Hajrasouliha and Yin (2015); Delso et al. (2018); Oswald Beiler et al. (2017); Garip et al. (2015); Gaglione et al. (2022),
To bring more walk-in shop visiting and purchasing opportunities; to improve wider economic impacts in transport infrastructure	Neighbourhood, City center/ Macro-scale	Citizen/ Commuters	Standard, Guideline, Survey & Design code, Strategic plan, Represent the distributional equity of transit accessibility among social groups.	Processed to design pedestrian network zone and regulation, Survey	Creating standard document related to the pedestrian network; Place-based policies in a dense city require improvement in the pedestrian network;	Chin et al. (2008); Arroyo et al. (2018); Tan et al. (2015); Ujang (2016); Zuo et al. (2020); Cui (2021); Zhou et al. (2022)
To increase urban vitality	Urban areas, Suburban/Multi-scale	Citizen/ Tourist/ Commuters	Public space typologies, pedestrian flows and retail uses	Survey, Typology, Using Open Street Map data	Interconnecting the pedestrian network in order to develop the well-function	Lunecke and Mora (2018); Osama and Sayed (2017); Pearce et al. (2021);
To find the potential urban space for the pedestrian network	Urban areas, Suburban/Multi-scale	Citizen/ Tourist/ Commuters	Static built environment data and Street network	Survey, GIS, Space Syntax, Rhino software	Developing model as a service in transportation system; Considering Multi-scale in model;	Bélanger (2007); Tal and Handy (2012); Özbil et al. (2015) ; Kwon et al. (2017) ; M. Jabbari et al. (2018); Fonseca et al. (2022); X. Yang et al. (2022); Azad et al. (2022); Zuo et al. (2020)

The increasing availability of spatial data with greater disaggregation promoted the use of Geographic Information Systems (GIS) in pedestrian network models. GIS has been used by many authors for various tasks, such as identifying high and low walkability, providing information on the walkability characteristics of a given region, and creating a standardized benchmark to compare different environments in terms of the characteristics shown to create the pedestrian network (Badland et al., 2013; Kim et al., 2014; Tal & Handy, 2012). Indeed, many pedestrian network attributes, namely density, land use mix, road network and accessibility, can be analyzed in GIS (Azad et al., 2021; Z. Guo & Loo, 2013; Tal & Handy, 2012). For these authors, the combination of GIS data and an environmental audit has proven to be a valid tool for assessing pedestrian network. GIS has been used in spatial analysis to assess the connectivity of the road network for cyclists and pedestrians (Lundberg & Weber, 2014). The GIS techniques are often used in combination with other approaches, namely: agent-based simulations, where GIS provides geographical data to model the walkability of neighborhoods (Badland et al., 2013; D'Orso & Migliore, 2020).

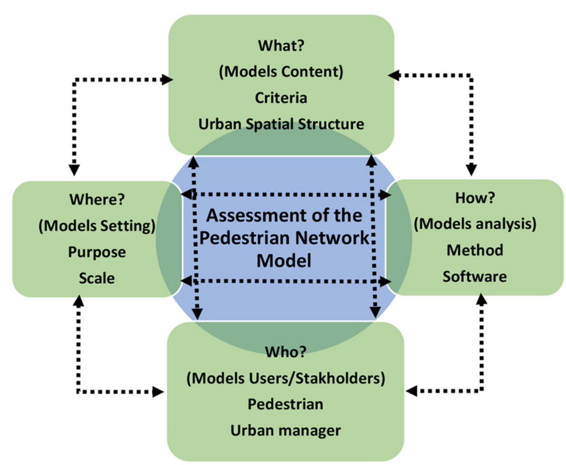

Fig. 1. Correlation among questions in the pedestrian network.

4. Discussion - Future directions for pedestrian network models

The review focuses on pedestrian network approaches in the field of urban planning. These studies rely on different data sources to achieve different objectives at different scales and areas. It can be concluded that the identification and assessment of a pedestrian network is a challenging process; especially since there are various contexts and levels of application, associated to the multi-functionality, mixed spaces, and natural features found in urban areas (Table 2). The results show that the majority of the studies focused on how to assess pedestrian network and on what criteria should be used in the evaluations of pedestrian network. Researchers mainly examined criteria related to the built environment, urban functions, accessibility, and the natural environment of pedestrian networks. Finally, these criteria were assessed using analytical tools and methods at the micro and macro level. In this context, GIS was increasingly used as a tool to analyze urban spatial attributes. Moreover, space syntax is applied to assess urban configuration and street connectivity. Less studies have been focused on where is the pedestrian network and who use the pedestrian network.

There is little evidence of where will be located the pedestrian network characteristics at site and area scale how to impact on the urban planning process. It raises up the question when the considering the pedestrian network in the urban structure how to make relationship with path segments that will be well-connected in the transportation network and have specific destinations along them. In addition, some researches were limited to city centers and neighborhoods in terms of the pedestrian network place-making and could be extended to suburban or even a large area. Other researches have taken micro, macro and even multi-scale approaches, mainly focusing on policy and guide-

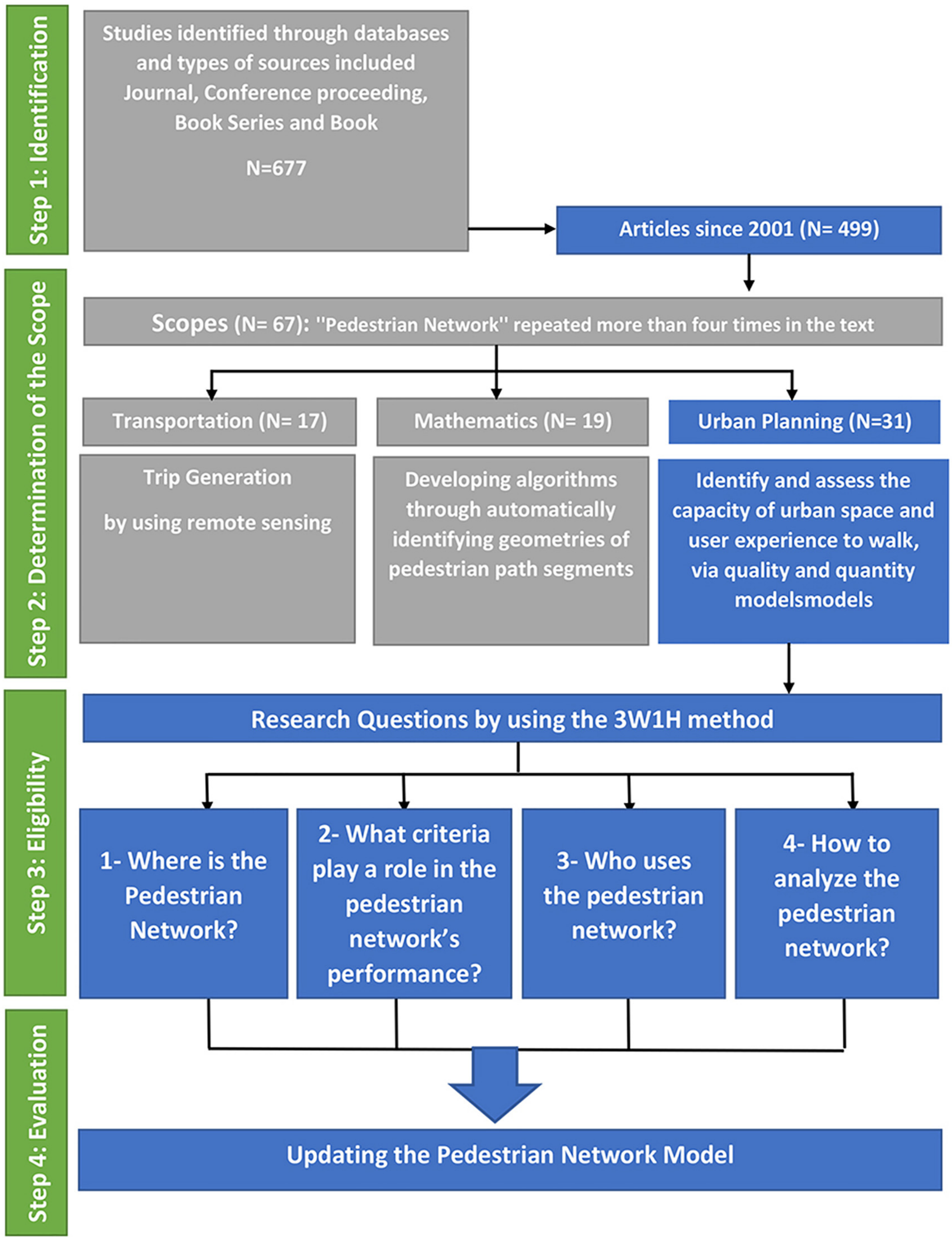

Fig. 2. Flow diagram of the selection process and final studies included in the systematic review.

line making. Pedestrians cross the current road network and there are various cars and other modes of transport. It seems that the pedestrian network should consider an independent urban structure and the urban transport system should support it as a main priority. However, since the role of conceptual research is to open more debate on where the pedestrian network is located and how to provide urban transport needs in the particular urban context, with a view to creating more sustainable urban transport.

Another question that would be highlighted for future studies is who uses the pedestrian network. Since the pedestrian network would be making attractive modes to a much wider range of people, not yet perceived: in particular paths are safer and pedestrian environments are more pleasant and such facilities are the norm in urban areas. Few researchers focused on pedestrians' needs; especially vulnerable pedestrians and disabled people. Vulnerable pedestrian groups may include children, elderly individuals, and people with disabilities, as well as individuals who are under the influence of drugs or alcohol. Understanding the behavior of these groups is important for designing and implementing effective safety interventions to reduce pedestrian injuries and fatalities. Research has shown that vulnerable pedestrian groups may exhibit different behaviors and risk-taking tendencies as compared to the general population (Gaglione et al., 2021). For example, children may have limited cognitive and perceptual abilities that affect their capability to accurately judge distances and speeds of oncoming vehicles. Elderly individuals may have physical impairments that affect their gait and balance, making them more susceptible to falls and collisions. People with disabilities may have limited mobility or sensory impairments that affect their capability to navigate their environment safely. It is important to consider these differences in behavior when developing interventions to improve pedestrian safety. For example, interventions may need to be tailored to the specific needs and abilities of different vulnerable groups, such as improving crosswalk markings and signal timing for elderly individuals, or providing extra supervision and education for children. Overall, understanding the behavior of vulnerable pedestrian groups is an important component of improving pedestrian safety and reducing pedestrian injuries and fatalities. The pedestrian network should provide inclusive environments for all users, encouraging people to walk and offering vibrant walking experiences.

Additionally, when designing a pedestrian network as an urban structure, it is significant to consider the element of a sufficient capacity of the transportation system. Parking often takes up valuable space that could be used to improve the pedestrian infrastructure. This can lead to conflicts between pedestrians and vehicles, making it unsafe for people to walk and increasing the risk for accidents. To address these issues, it is important for urban planners and policymakers to prioritize the pedestrian infrastructure in transportation plans and policymaking. This may involve reallocating space currently used for vehicle parking for the pedestrian infrastructure, such as wider sidewalks, improved lighting, and more accessible crosswalks. It may also involve developing and enforcing policies that prioritize pedestrian safety and convenience over vehicular traffic, such as reducing speed limits, creating more pedestrian-only zones, and installing more traffic calming measures. Overall, improving the pedestrian network infrastructure is critical for promoting safe and convenient pedestrian movement and creating more livable and sustainable urban environments.

Likewise, it seems to define a combined system involves an urban planning process and also the opinions of residents, which can be useful to strengthen the robustness of the assessment approach based on Sustainable Urban Mobility Plans (SUMPs). In addition, the physical environment is expressed through the structural characteristic of the space, which influences the overall perception of walkability. For this reason, many pedestrian studies in the literature refer to behavioral experiences related to the physical environment (Bahrainy & Khosravi, 2013; Forsyth et al., 2009; Gaglione, Gargiulo, & Zucaro, 2022; Gilderbloom et al., 2015b; Lamíquiz & López-Domínguez, 2015; Nasir, Lim, Nahavandi, & Creighton, 2014). It is important to check the results of the pedestrian models and compare them with real pedestrian behavior. Such a comparison is useful to identify the discrepancy between the pedestrian requirements and the results of the model defined by urban planners, providing additional support for the creation of the pedestrian network.

5. Conclusion

This paper examines the pedestrian network concept through a systematic literature review. The aim of this paper is to evaluate the theoretical and practical questions about pedestrian networks in an urban planning approach in order to support the development of future models/plans for pedestrian networks. Hence, the analysis of the literature review was carried out using the 3W1H method by answering the following questions: (1) Where is the pedestrian network located? (2) What criteria play a role in the pedestrian network's performance?, (3) Who uses the pedestrian network? and (4) How can the pedestrian network be analyzed?

Given the ever-increasing complexity of cities and the increasing focus on sustainability, urban structures may be undergoing major changes (S. Hong, Hui, & Lin, 2022). This paper has conducted a comprehensive systematic literature review focused on the concept of Pedestrian Network studies by applying 3W1H analysis method. The review showed that there is a significant body of research that emphasizes the importance of well-designed and connected pedestrian networks in promoting walking, active transportation system, and improving the overall livability of cities. It was found that connecting the pedestrian network to the transportation system requires a comprehensive and integrated approach that considers the needs and safety of pedestrians in transportation master plans and policy-making. This will support the creation o a more accessible, safe, and efficient transportation system for all users. Although, many research projects on the topic have been conducted over more than a decade, and some of them even predict and conceptualize the future, there is not yet a systematic and coherent study that synthesizes the full range of knowledge concerning ''pedestrian network''. In addition, there is a need for further research on the topic, particularly in the areas of network analysis, design guidelines, and implementation strategies to effectively promote pedestrian active mobility and safety.

Hence, it is crucial to shed light on the existing and new concepts underlying the vision of the future urban fabric and to capture and analyze the perceptions, insights and expectations of relevant scholars and practitioners. Addressed to analyze the condition of pedestrian networks is still a challenge due to the diverse urban environments and the different attributes that influence the decision to walk. However, considering the pedestrian network as a new urban structure in the urban planning process include global overview to where, what, who, and how that will provide good conditions for walking, encourage people to walk and change cities towards more sustainable urban development is a crucial goal. (Fig. 1)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The preferences of transport mode of certain travelers in the age of autonomous vehicle

Jamil Hamadneh[a,b,*], Domokos Esztergár-Kiss[b]

[a] Department of Civil Engineering and Sustainable Structures, Engineering and Technology College, Palestine Technical University-Kadoorie, Tulkarem, Palestine
[b] Department of Transport Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics (BME), 1111 Budapest, Hungary

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ABSTRACT

Individuals choose transport modes to travel based on their preferences and journey characteristics. The availability of autonomous vehicles (AVs) on the market will affect the traditional mode choice models. In this regard, this research studies three transport modes: conventional car, privately-owned autonomous vehicle (PAV), and shared autonomous vehicle (SAV). The potential changes in transport mode choice are evaluated, where the impact of changes of some sociodemographic and travel variables on choices are estimated. A discrete choice modeling approach is applied in this study to develop a transport choice model. A stated preference (SP) approach is used, where 306 answers are collected in Hungary. A discrete choice experiment (DCE) is designed to collect the choices of people. Multinomial Logit (MNL) model is applied to the data to develop a transport mode choice model, where differentiations between some parameters across transport modes are presented. People are varied in their willingness to use a transport mode across groups, such as the income, the family size, and the current transport mode. The results demonstrate that people are more likely to use a conventional car than PAV, while they are more likely to use PAV than SAV. The output of this study can be used to support policy implications in the AV era.

Introduction

One of the smart mobility innovations is the Autonomous Vehicle (AV) which aims to improve the mobility of people where sustainable transport modes are needed (Butler, Yigitcanlar, & Paz, 2020). Policymakers foster smart mobility initiatives that participate in increasing the safety of people, decreasing the fuel consumption, environment friendly, and participating in managing and alleviating the roads congestion (Butler et al., 2020). AV is considered a new paradigm in transportation, because this technology will not only impact the travel time but all aspects of life as stated by Rashidi, Waller, and Axhausen (2020). The characteristics of AVs are different than conventional cars, such as the fact that the AV can drive itself alone (Monarrez, 2020). The advancement of this technology motivates policymakers to take decisions to adapt to potential consequences, such as the change in the transport mode split. The decisions should be based on and supported by further research and studies. Transport planners use transport mode choice models to predict future changes in travel behavior. Different variables affect the transport mode choice, such as sociodemographic variables and travel characteristics (Hanson & Huff, 1986; Ruiz, Arroyo, Mars, & Casquero, 2018). The variables are exposed to change, for example raising the fares, embedding new transport mode, reduction in travel time, and people economic status (i.e., income class) (Tyrinopoulos & Antoniou, 2013). In transport mode choice evaluation, the way how travelers choose a transport mode depends on several variables. The variables are connected to the travelers themselves or the travel characteristics. The value of travel time (VOT) is an indicator of how people exhibit their travel. The VOT measures the people's willingness to pay for using a particular transport mode rather than another. The VOT is affected by factors connected to each transport mode and the characteristics of travelers (Small, 2012).

The literature is rich in studies about the travel behavior of people concerning conventional transport modes. However, research about the impact of AV technology on the travel behavior is still in need and recommended. Few efforts are conducted before by Polydoropoulou et al. (2021) and Etzioni et al. (2020). They examined the preferences of people when AVs are on the market across seven countries. The findings of the studies are promising. Etzioni et al. (2020) show that people in Hungary show reservations about using AV compared to the regular car, and Polydoropoulou et al. (2021) observe that VOT of shared autonomous vehicles (SAVs) is higher than privately-owned autonomous vehicles

* Corresponding author.
E-mail addresses: jamil.hamadneh@kjk.bme.hu, jamil.hamadneh@ptuk.edu.ps (J. Hamadneh).

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(PAVs). The inference of the study of Polydoropoulou et al. (2021) is SAV is not a convenient transport mode compared to AVs and conventional cars. Additionally, Hamadneh and Esztergár-Kiss (2021b) study the impact of multitasking on board public transport and SAV using discrete choice modeling. They find that people are more willing to use public transport than SAV. Hamadneh and Esztergár-Kiss (2021c) examine the impact of multitasking onboard across PAV and SAV. The finding demonstrates that people are more willing to use SAV over PAV. Tian, Feng, Timmermans, and Yao (2021) conduct a choice experiment study to examine people's tendency of buying an AV or an SAV. The results of the study highlight that people prefer to buy AV over SAV while SAV is more favorable compared to conventional cars. The last two studies of Hamadneh and Esztergár-Kiss consider the impact of the availability of multitasking on board a transport mode choice, in urban areas for main trip purposes. The impact of PAVs and SAVs on the travel time of commuters is studied by Felix Steck, Viktoriya Kolarova, Francisco Bahamonde-Birke, Stefan Trommer, and Barbara Lenz (2018b). They conclude that the VOT of travelers who will use the AVs is smaller than those who will not. Several researchers show AVs might replace motorized modes based on the examination of several factors, such as the VOT, the sociodemographic, and trip characteristics (Boesch & Ciari, 2015; Bozorg & Ali, 2016; Fagnant, Kockelman, & Bansal, 2015; Hamadneh & Esztergár-Kiss, 2019). A study of Jiang, Zhang, Wang, and Wang (2019) in Japan demonstrates that people, especially the ones owning a car, are willing to pay extra money to own an AV in the future. Thus, the number of conventional cars on the market might change in the future. Zhang, Guhathakurta, and Khalil (2018) study the impact of AVs on car ownership. They conclude that AVs might reduce vehicle ownership, and people with low income are less likely to use AVs. Menon, Barbour, Zhang, Pinjari, and Mannering (2019) show that the availability of AVs will impact the number of household cars, for example, households with a single car might relinquish their cars, while households with multiple cars may relinquish one of them.

However, this study examines the impact of introducing PAV and SAV on the conventional car, where only the travel time and travel cost are included. The study simulates the actual travel of people when they travel to their main destination, such as the travelers are asked to imagine using PAV, SAV, and conventional car. Besides, using the Bayesian D-efficient design method in designing the stated choice experiments is presented in this study, which has not been used earlier in modeling the transport choice behavior of travelers when PAV, SAV, and conventional car are the available transport modes, such previous studies use the orthogonal design (Hamadneh & Esztergár-Kiss, 2021b, 2021c). The study uses customized attributes of travel time and travel cost to represent the realistic travel behavior of different groups of people, where a traveler can compare his/her actual travel time and travel cost with other transport modes and take a decision.

Several transport mode choice studies are available in the literature, where travelers' preferences are modeled. The contribution of this study is examining the impact of PAV, and SAV on conventional cars through a stated preference (SP) survey, where people choose a proper transport mode based on the characteristics of their actual trips departing from their homes to their destinations. The study focuses on car and two types of AVs (where PAV is personally owned, and SAV is not personally owned) because one of the aims of using this smart mobility innovation is to decrease the car ownership as well as decrease the number of accidents caused by human errors. The study limits the choices of travelers to three modes to make a comparison among them giving a glance at travelers' preferences. The main difference between PAV/SAV and car is the availability of a human driver. This study is not limited to urban areas, but it is valid for other areas where AVs have an impact on the mobility of people.

This research studies the preferences of skilled people on three transport modes, i.e., conventional car (car), PAV, and SAV. The paper aims to develop a transport choice mode model to predict the future modal share of three motorized vehicles in the AV driving age. Besides, it evaluates the impact of different factors on the transport mode choice, such factors are the demographic, journey, and economic factors.

This research is structured as the following: The first section is the introduction. The second section gives a review of the related literature. The third section presents the methodology, which includes the survey design, the data collection, and the modeling techniques. The fourth section presents the results of the models. Finally, section five presents the discussion and the conclusion.

Literature review

AVs are going to be on the market soon (Musk, 2020). Further studies about AV's implication on different aspects of life are needed. One of the studies that help in predicting the behavior of people when AV is introduced to the market is the transport mode choice modeling and acceptability of people to AVs. Discrete choice models are widely used to assess transport related problems (Aloulou, 2018; Bierlaire, 1998). Choice models are applied to understand the behavior of travelers and how they interact with the available transport modes based on their preferences and the characteristics of the journey (Ben-Akiva, Lerman, & Lerman, 1985). Natural and quasi-natural experiments are used to examine the propositions in a cost-effective, robust, and flexible set of methods. For example, Henao and Marshall (2019) use quasi-natural experiments to analyze the impact of ride-hailing on the efficiency of transport system considering vehicle occupancy, mode replacements, and empty-driven vehicles. The authors use vehicle mile travel (VMT) and passenger miles traveled as criteria. The results demonstrate the ride-hailing leads to more than an 80% increase in VMT. This leads to the conclusion that AVs drive additional distances more than conventional cars. Transport choice helps scholars recognize the consequences of new actions that might change travel behavior factors, such as travel time, travel cost, or comfort level. Several researchers study AVs as a replacement or competent transport mode (Etzioni et al., 2020; Hamadneh & Esztergár-Kiss, 2021a, 2021c; M Maciejewski, Horni, Nagel, & Axhausen, 2016; Michal Maciejewski & Nagel, 2013; Polydoropoulou et al., 2021; Felix Steck, Viktoriya Kolarova, Francisco Bahamonde-Birke, Stefan Trommer, & Barbara Lenz, 2018a). Different analysis methods are used, such as multi-agent simulation, discrete choice experiments, and SP surveys. However, research on the impact of AVs on the existing transport modes needs more attention to cover the gaps in the literature.

People generally look for a transport mode that decreases the negative utility of travel time during traveling (Hamadneh & Esztergár-Kiss, 2021a). The evaluation of travel time with different transport modes varies because it depends on the trip and the traveler's characteristics. The results of Singleton (2019) show that the impact of AVs will reduce stress of driving, but its impact on VOT will be limited. Kolarova, Steck, and Bahamonde-Birke (2019) find that the VOT of AV is 41% less than a conventional car's for commuters, and the SAV is the least attractive compared to AV and public transport. The authors present that leisure and shopping trips are insignificant regarding the VOT, and riding an AV is similar to riding public transport regardless of the access and egress distances in case of public transport. Yap, Correia, and Van Arem (2016) study the AVs as a feeder system to the last mile of travel of the first-class train riders (i.e. travelers use AV to and from the train station). The results show that the in-vehicle time of AVs is perceived less negatively than that of the conventional cars. Bozorg and Ali (2016) show a 35% decrease in the VOT when AVs are used. Simoni, Kockelman, Gurumurthy, and Bischoff (2018) conclude that the VOT is decreased once AVs are in use. Steck et al. (2018a) state that AVs might reduce the VOT for commuters either traveling by a shared or unshared AV. The authors declare that the unshared AV is more likely to be used instead of SAV. Bansal and Daziano (2018) conduct a study to evaluate the VOT of using AVs, and they conclude that travelers are more likely to pay $3 less per AV's trip when compared to conventional transport modes. This reduction occurs because the travelers consider it inconvenient not to have a driver. One of the potential user groups of AVs is people who live in rural areas or places where no access to public transport is provisioned, and elderly and disabled people (Meyer, Becker, Bösch, & Axhausen, 2017). Zhong, Li, Burris, Talebpour, and Sinha (2020) study the VOT of commuters in AVs in urban areas of various sizes. They find that AVs reduce the VOT in suburban areas to a larger extent than in urban areas (32%>24%) and in urban areas to a greater extent than in rural areas (24%>18%). The authors state that the reduction in the VOT in AVs is twice as high as in SAV. The study of Litman (2008) presents that the VOT for high-income people is higher than others'. It shows that the VOT is 20-35% of the salary rate of walkers, cyclists, and transit users, but it is 35-50% for a driver. In terms of monetary changes caused by AVs, the generalized cost of car travel decreases with the introduction of AVs, as stated by Krueger, Rashidi, and Dixit (2019). Zhou et al. (2020) examine the heterogeneity in the travelers' preferences toward the automated car-sharing program. The scholars show that the SAVs might facilitate car-sharing because there is no need to park, and the access time is removed, as well. The results show that the travelers, who possess more money, have more positive attitudes toward the self-driving transport modes. Kyriakidis, Happee, and de Winter (2015) find that people who travel long distances are more likely to use AVs and more willing to pay for this service. The factors that govern the acceptability of AVs are sociodemographic and attitudinal variables, trip characteristics, and current behavior factors. As defined by Becker and Axhausen (2017) each category includes more than one variable, such as trip characteristics, trip distance and trip purpose.

Ashkrof, Homem de Almeida Correia, Cats, and van Arem (2019) conduct a stated preference survey in the Netherlands to study the impact of AVs on travel behavior. 663 participants are asked to choose either public transport, conventional car, or AV. The scholars study the mode choice selection considering the travel time and travel cost. The result of the study shows that public transport and conventional cars perceive less attractiveness in both long and short distances when compared to AVs. While AVs perceive much more attractiveness in case of long trips and leisure trip purposes. Moreover, the VOT for leisure trips has a value less than commuting trips. The study concludes that using the AVs might be affected by trip purpose, travel time, and sociodemographic variables. Polydoropoulou et al. (2021) study the impact of gender and companions on the adoption of shared autonomous vehicles across seven European countries. The results demonstrate the willingness of people to adopt and share the riding with co-travelers. Furthermore, Etzioni et al. (2020) model the mode choice of PAV and regular cars across seven European countries. The findings that generally people show conservation on switching to the PAV compared to regular cars. Hamadneh and Esztergár-Kiss (2021c) model the transport choice between PAV and SAV. The travelers choose a transport mode based on three attributes, time, cost, and the availability of multitasking onboard. The finding is people are more willing to use SAV over PAV. Additionally, public transport and SAV are modeled, and the result shows that people are more willing to public transport than SAV (Hamadneh & Esztergár-Kiss, 2021a).

When considering different user groups, it is shown that rich people, who spend a lot of money on other expenses compared to travel, are more willing to pay for saving time, based on the economic theory of travel time as described by DeSerpa (1971). Saeed, Burris, Labi, and Sinha (2020) study people's behavior to understand the early adopters' needs in the AV era. They conclude that users of car-sharing, privately owned, and ridesharing will be the first adopter of AV. Moreover, people prefer AV mostly, while AV is a great opportunity for age seniors. Haboucha, Ishaq, and Shiftan (2017) show that people hesitate to use AV, and people who are young, educated and students are more likely to use AV than others. Travelers with higher education levels are more likely to use AVs than other modes as presented by Wicki, Guidon, Becker, Axhausen, and Bernauer (2019) and Zhou et al. (2020). Winter et al. (2019) study the interest and the trust of AVs by developing a discrete choice model based on a sample of 282. The results show that those travelers who use public transport prefer the autonomous bus over the other public transport possibilities. The researchers demonstrate that people with driving knowledge accept the technology more than those who cannot drive (Winter et al., 2019). Moreover, gender has an impact on acceptability, as women trust the self-driving bus to a greater extent than men. However, in another study by Hohenberger, Spörrle, and Welpe (2016), it is found that women are more anxious about AVs, which affects their willingness to use AVs in the future.

Previous studies focus on several topics related to AVs, such as the benefits of AVs, the impact of qualitative measures on the VOT of conventional transport modes, the impact of quantitative measures on the VOT of AVs, and the VOT of certain groups of users, such as high-income people, commuters, educated travelers, or long trip commuters. Moreover, the literature includes different aspects of AVs, such as autonomous buses, combined transport modes, or the willingness of people to buy AVs. In this study, a more realistic situation that considers the current travel behavior of travelers when they use/switch to car, PAV, and SAV departing from their homes to destinations are presented where skilled people are chosen for participation in this survey (i.e., people who are more involved in the characteristics of AVs). The study investigates the marginal utility of discrete variables on the use of PAV, SAV, and car. It focuses on the willingness of travelers to switch to AVs (either individual or shared) regarding time and cost factors.

Method

As AVs are still not on the market, the SP surveys seem to be a suitable method to study the future behavior of travelers, where a discrete choice experiment is included in the SP (de Almeida Correia, Looff, van Cranenburgh, Snelder, & van Arem, 2019; Gkartzonikas & Gkritza, 2019). The research methodology consists of the survey design and the modeling techniques (Koul & Eydgahi, 2020). Moreover, a design choice experiment is built to study the preference of travelers toward three transport modes.

Survey design

An SP survey and stated choice experiment are created and distributed in Hungary to study the current behavior of travelers and their future travel behavior once AVs appear on the market. Some travel characteristics and socio-demographic variables are included in the SP survey, such as trip time, trip cost, trip purpose, the transport mode, the gender, the age, the education level, the employment, the family size, whether the travelers are children/disabled people, the income, the ownership of a driving license, and the car ownership variables. Collecting these variables is essential to understand the impact of groups on travel behavior, such groups are gender, trip purpose, car ownership, and income.

The discrete choice experiment (DCE) approach is used to study the traveler preferences based on certain alternatives (i.e. transport modes) and their pertained attributes and levels (Hauber et al., 2016; Rose & Bliemer, 2009). Ngene choice experiment design software is used to generate Bayesian D-efficient design (Hauber et al., 2016; Walker, Wang, Thorhauge, & Ben-Akiva, 2018). The efficient design is used to reduce the standard errors of the estimated parameters. D-efficient design can be used when some preliminary parameters are known; in this paper, only the signs of travel time and travel cost signs are known. Due to the absence of known parameters, the Bayesian D-efficient design is used rather than D-efficient designs because it considers the errors in prior estimates (Walker et al., 2018).

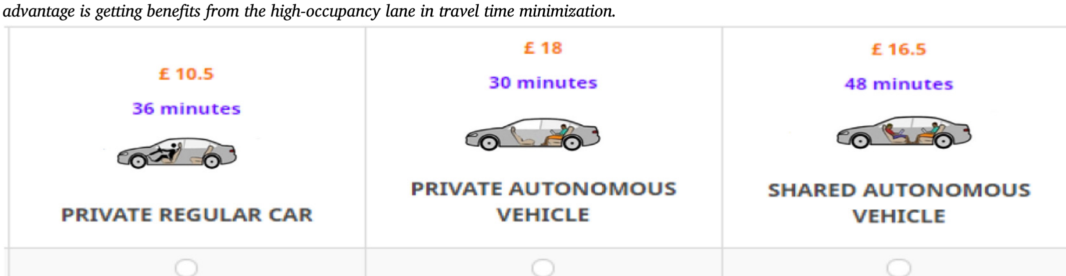
The three alternatives of transport modes that are examined in this paper are car, PAV, and SAV. Information is given to the respondents about the three alternatives, such as using car is similar to conventional private cars, PAV is similar to the car with different size and type as car. The PAV and SAV drive alone autonomously without intervention and help of humans. Thus, driving and parking are not the concern of travelers with PAV and SAV. The difference between SAV and PAV is that the PAV can be owned by a traveler, while SAV cannot be owned by a traveler. The SAV can pick up one or more passengers which makes you wait for picking up passengers and dropping them off along a trip, if any.

The travel time represents door-to-door time, and the travel costs simulate the current situation in Budapest, such as the cost of maintenance, fuel, parking, and insurance. The travel time is weighted based on the travelers' estimation of their travel time (door-to-door) by the car mode when they depart their homes (i.e., people who usually do not use car can estimate their trip time), and a plausible range of travel cost levels is used. The Bayesian D-efficient design values are pivoted around the estimated travel time of respondents, where each respondent has a customized travel time and travel cost (i.e., the travel cost equals the travel time multiplied by a cost rate per minute). The travel cost in car, PAV, and SAV are explained, for example, PAV is practically more expensive than car due to the cost of smart technology, and this is reflected in the design of choice experiments. It is worth mentioning that for few cases, the PAV is treated cheaper than car to consider the people who are more reluctant to PAV. It is ensured that no dominant scenarios are included, where the realistic situation is reflected by introducing a definition for each alternative with its characteristics, such as removing parking, and access time to a vehicle in case of AV and SAV. The target group is diverse, in which the respondents represent the general public, such as public transport providers, transport agencies, engineers' bodies, car clubs, and interest groups (i.e., motorized and no-motorized groups). The level intervals are chosen to mimic the real situation in AV driving time as well as based on the methodology of the discrete choice modeling approach (Hauber et al., 2016). The respondents are asked to choose one of the alternatives based on their preferences concerning the attributes and levels in the given DCE. Each respondent is randomly assigned one block of six choice sets out of four blocks of 24 choice sets.

The data are collected by LimeSurvey online survey tool, which supports the study by providing the required features, such as randomization of the questions (Schmitz, 2012). The survey was reviewed and complies with the EU's General Data Protection Regulation (GDPR).

The SP survey is given in the appendix, while a sample of the survey is given below:

Which transport mode that you regularly choose to go to your regular destination?
Private car Public transport
Imagine that you are going to make your regular travel by car (in case you do not use car)
What is the duration of this regular travel if made by car (please consider door to door time)?
Please choose one transport mode based on time and cost variables, in which each scenario has three transport modes?
1. Car: Using a Privately-owned Regular Car like conventional private cars used today.
2. PAV: Using a Privately-owned AV. This option is like car. PAV will drive itself without a human driver and will leave you at your destination, where no parking is needed.
3. SAV: like PAV but not owned by individuals. The car can pick up passengers along the travel if any. Thus, the riding is shared with family or strangers. The advantage is getting benefits from the high-occupancy lane in travel time minimization.



Modeling techniques

There are common discrete choice modeling methods that might be used to analyze the collected data from the SP survey (Hauber et al., 2016). The concept of the discrete choice modeling is to define the choice by using attributes and levels to understand how people choose an alternative. The understanding of the problem's properties determines which statistical model is appropriate for the data. Hereafter, the background of the random utility theory and the common discrete choice models are presented. The theory of utility maximization summarizes the mathematical framework of the travel demand (Ben-Akiva et al., 1985).

Travelers make choices to maximize their utility generated from a set of available utilities. The Multinomial Logit (MNL) model assesses the utility based on the characteristics of a traveler rather than the selected alternative (Hoffman & Duncan, 1988). In the MNL model, the probability that a traveler (i) selects one alternative (j) from the (m) alternatives in the choice set (C) is expressed in equation (1).

$$P(cij/C) = \frac{\exp(V(j))}{\sum_{j=1}^{m}\exp(V(j))} = \frac{\exp\left(\mathbf{X_i}\boldsymbol{\beta_j}\right)}{\sum_{j=1}^{m}\exp\left(\mathbf{X_i}\boldsymbol{\beta_j}\right)} \quad (1)$$

where $\mathbf{X_i}$ is a vector of the alternative attributes, and $\boldsymbol{\beta}$ is a vector of the unknown parameters. **V(j)** is the utility of alternative (j), which is a linear function composed of attributes. The probability that a traveler (i) selects one of the (m) alternatives (j) from the choice set (C) is the exponential of the utility of the alternative (j) divided by the sum of all the exponentiated utilities of alternatives in that choice set (C). The model specification of the MNL model is expressed in equation (2).

$$U_j = V(\beta * X_j) + \varepsilon_j \quad (2)$$

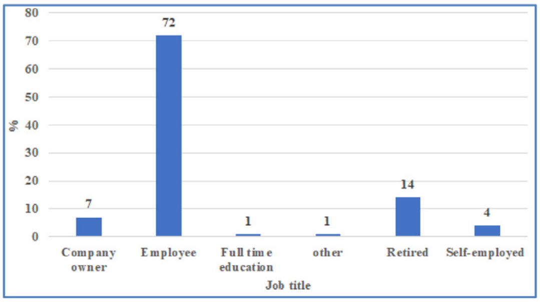
where V is a deterministic part, which can be defined from the attributes and the levels of the selected alternative (j), $\varepsilon_{(j)}$ is a random error term, $\mathbf{X_j}$ is a vector of the attribute levels of alternative (j), and $\boldsymbol{\beta}$ is a vector of the estimated coefficients.

In this study, panel data MNL model is used, where repeated observation for the same respondent (i) is considered. From equation (1), the value of travel time can be calculated by using equation (3).

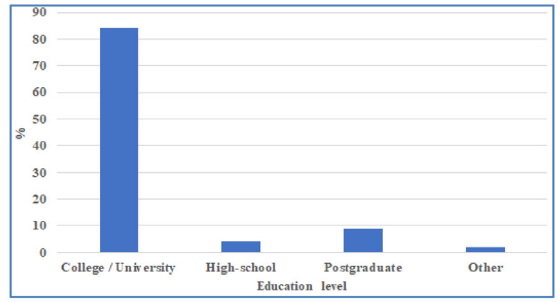
$$VOT = \frac{\beta_{tt}}{\beta_{tc}} \quad (3)$$

where VOT $_j$ is the value of travel time, β_{tt} is the marginal utility of travel time I, and β_{tt} is the marginal utility of travel costs.

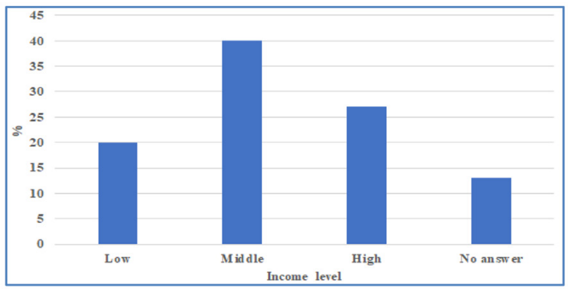
The MNL model is a good fit for the data and provides high accuracy based on the likelihood ratio index. The developed model is also tested for prediction potential. Akaike's information criterion (AIC) and Bayesian information criterion (BIC) are two popular measures for comparing maximum likelihood models (Stata Corporation, 2019). The BIC is applied to compare models, where the BIC difference 0-2 is weak, 2-6 is positive, 6-10 is strong, and >10 is very strong (Raftery, 1995). The socioeconomic and personal variables are examined in the choice model



a. Job type



b. Education level



c. Income level

Fig. a. Job type, b. Education level, c. Income level.

Table 1
Descriptive statistics about the socio-demographic variables

Age group	%	Gender	%	Driving license	%	Car ownership	%
25-34	11.76%	Female	15	Yes	97	Yes	93
35-44	18.95%	Male	85	No	3	No	7
45-54	21.57%						
55-64	27.45%						
65+	20.26%						

to see the variation in parameter estimates (i.e., the marginal utility of time and cost) concerning income, age, gender, trip purposes, car ownership, and driving license holders' groups.

Results

The number of participants is 639 respondents, and the complete responses are 306. The survey was distributed from 28th December 2019 to 28th February 2020. The responses are analyzed using Stata 16 software. Based on the literature, the collected sample is sufficient for conducting the analysis, where the used method in the stated choice experiments requires a smaller sample size than the random orthogonal design (Rose & Bliemer, 2013).

Descriptive analysis

First of all, descriptive statistics are presented, as shown in Fig. a, Fig. b, Fig. c, and Table 1. These statistical data are studied to check the distribution of the participants across variables. The below figures and table present the sociodemographic information of the 306 respondents, for example, employment, income, age, family size, car ownership, education level, and gender are demonstrated. Data analysis shows that most of the respondents (72%) are employees, whereas full-time education and other professions have a low representation (1% for each). 93% of the respondents own a private car, 15% are female, 97% of the participants have a driving license, and 84% are college graduates.

The average age is 52.2 years with a standard deviation (SD) of 13.7 years. The average family size is 2.8 members with an SD of 1.3, while the average productive family size is 1.7 members with an SD of 1.6.

It is noted that the sample composition does not represent the population of Hungary because the survey was sent to a certain group of people who are familiar with the research and have heard of AVs. Thus, the sample represents people who are more likely to use AV than others in the initial stage of AV introduction when launching AV to the market. The decision was made because the AV is not on the market and understanding of the behavior of this vehicle is well maintained by skilled people.

Besides, the survey includes information about the main trip characteristics of the participants, like transport modes and trip purposes. Table 2 shows the highest percentage of the respondents is people who go to work (75%), and the lowest percentage is people who travel due to educational activities (1%) or other purposes (1%). Most frequently, private cars (47%) and public transport (36%) are used, and the lowest percentage chooses shared cars (1%) and walking (1%). Table 2 illustrates the main daily trip purpose, where the activities are grouped to see their impacts on the AVs, for example, a business trip is different from a work trip. The output of this table demonstrates that most of the people who participate in this survey are workers who use their cars to get to work (i.e., car owners).

The survey includes questions about people's past experiences on the specific characteristics of the travel, like accidents during the past three years, Adaptive Cruise Control (ACC) use (it is a system that can keep its speed at the selected level and reduce it, if necessary, whether to keep an appropriate distance from a car in front), the knowledge about

Table 2
Transport mode and trip purpose statistics

Main daily transport mode	%	Main daily trip purpose	%
Private car (owned by myself or someone in my household)	47	Work	75
Public transport (e.g. bus, tram, underground, metro or train)	36	Other professional reasons (e.g. business trips)	5
Shared car (e.g. a car which is shared with other travelers)	1	Groceries, errands, administrative purposes, medical appointments	6
Micro mobility (bikes and scooters)	3	Leisure (e.g. sports or cultural activities)	2
Walking	1	Educational activity	1
Other	13	Pick-up or drop-off someone	3
		Visiting someone (e.g. friends or relatives)	2
		Other	1
		No daily or regular mobility	6

AVs, and the experience in using AVs. The respondents show that around 83% have good knowledge about AVs, and 13% of the respondents have already had an opportunity to try riding an AV. The output of this table demonstrates that the participants are involved in the topic of this study, and this is reflected in the quality of the answers they give. 100% of participants have heard or read about the AVs as well as 83% have good knowledge about AVs; that means that respondents did not find difficulties in understanding the survey.

Model development and estimates

The collected responses show that 45.10% of people would choose car, 22.93% PAV, and 31.97% SAV. The respondents show reservations in the sample towards PAV and SAV compared to car, as demonstrated in another study conducted for seven countries in Europe by Etzioni et al. (2020).

The choice modes are examined across certain significant variables, like income, regular transport mode, family size, trip purpose, age, and car ownership. The most significant parameters are kept in the mode where the developed models are compared based on the best-fit model criteria of the collected data, and the superior one is selected (Ghosh, Maitra, & Das, 2013). The factors that show significant results and affect the choice of a transport mode are regular transport mode, income, and family size.

Mathematically, the utility function of choosing a transport mode considering the travel time and travel cost is presented in equation (4).

$$\begin{aligned} U_{\text{Alternative (j)}} = {} & \beta_{o\ (j)} + \beta_{tt\ (j)} * \ TT + \beta_{tc\ (j)} * TC \\ & + \beta_{\text{income (j)}} * \text{Income (dummy)} * \ \text{Dummy}_j \\ & + \beta_{\text{regular tranport mode (j)}} * \text{Regular transport mode (dummy)} \\ & * \text{Dummy}_j \ + \beta_{\text{family size (j)}} * \text{Family size} \ * \ \text{Dummy}_j \ + \varepsilon \end{aligned} \quad (4)$$

The Stata 16 is used in the analysis to develop transport choice models that predict the probability of choosing an alternative based on the travel time and travel cost attributes (StataCorp, 2007). The parameters of each model are estimated by using the Stata/IC 16.1 software and RStudio (StataCorp, 2007; Team, 2015). The panel data MNL model (later referred to as MNL) is used, where the behavior of travelers across variables and across panels is checked. The data with repeated cases from the same units are referred to panel data. The MNL is presented, where the participants choose from the repeated options at different periods (number of sets in each block). The negative sign of the estimated values presents the (dis)utility of travel, which is consistent with the travel utility theory. The results are summarized in Table 3, which shows the goodness to fit criteria of the model and estimates the standard error of the mean (SEM), z value, p-value, and the exponential value of the estimates.

Finding the best-fit model of the collected data based on the properties of each model is an aim, as well. Panel data MNL model is applied as it was the best-fit model, where different distributional assumptions of random parameters are examined (Ghosh et al., 2013; Hensher & Greene, 2001). Thus, the panel data MNL is used and presented in Table 3. The developed model can be used in the prediction and determination of the impact of explanatory variables on the dependent variable.

Interpretation of estimates

The mean marginal utility of travel time is -0.035 with an SD of 0.004 based on the normal distribution of errors. The marginal utility of the travel cost is -0.129 with an SD of 0.021 based on the normal distribution of errors, as shown in Table 3. The marginal utility of travel cost is less than the marginal utility of travel time, which means that the impact of one unit of the travel time on the traveler preferences is larger than the impact of one unit of travel cost. The alternative specific constants (ASCs) show that the base alternative (car) has the highest probability compared to SAV and PAV when the variables are set to zero, while the probability of people to choose PAV is 0.93 less than choosing car, and to choose SAV is 0.89 less than choosing car.

VOT

The VOT reflects the willingness of people to pay money to decrease the travel time, and its estimated value is €39.14 per hour (-0.0092/-0.0141) * 60). The VOT of this study is larger than of Etzioni et al. (2020) study which shows around 26 euros per hour.

Regular transport mode

The regular transport mode that a traveler frequently uses affects the travelers' decisions when they choose a transport mode.

In case of SAV, the private car, public transport, shared car, walking, micro-mobility (i.e. scooters and bikes) and others show significant results at a confidence level of 95%. The probability of staying in SAV for travelers who use the private car is smaller than for those who use others by 0.67. The probability of staying in SAV for travelers who use public transport is higher than for those who use others by 1.58. The probability of staying in SAV for travelers who use shared cars is higher than those who use others by 8.04. The probability of staying in SAV for travelers who walk is higher than for those who use others by 3.69. The probability of staying in SAV for travelers who use micro-mobility is higher than those who use others by 2.16. It is demonstrated that SAV is preferred by shared car users, and walking.

In case of PAV, the private car, public transport, walking, and shared car show significant results at a confidence level of 70%. The probability of staying in PAV for travelers who use private car is smaller than those who use others by 0.70. The probability of staying in PAV for travelers who use public transport is higher than those who use others by 1.23. The probability of staying in PAV for travelers who use shared cars is higher than those who use others by 4.91. The probability of staying in PAV for travelers who walk is smaller than those who use others by 0.3. It is demonstrated that PAV is preferred by shared car users.

Income level

The income of travelers impacts the travelers' decisions when they choose a transport mode. The probability of low-income people choos-

Table 3
The estimates of parameters of the MNL model

Alternative	Variable	Value (β)	SEM	z	P>z	Exp (β)
	Time	-0.0092	0.001	-7.74	0.000*	0.97
	Cost	-0.0141	0.006	-6.060	0.000*	0.88
SAV	ASC	-0.892	0.250	-1.32	0.187****	
	Regular transport mode					
	Private car	-0.397	0.221	-1.79	0.073***	0.67
	Public transport	0.455	0.231	1.97	0.049**	1.58
	Shared car	2.084	0.362	2.42	0.016**	8.04
	Walking	1.306	0.267	2.30	0.021**	3.69
	Micro mobility	0.770	0.253	2.18	0.030**	2.16
	Others	Base	-			
	Income					
	Low income	0.241	0.088	1.28	0.199****	1.27
	Middle income	0.314	0.059	1.97	0.049**	1.37
	No answer	-0.137	0.222	-0.62	0.536	0.87
	High income	Base	-			
	Family size	0.066	0.010	1.32	0.187****	1.07
PAV	ASC	-0.931	0.270	-3.42	0.001*	0.39
	Regular transport mode					
	Private car	-0.354	0.027	-1.55	0.120****	0.70
	Public transport	0.203	0.042	1.11	0.267	1.23
	Shared car	1.594	0.064	1.56	0.120****	4.92
	Walking	-1.220	0.114	-1.09	0.274	0.30
	Micro mobility	-0.258	0.447	-0.58	0.563	0.77
	Others					
	Income					
	Low income	0.430	0.112	2.03	0.043**	1.54
	Middle income	0.288	0.125	1.65	0.100***	1.33
	No answer	0.323	0.140	1.34	0.179****	1.38
	High income	Base	-			
	Family size	-0.027	0.015	-1.31	0.190****	0.97
Car		base				

Number of observations = 5508; Number of individuals/panels: 306; Number of cases: 1836; Chi2(2) = 141.91; Log likelihood-model = -1801.72; Log likelihood (null model) = -2082.34; Prob > chi2 = 0.000; AIC = 3651.441; BIC = 3783.809.

* p<0.01

** p<0.05

*** p<0.1

**** p<0.2

Table 4
Predictive margins (Delta-method)

Alternative (i)	Margin	SEM	Z	P>z
SAV	0.331	0.010	31.820	0.000
PAV	0.227	0.010	23.140	0.000
Car	0.441	0.011	39.620	0.000

Table 5
Conditional marginal effects of the travel cost

Alternative (i)	dy/dx	SEM	Z	P>z
SAV	-0.010	0.001	-6.720	0.000
PAV	-0.004	0.001	-2.750	0.006
Car	-0.010	0.002	-5.890	0.000

Table 6
Conditional marginal effects of travel time

Alternative (i)	dy/dx	SEM	Z	P>z
SAV	-0.0018	0.000	-5.580	0.000
PAV	-0.0017	0.000	-7.250	0.000
Car	-0.0023	0.000	-6.740	0.000

ing SAV is 1.27 larger than the probability of high-income people. The probability of middle-income people choosing SAV is larger than the high-income people by 1.37. On the other hand, the probability of others' group people to choose PAV is 1.54 larger than the probability of high-income people.

Family size

The family size (household members) influences the choice of a transport mode. In case of SAV, one unit increase in the family size increases the probability of choosing SAV by 1.07. While in case of PAV, the probability is decreased when one family size is increased.

Marginal effects

The margins are applied to estimate the effects of variables on the transport choice. In Table 4, the choice probabilities are averaged over all time periods, and the predicted probability is 33.1% of the people who would use SAV, 22.7% of those who would use PAV, and 44.1% of those who would use car. The results are significant at a confidence interval of 95%. The preferences of people are still car as a first choice, SAV, then PAV based on the developed model and the collected sample data.

Table 5 and Table 6 show the direct marginal effects of the covariates on the probability of alternatives, where a change in one alternative-specific covariate (time or cost) affects the choice probabilities of the alternatives. The estimates of the direct average marginal effects (dy/dx) are around -0.01, -0.004, and -0.01 suggesting a decrease in the probability of choosing SAV, PAV, and car, respectively, if travel cost increases. This result demonstrates that SAV and car have equal direct effects when travel cost is changed, while PAV has lower direct effects than them.

Table 7
The indirect marginal effect of travel time

Alternative @ Alternative covariate mean	dy/dx	SEM	z	P>z
SAV @ PAV	0.0008	0.000	8.910	0.000
SAV @ Car	0.0010	0.000	5.450	0.000
PAV @ SAV	0.0008	0.000	8.500	0.000
PAV @ Car	0.0012	0.000	7.910	0.000
Car @ SAV	0.0009	0.000	3.990	0.000
Car @ PAV	0.0009	0.000	6.010	0.000

Table 8
The indirect marginal effect of travel cost

Alternative @ Alternative covariate mean	dy/dx	SEM	z	P>z
SAV @ PAV	0.002	0.000	5.080	0.000
SAV @ CAR	0.007	0.001	7.790	0.000
PAV @ SAV	0.002	0.000	4.990	0.000
PAV @ Car	0.002	0.001	2.770	0.006
Car @ SAV	0.007	0.001	7.320	0.000
Car @ PAV	0.001	0.001	1.350	0.177

On the other hand, the estimates of the direct average marginal effects are around -0.0018, -0.0017, and -0.0023 suggesting a decrease in the probability of choosing SAV, PAV, and car, respectively, if travel time increases. This result demonstrates that car is exposed to the highest direct effects when travel time is changed, while PAV has the lowest direct effects among them.

From the results of the direct marginal effects of travel time and travel cost, it might be concluded that the car is the largest affected mode once the travel time and travel cost are increased, then SAV, and the lowest one is PAV. The probability of people choosing car when either travel time or travel cost is changed is the lowest, while the probability of choosing PAV rises when either travel time or travel cost increases.

The indirect marginal effects of travel time and travel cost on the probability of the alternatives are shown in Table 7 and Table 8, where the impact of changing the attributes of one alternative is presented. Table 7 presents the indirect marginal effect of travel time based on the developed model. For instance, the impact of changing the travel time of alternative PAV on the probability of choosing SAV is 0.0008, while it is 0.001 in the travel time of alternative car.

Table 8 presents the indirect marginal effect of travel cost based on the developed model, such as the impact of changing the travel cost of alternative PAV on the probability of choosing SAV is a positive value of 0.002.

The direct marginal effects are higher than the indirect marginal effects, which leads to the result of the selected alternative being affected more by the occurred change in its attributes rather than other alternatives' attributes.

Discussion

The developed transport choice model estimates the preferences of a certain category of people on PAV, SAV, and car. The utility of traveling is negative in the model because traveling itself is considered unwanted (dis-utility). The marginal utility of travel time (β time) is -0.035, while the marginal utility of travel cost (β cost) is -0.126. Moreover, the probability of people choosing SAV is lower than choosing PAV, and choosing car is higher than choosing PAV. The impact of sociodemographic and travel characteristics on the mode choice is estimated, where income, regular transport mode, and family size show reasonable significant results.

The results of this study demonstrate that people are more willing to use car than PAV or SAV, while they are more attracted to PAV than SAV. This demonstrates that people are less likely to use ridesharing. In the literature, Tian et al. (2021) show that people's tendency to buy PAV is higher than SAV. Tian et al. (2021) also show that SAV is favorable over conventional cars by travelers. Etzioni et al. (2020) present that people in Hungary have reservations about using AV compared to the regular car, and Polydoropoulou et al. (2021) observe that VOT of SAV is higher than PAV. The inference of the study of Polydoropoulou et al. (2021) is that SAV is not a convenient transport mode compared to AVs and conventional cars. Hamadneh and Esztergár-Kiss (2021b) find that people are more willing to use public transport than SAV, while Hamadneh and Esztergár-Kiss (2021c) demonstrate that people are more willing to use SAV over PAV when multitasking is considered as a factor.

The direct marginal effects of the travel time and travel cost on the alternatives demonstrate higher effects on the mode choice than indirect marginal effects. For example, an increase in the travel cost of car is accompanied by a shift toward other alternatives. The values of marginal utilities of travel time, travel cost, income, transport mode, and family size variables are estimated. The marginal utility of travel cost and the marginal utility of travel time is used to calculate the VOT. Besides, the car alternative is the most sensible in case of the decrease in the travel time or travel cost, while the change in the travel time and travel cost affects PAV positively (or less negatively compared to other alternatives). This means that travelers with big families prefer using SAV over PAV.

The regular transport mode that a traveler frequently uses affects the travelers' decisions, such as the shared car users are more willing to use SAV and PAV than other transport mode users. It is demonstrated that those travelers (i.e., shared car users) prefer SAV over PAV. Middle-income and low income are more likely to use PAV and SAV than high income people. The increase in the family sizes impacts using SAV positively while the impact is negative in case of PAV. The result of this study demonstrates that people in the AV era are more likely to use AV as a private vehicle and are less attracted to ridesharing schemes even if it is an SAV. Also, car ownership will be affected to a certain extent because of the availability of PAV and SAV on the market.

Limitations and recommendations

The limitations of this study are presented in the sample size, the variety of participants, and theoretical responses as well as in the case study. The sample size is acceptable for this analysis but having a larger size definitely increases the reliability of the results and represents the population more accurately. Moreover, having a larger sample size with a wide variety of users helps the decision-makers to assess the impact of some other variables (i.e. sociodemographic, economic, and trip characteristics) on the mode choice.

It is obvious from the sample composition that skilled people have participated in this study. A convenience sampling approach was used, and the potential bias caused by the literacy level in case of online surveys has to be mentioned, thus any conclusion is conditional upon the data collected. The results are not representative of the Hungarian population. However, it represents how people would choose a transport mode in the presence of PAV and SAV, at the early age of introducing AVs. The respondents demonstrate familiarity with AVs characteristics and some of them have already tested such a vehicle. Furthermore, the focus of this study was to compare individual transport modes with each other, but it has to be noted that other transport modes may also have an effect on the mode choice. Also, the survey was distributed among people, who mostly live in an urban area, but this characteristic was not specifically asked for the respondents. It has to be noted that there may be some differences between people living in urban and rural areas.

Another limitation of the study is that the collected data does not have a large variety across sociodemographic variables. For example, 15% are female, and the people who do not own private cars are represented by 7%. Therefore, the prediction power for the groups with low percentages is not significant. The study used data from Hungary and does not include other locations. Thus, it is recommended to combine various countries and make comparisons among them. The behavior, in reality, might be different from the theoretical behavior of people because they answer the questions based on their understanding rather than their experience. This is reflected in the size of the people who have not heard about the technology and have not tried it yet. This study takes into account only three transport modes with certain characteristics, where it is assessed, how much new transport options have an impact on the transport mode choice. Private cars regardless of the number of passengers in car are studied, as well as this study considers the AV as a shared car or a privately owned car, while ridesharing is not included.

The paper presents the preferences of certain travelers towards three selected transport modes where integrating AV into the transport system is a step toward sustainable and smart mobility. It is worth mentioning that simulation studies are conducted so far in the literature to predict the mode share in the AV driving era (Hamadneh & Esztergár-Kiss, 2021a). As future research, other transport modes could be included using the same methods and framework as well as enhancing the travel experience by riding the AVs in labs or open areas.

Conclusions

The travel behavior of people toward three transport modes is modeled. The examined transport modes include PAV, SAV, and car. An SP survey and stated choice experiment are designed and distributed in Hungary. A certain group of car users is studied in this study. The discrete choice modeling approach is applied to study the behavior of people towards the three examined transport modes based on travelers' actual travel time and travel cost. The results demonstrate that the utility of traveling is negative in the model because traveling itself is considered unwanted (dis-utility), people are varied in their willingness to use a transport mode across groups, such as the income, the family size, and the current transport mode. Moreover, the results demonstrate that people are more likely to use conventional car than PAV and more to PAV than SAV. The findings of this research are encouraged to be used in policymaking that tries to manage the demand for PAVs in the future, where people show less interest in ridesharing (e.g., SAV) which leads to more vehicles on the road network.

Declaration of Competing Interest

The authors declare that there are no potential competing interests.

CRediT authorship contribution statement

Jamil Hamadneh: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Domokos Esztergár-Kiss:** Investigation, Writing – review & editing, Visualization, Supervision.

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Appendix

The survey structure and information

I had the opportunity to ask any questions and I am willing to take part in this survey

I agree

I do not agree

A1: What is the main mode of transport you use for this important journey of yours?

Private car (owned by myself or someone in my household)

Shared car (e.g. a car which is shared with other travellers)

Public transport (e.g. bus, tram, underground, metro, train)

Shuttle service to work

Private bicycle (owned by myself or someone in my household)

Shared bicycle (a shared bicycle e.g. through my city bicycle sharing scheme)

Motorbike (owned by myself or someone in my household)

Shared motorbike (a shared motorbike)

Scooter

Walking

None, as I do not travel daily

Other

A2: Some modern cars are equipped with Adaptive Cruise Control (ACC): A system that can automatically follow another car. How often did you use Adaptive Cruise Control while driving a car in the last 12 months?

Every day

4 to 6 days a week

1 to 3 days a week

About once a fortnight

About once a month

Less than once a month

Never

I do not have ACC

I do not know what ACC is

I do not drive a car

I prefer not to respond

A3: In the last twelve months, have you heard, read or seen anything about Autonomous Vehicles?

Yes

No

I do not know

An Autonomous Vehicle (AV) is a vehicle which takes over speed and steering control completely and permanently, on all roads and in all situations. The driver-passenger cannot drive manually because the vehicle does not have a steering wheel. The driver-passenger only sets the travel destination through a touch-screen.

A4: Have you ever travelled in an Autonomous Vehicle?

Yes

No

I do not know

An Autonomous Vehicle (AV) is a vehicle which takes over speed and steering control completely and permanently, on all roads and in all situations. The driver-passenger cannot drive manually because the vehicle does not have a steering wheel. The driver-passenger only sets the travel destination through a touch-screen.

Part B

You are almost done! Welcome to the second and shorter part of our survey. Now think of one of your regular journeys which starts from home at least once a week.

B1: The regular journey I am thinking of now is from home to...

Other

Work

Other professional reasons (e.g. business journeys)

School or College or University or other educational activity

Groceries, errands, administrative purposes

Leisure (e.g. sports, cultural activities)

Visiting friends or relatives

Pick-up or drop-off someone

We will use this regular journey you are thinking of as our basis in this part of the survey.

B2: The transport mode I usually use for this regular journey is...

Other

Private car (owned by you or someone in your household)

Shared car (e.g. a car which is shared with other travellers)

Public transport (e.g. bus, tram, underground, metro, train)

Shuttle service to work
Private bicycle (owned by you or someone in your household)
Shared bicycle (a shared bike e.g. through your city bicycle sharing scheme)
Motorbike (owned by you or someone in your household)
Motorbike (a shared motorbike)
Scooter
Walking
Combination of different modes
None, as I do not travel daily

B3: You may complete this regular journey you are thinking of by any mode, but we want you to imagine making this journey by car.

What is the duration of this regular journey if made by CAR?

The duration of this regular car trip is: … minutes

If you do not use a car, please try to estimate the time it would take you to complete this journey by car, including your whole door-to-door journey e.g. walking, parking.

B4: Now you will be presented with different options and you will need to choose ONE option in each question. In each question, you will be provided with three vehicle options

1. Using a Privately-owned Regular Car similar to conventional private cars used today.

2.Using a Privately-owned Autonomous Vehicle. This option is similar to Privately owned Regular Cars, but it could be a different type and size vehicle. This vehicle will drive itself without a human driver and will leave you at your destination, to then park itself.

3. Using a Shared Autonomous Vehicle which you do not own. You will be able to travel in it just by yourself (shared vehicle) or to travel with strangers (shared ride). If you choose to share it with others (shared ride), you may save some money. However, on some occasions you will waste time picking up and dropping off other passengers. Occasionally, you will be able to travel faster on special road lanes and save time travelling.

You will now be presented with the six sets of options. The Total Cost of your journey includes all vehicle costs e.g. fuel, insurance, maintenance, parking. Select please your preferred option at each screen, noting that Other Passengers travelling with you can be of different gender.

Assume that you are about to leave your home for your regular journey to … . Please choose your preferred travel option based on the characteristics provided below:

Currency sign
Minutes
OTHER PASSENGERS:
PRIVATE REGULAR CAR
PRIVATE AUTONOMOUS CAR
SHARED AUTONOMOUS CAR
For my regular journey I would choose...

Part C

Nearly done! Tell us please a few details about yourself and your household.

What is your gender?
Other
Female
Male

How old are you?
Younger than 16
Help: Please tell us your age in years.

What is the highest-level educational degree you have acquired?
Primary school or equivalent
High-school
College / University
Postgraduate
Other

What is your current employment status?
Employee
Self-employed
Company owner
Unemployed
Retired
Full-time education

How many members live today in your household, including yourself?

How many members living today in your household need caring responsibility, including yourself (e.g. children, disabled, elderly)?

What is your gross annual household income?
Less than
More than
Not willing to disclose

Do you have a valid driving licence today ?
Yes
No

How many operational cars does your household own today?

How were you informed about this survey?
Employer
Colleague
Friend or relative
Public transport authority
Car club
Cycling group
Local or Regional or National authority
Activity group
University

Thank you!

Thank you very much for your time and input which are valuable for our survey!

Follow WISE-ACT activities at http://www.wise-act.eu and @WISEACT2050

If you have any comments and questions about this survey or if you would like to participate in a future WISE-ACT survey, then please contact us at surveyAV@wise-act.eu

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Understanding the determinants of x-minute city policies: A review of the North American and Australian cities' planning documents

Michael Lu[a], Ehab Diab[b,*]

[a] University of Saskatchewan, Department of Geography & Planning, 117 Science Place, Room 10.3, Saskatoon, SK S7N 5C8 Canada
[b] University of Saskatchewan, Department of Geography & Planning, 117 Science Place, Room 111, Saskatoon, SK S7N 5C8 Canada

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ABSTRACT

The concept of a x-minute city (or 15-minute city) has recently emerged and has been endorsed by many policymakers across the globe, with the aim of achieving a wide array of economic, environmental, and social goals related to people's quality of life and community cohesion. The concept refers to developing neighborhoods in which destinations of interest are accessible locally by active transportation modes. Despite the popularity of this concept, there has been little effort to understand its determinants, and policy directions related to this concept seem thematically and geographically dispersed. To address this gap in the literature, this study aims at understanding the developed x-minute city policies across North America and Australia. To achieve this goal, a detailed analysis of different x-minute city policies that have been recently developed was conducted. Using scholarly work, news articles, and a systematic identification approach several cities in North America and Australia were identified to be included in the research by reviewing their planning documents. In total, 15 cities were identified with very recent plans and documents that incorporated the concept of x-minute cities. Based on the analysis, several cities incorporated the concept of x-minute city with the idea of achieving complete local living, while introducing several targets, goals, and measures. Nevertheless, most of the cities operationalized the concept differently by using various types of modes of transportation, cut-off values, and destinations. This study offers transit practitioners and planners a better understanding of the determinants of the concept, helping them in incorporating it into future plans.

1. Introduction

The concept of a 15-minute (or x-minute) city has recently emerged as a popular planning approach and has been endorsed by many policymakers across the globe. First introduced by Carlos Moreno in 2016, the concept has gained increased interest in popular media and has been introduced at policy level in various cities (Moreno et al., 2021). For example, the mayor of the City of Montréal in Canada has pledged to move Montréal towards carbon neutrality by 2050 by building a "15-minute" city, in which residents will have access to different amenities and services close to home (Bruemmer, 2021). Similarly, the mayor of Paris in France has pledged to transform Paris into a "15-minute" city during her re-election campaign (Willsher, 2020). Another good example is Milan's Piazze Aperte program, which aims to redesign streets as places of social interaction, with about half of Milan residents now living within 15 min of a piazza aperta (City of Milan, 2022). This emerging vision not only aims to reduce emissions, but also to achieve a wide array of social goals such as improving people's quality of life and community social cohesion. The concept has also seen a surge of interest with the wake of the COVID-19 pandemic. The pandemic "exposed the vulnerability of cities in their current establishment" and "prompted the need for novel and innovative mechanisms for cities to pursue their economic activities while enforcing strict health protocols" (Moreno et al., 2021).

The x-minute city concept, which is commonly known as the 15-minute city concept, refers to developing complete neighborhoods in which destinations of interest are accessible by walking and/or cycling within 15 or 20 min from home (C40 Cities, 2020). This concept offers an intuitive, easy-to-understand, adaptable, and popular vision of urban living that has recently been introduced around the world with examples including Ottawa's 15-minute neighborhood, Portland's complete neighborhoods, Melbourne's 20-minute neighborhoods, and more.

Despite the popularity of this concept, there has been little effort to understand the determinants of the concept and how it was utilized. Additionally, policy directions related to this concept, in general, seem thematically and geographically dispersed. To address this gap in the literature and practice, this research aims at understanding the developed x-minute city policies across cities in North America and Australia. To achieve this goal, a detailed analysis of different x-minute city poli-

* Corresponding author.
E-mail address: ehab.diab@usask.ca (E. Diab).

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cies that have been recently developed was conducted. This policy analysis aims at assessing how each city defines the concept in terms of what types of destinations were included, how these destinations were weighted, which modes were chosen, and selected cut-off values. The analysis also looks at which performance measures were utilized to achieve and measure the success of 15-minute city's objectives, and to what extent equity and other issues were taken into consideration. Using scholarly work, news articles, and a systematic identification approach several cities in North America and Australia were identified to be included in the research by reviewing their planning documents.

It should be noted that as the concept is more known as the "15-minute city," in this study, we use "x-minute city" interchangeably with "15-minute city." By synthesizing information related to the x-minute city concept, the paper contributes to our current understanding of how the concept can be incorporated, operationalized, and communicated, helping cities and policy makers in developing sustainable communities. This paper starts with a literature review section that discusses the relationship between the concept of accessibility and the x-minute city concept. Then, the paper discusses the methodological approaches used to identify cities that implemented the concept and extract data from their planning documents. It, then, provides an in-depth analysis of the developed x-minute city policies from the identified cities' documents, while focusing on discussing how the cities incorporated and operationalized the concept, and how it was intersected with other areas of concerns such as equity.

2. Literature review

2.1. Accessibility

Accessibility is a major component of the concept of a 15-minute city. A steady increase in interest in active mobility and accessibility through proximity in recent years has promoted the concept of the "15-Minute City" as an organizing principle for urban development (C40 Cities, 2020). However, despite being a major component of the concept of the "15-Minute City", accessibility as a concept is often misunderstood, poorly defined, and measured in an inconsistent manner (Geurs & van Wee, 2004; Boisjoly & El-Geneidy, 2017).

There are several definitions for the concept of accessibility. According to Hansen, which is one of the earliest efforts that define accessibility, accessibility is a measure of *"the potential for opportunities of interaction"* (Hansen, 1959). Geurs and van Wee (Geurs & van Wee, 2004) defined accessibility as the extent to which land-use and transport systems enable individuals to reach activities by means of different transport modes. A considerable number of studies introduced and investigated the use of the concept of accessibility in the academic literature, for example, Bertolini, Clerq and Kapoen (Bertolini et al., 2005) used the concept of accessibility as a framework for the integration of land use and transport planning. Wu et al. explored accessibility across the globe using different transport modes (Wu et al., 2021). Several studies used the concept of accessibility to explain changes in travel behavior. For example, Geurs and Van Wee explored the main components of accessibility, while Boisjoly and El-Geneidy (Boisjoly & El-Geneidy, 2017) assessed 32 metropolitan transport plans and their accessibility objectives and indicators. Moreover, studies like Lussier-Tomaszewski and Boisjoly (Lussier-Tomaszewski & Boisjoly, 2021) investigated the influence of local and regional accessibility on the transport mode used commuting for work trips in Montreal. Other studies focused on distinguishing between local and regional accessibility. Local accessibility generally refers to what people can access around them within 5- or 10-minutes walking distance, while regional accessibility is related to what people can access within the region (Handy & Niemeier, 1997; Levinson & Krizek, 2018).

Accessibility is often measured through a simple count of all specific destinations reachable within a certain threshold via a chosen method of transportation (Handy & Niemeier, 1997). This is the simplest approach and is known as the cumulative opportunities approach. El-Geneidy and Levinson (El-Geneidy & Levinson, 2007) used the cumulative opportunities measures at 15 min travel time to compare job accessibility via car and transit from 1990 to 2000 in the Minneapolis-St. Paul region. Deboosere and El-Geneidy (Deboosere & El-Geneidy, 2018) further refined the cumulative opportunities approach by acknowledging that not all destinations, in this case jobs, are available for everyone. They identified vulnerable residents and compared their accessibility to low-income jobs to that of all jobs across Canada's 11 largest metropolitan regions. Similarly, Ermagun and Tilahun (Ermagun & Tilahun, 2020) used the cumulative opportunities approach to examine the equity of transit accessibility in the City of Chicago across six different destinations and reinforces the necessity to address inequities on a case-by-case basis. Chen and Wang (Chen & Wang, 2020) evaluated the variety of urban opportunities and population groups from a green transportation perspective. Another recent study used 30-minute cumulative access to jobs for four different methods of transport to examine the relationship between population-weighting access and metropolitan population in global metropolitan cities (Wu et al., 2021). Zuo, Wei, and Chen (Zuo et al., 2020) examined how transit ridership would increase via hardening first and last mile connections through modeling commuters' transit use. In 2020, Bree, Fuller, and Diab (Bree et al., 2020) studied local transit accessibility for the City of Saskatoon using multiple accessibility measures, including a gravity-based measure that applies a distance decay function. It should be noted that most of the discussed studies used different isolated accessibility measures to a specific destination, in contrast to the concept of 15-minute city that calls to improve accessibility to several destinations by more than one mode. Additionally, it is important to understand the usage of accessibility and how to measure it due to their use in the reviewed cities below. Many cities used a common accessibility approach (i.e., cumulative opportunities) to measure their success in implementing the "15-minute city" concept.

2.2. 15-minute city

The 15-minute city concept refers to developing complete neighborhoods in which destinations such as quality public schools, grocery stores, public libraries, and other commercial services, parks and recreational facilities, and healthcare services are accessible by walking and/or cycling within 15 min from home (C40 Cities, 2020). This is different from the concept of "neighborhood unit" that was first introduced by Clarence Perry in the late 1920s, which utilized the 5-minute walk to define the area of neighborhoods (Perry, 1929). This neighborhood unit includes cores of urban amenities that can be reached be walking, with elementary schools as one of the main functions, which is surrounded by a hierarchical system of separated urban amenities to form larger subdivisions and then cities. Stemming from this concept segregation of land uses was used as a model for developing suburban areas and urban planning until recently (Smętkowski et al., 2021). In contrast to this model, the 15-minute city concept mainly calls for the redistribution of amenities to be accessible by active transportation modes from people locations (Di Marino et al., 2022). Moreno, Allam, Chabaud, Gall, and Pratlong examined temporary infrastructure services implemented during the Covid-19 pandemic that coincides with the pursuit of the "15-minute city" concept. They have stated that "its adoption in long-term planning would result in a higher quality of life" (Moreno et al., 2021), by decreasing congestion and increasing the use of sustainable transport modes. Caselli, Carra, Rossetti, and Zazzi (Caselli et al., 2021) examined the relationship between the 15-minute city and the concept of Perry's neighbourhood unit, along with the concept of New Urbanism, Transit Orientated Development, Slow cities, and Organic urbanism. They also proposed a GIS-based method for evaluating accessibility to public services at the neighbourhood level.

Only very few studies focused on quantifying the concept or providing a methodological approach to measure it (Kamruzzaman, 2022; Pozoukidou & Chatziyiannaki, 2021). For example, Pozoukidou and Chatziyiannaki (Pozoukidou & Chatziyiannaki, 2021) provided a methodological review of three case cities that have adopted the "15-minute city" model. These cities were Portland, Oregon, Melbourne, Australia and Paris, France. This study evaluated each of these cities' approaches and identified their weak, medium, and strong attributes. They found that 15-minute cities are neither radical nor a -fit for all-idea. Kamruzzaman (Kamruzzaman, 2022) studied the statistical areas of Greater Melbourne to identify five different 20-minute neighborhood typologies based on the distribution of amenities, population threshold, and street patterns. A study published in 2019 proposed a practical approach to measuring 15-minute walkable neighborhoods, using varying weights for amenities based on the percentage of age groups to account for social inequalities in walkability (Weng et al., 2019). Di Marino, in a recent study explored the relationship between the 15-minute city concept and the distribution of collaborative new working spaces in the two cities of Oslo and Lisbon (Di Marino et al., 2022). A variation of the concept proposed by Da Silva, King, and Lemar is called the "20-minute" city (Capasso Da Silva et al., 2020). Besides the different distance-based indicator, this concept includes transit as a method of travel for residents. Despite the previous efforts, none of them synthesized how different cities incorporated, measured, used, and communicated the concept of 15-minute cities in their planning process to achieve a large range of goals. This is important to help planners and transport professional in understanding of how the concept can be incorporated and operationalized, assisting cities in developing more sustainable and equitable communities.

3. Methodology

A systematic method was adopted in this paper to identify cities that introduced the 15-minute city concept and to analyze their policy documents regarding the concept. This process included two major stages. The first stage started with reviewing recent reports and manuals, transportation research centers publications, and news articles regarding accessibility and 15-minute cities to identify which cities are in the process of or have already implemented this concept into practice. Then, a separate search was devoted to reports and documents produced by cities and their planning agencies. The second stage utilized a systematic review method to identify relevant sections in these planning documents and reports to analyze their contents, while understanding the documents' overall scope and purpose. These reports and documents are important outputs that represent the cities' policies and approaches used to communicate these vital aspects to the public. The following section discusses this process in more detail.

The scope of this analysis focused on cities within North America and Australia due to the large similarities between both in terms of land use, density, and transportation systems, which helps in understanding the implemented policies within a comparable context. For example, recent research indicated that Australian, Canadian, and American cities have comparable accessibility to jobs by different modes (active transportation modes, transit, and car) that is lower than accessibility in other areas in China and Europe (Wu et al., 2021). The first stage sought to investigate which cities are in the process, or already implementing policies regarding 15-minute cities. To achieve this goal, two sub-tasks were performed. The first subtask (Subtask 1) is to identify some cities using news articles, academic papers, and other resources such as blogs, manuals and transportation research centers publications (Pozoukidou & Chatziyiannaki, 2021; Levinson & King, 2020). The second subtask (Subtask 2) is to use population data collected from the national censuses for Canada, Australia, and the United States to identify the top 20 most populous cities for each of these countries. These cities were then included into a search strategy to identify whether that city has any documentation regarding the 15-minute city concept.

For the second stage, a search process was carried out to collect the documents, which included two phases of web-based searches. The first phase (Phase 1) involved using the Google search engine, and through a basic syntax, *("city name" AND ("15 min city" or "20 min city" or "complete neighborhood")*. This is done to identify cities that have implemented or are implementing the 15-minute city concept. The search protocol for Google was on a page-by-page basis, such that if no relevant information was found on the first page, then there would be no proceeding to the second page, and so on. Using these very general research keywords on Google helped in identifying a wide array of relevant news articles, documents, and blogs, which were reviewed to understand if a city has introduced or are introducing the concept. If the city is still introducing the concept, with no relevant planning or policy documents to guide their implementation, it was considered "emerging" city. In contrast, if the city has any official planning or policy documents that included sections related to the concept, it was considered an "implemented or in the process of implementation" cities. The outcomes of this process were documented in Ms-Excel sheets for revisiting. This resulted in the identification of 15 cities and 1 additional neighborhood within one of those cities that had information regarding the 15-minute city concept. More importantly, this search provided a guide of relevant keywords for each city to be used for the second stage of web searches. This was important because different cities used different wording when implementing the concept, for example Portland has a 20-minute city approach, while Brampton calls it a complete living.

Table 1
Results from Google search.

Number of cities	Status
38	No information
10	Emerging
15	Implemented or in the process of implementation

The second phase (Phase 2) of the search focused on identifying official documentation, reports, and publications by cities and was performed using the Google search engine. This search followed the general principal of Phase 1, using the keywords identified, a search query was performed for each city. The syntax for this search is as follows: "city name" AND "keyword". This provided documents and more importantly the official city's planning agencies webpages, which were used to extract the relevant documents. With these cities identified, a comprehensive review of city webpages, documents, and official plans and policies was conducted, identifying factors and accessibility parameters incorporated into their 15-minute city policies. In total, 24 plans, reports, and documents were identified for the 15 cities and additional neighborhood, each of which was subject to an in-depth review. After downloading all the relevant documents and keeping a PDF copy of relevant webpages, a screening process using keywords was used to identify sections of plans that discuss the 15-minute city concept. The criteria for which included using a wide array of key words that included "Keyword in Context," "minute", or "complete." After identifying the relevant section, these sections were reviewed in depth while recording the results in Ms-Excel sheets. While reviewing these sections another keyword search was conducted to ensure the identification of certain ideas. These keywords included "equity," "inclusion," "fund", "safety," "security," "gentrification," "segregation," "mental," and "mobility," to ensure the inclusion of these issues in the analysis. This is combined with reviewing the documents' overall structure, purpose, and scope to understand the context. Finally, using cities websites and different links in documents, the use of visualizations such as videos, diagrams, or maps to present the concept of 15-minute cities were identified.

4. Results

The first stage of this research was to identify cities with the 15-minute city concept. In total, 63 cities were included in the process (3 from Subtask 1 and 60 from Subtask 2). From the original 63 cities, 15 cities were found to have relevant information to this study, while 10 cities were identified as emerging (see Table 1). "Emerging" means

Table 2
Cities and their keywords.

City	Country	Keyword/ Policy objective
Ottawa	Canada	15-minute neighborhoods
Portland	US	20-minute living
Sydney	Australia	Walkable neighborhoods
Montrose	US	20-minute neighborhoods
Houston	US	Complete communities
Melbourne	Australia	20-minute neighborhoods
Edmonton	Canada	Community of communities
Vancouver	Canada	Complete community
Brampton	Canada	Complete living
Surrey	Canada	15-minute neighborhoods
Waterloo City	Canada	20-minute city
Los Angeles	US	Complete neighborhoods
San Antonio	US	Complete neighborhoods
Charlotte	US	15-minute neighborhoods
Greater Newcastle	Australia	15-minute region
Launceston	Australia	15-minute city

that there were discussions related to the concept in newspapers, online official forums, and websites, but with no further planning and policy documents yet. An example of an emerging city would be Detroit. Detroit's city Mayor Mike Duggan gave a keynote address in 2016 that laid out his vision for 20-minute neighborhoods in Detroit (Runyn, 2016). However, no further documents could be found to show their progress towards the concept implementation.

Table 2 includes the list of cities that incorporated the 15-minute city concept along with the identified keywords. These cities along with the accompanying keywords were used in Phase 2 to identify official publications from these cities. Of the 15 cities, 13 had documents such as city official plans, regional plans, or transportation plans related to 15-minute cities. Two had mainly information related to 15-minute cities on their official websites, with some planning documents supporting it, these two were Houston, TX and Surrey, BC. Additionally, the neighborhood of Montrose, Houston was identified as having its own plan with relevant information regarding the 15-minute city concept and was subject to the in-depth review.

4.1. How the 15-minute cities concept incorporated, defined, and measured

This section explores how cities incorporated and defined the concept. It also looks at what actions or measures were used to progress it, while looking at how public feedback were incorporated. A summary of findings from all documents can be found in Table 3 . Collectively, this section focuses on the implementation strategy and guiding principals that were developed by each city.

4.1.1. 15-minute city concept in urban plans

This section discusses how different cities incorporated the concept in their plans, while the following section discusses in more detail how it was defined. As seen in Table 2, the concept was incorporated into the planning document as a policy objective using different wording. In total, six out of the 15 cities included in the analysis incorporated the concept of 15-minute city with the idea of achieving "Complete Living," "Complete Neighborhoods" or "Complete Communities." While using the wording of "complete" communities, living, and neighborhoods might make it easier for the public to understand, other cities used other wording. For example, one city incorporated it as achieving "Walkable neighborhoods" as in the case of Sydney. The rest of the cities incorporated the concept using direct wording of "15-minute neighborhoods," "20-minute neighborhoods," "15-minute city," and "20-minute living." In other words, most of the cities added a time threshold of "x-minute" to the policy name. This might be related to that this concept has started to get more popularity among the public and policymakers over the past few years (Bruemmer, 2021; Willsher, 2020; City of Milan, 2022; C40 Cities, 2020).

As seen in Table 3, 12 cities out of 15 cities have incorporated the 15-minute city concept as a goal, target, or planning priority. The rest of the cities incorporated it as an indicator to achieve other goals or included it in their general discussion. Cities that have formated the concept as a goal and planning priority often have detailed benchmarks or targets for its implementation. For example, cities like Ottawa, Portland, Melbourne, Edmonton, and Brampton (City of Brampton, 2018; City of Edmonton 2020, City of Melbourne 2016, City of Ottawa 2021, City of Portland 2012) have detailed lists and action plans for the incorporation of this concept. In contrast, cities like Vancouver (City of Vancouver 2012, City of Vancouver 2015) acknowledged that complete communities will help with the high cost of housing, but they did not provide information regarding how they will meet their goals. The concept was mainly incorporated in cities' official plans and action plans. A few cases such as in Vancouver and Waterloo was the concept integrated into city transportation plans.

4.1.2. Definition and rational

There is a great overlap between cities in terms of how they define and rationalize the implementation of the concept. Most cities define the concept in terms of enabling residents to access everyday needed services and places, while focusing on incorporating a specific time or distance, or a general sense of distance or time in order to make it easier to comprehend. For example, Melbourne defines it as the ability of residents to live locally by meeting most of their daily needs within a 20-minute walk from home, or within safe cycling and local transport options (City of Melbourne 2016, Victoria State Government 2022). The 20-minute neighborhood is all about 'living locally'—giving people the ability to meet most of their daily needs within a 20-minute walk from home. Similarly, Waterloo defines it as the ability of residents to have convenient access to everyday services and places within a 20-minute walk of their home (City of Waterloo 2021). On the same line, Vancouver defines a "complete community" as one that provides all needed services that residents use within a convenient distance from where they live.

Other cities provided more generalized definitions related to residents' experience and well-being. For example, Edmonton, which looks at it from a "community of communities" perspective, is defining it in terms of making big city life feel less anonymous and more personal (City of Edmonton 2020, City of Edmonton 2020). San Antonio looks at it as a way of providing residents with safe and convenient access to the goods and services they need on a daily or regular basis (City of San Antonio 2016, City of San Antonio 2022). A few cities used a definition that linked the concept to a number of subobjectives such as Montrose and Houston. For example, Montrose defines a successful 20-minute neighborhood as a neighborhood that is safe, connected, affordable, and with enduring livability (Montrose TIRZ 27 2020). All definitions focused on the idea of access from residents' home. Only a few definitions went beyond distance-based approaches to incorporate more goals related to residents' experience and well-being.

4.1.3. Targets and goals

The concept of 15- minute cities was mainly utilized to achieve several goals that are related to increasing local access to services and amenities to encourage the use of active transportation modes, reducing emissions, and improving residents' health. More specifically, several cities including Portland, Vancouver, Brampton, and Edmonton employed the concept to improve local access to amenities and services that are needed by residents. For Vancouver, the target is to ensure that 90% of people live within an easy walk or roll of their daily needs by 2030 to allow people to easily complete their daily needs locally. For surrey, the target is to have 75% to 90% of households by 2050 to meet our climate targets. For Portland, the target is to increase the percentage of population with safe walkable access to goods and services to 80%.

A few cities linked the concept to achieve mode share goals. Ottawa, for example, is seeking to achieve the goal of having most of trips made

Table 3
Summary of documents.

City	Document type	Incorporation	Definition/rationale	Key targets/goals	Measures/actions	Public feedback
Ottawa (City of Ottawa 2021)	Official plan & documents	Target goal, detailed plans	Healthy, walkable, 15-minute neighborhoods are compact, well-connected places with a clustering of a diverse mix of land uses	Big Policy Move 2: By 2046, most trips in the city will be made by sustainable modes.	Cumulative opportunities approach, measuring access to amenities and services	Yes
Portland (City of Portland 2012)	Official plan	Target goal, detailed plans	Businesses, frequent transit service, schools, parks or greenspaces and other amenities close enough to safely and easily walk or bike	To increase the% of population with safe walkable access to goods and services to 80 percent	% of population within 1/2 mile of a grocery store, a park, an elementary school, and frequent transit	Yes
Sydney (City of Sydney 2020)	Official plan	Planning priority	Plan local neighborhoods so people have access to daily needs within a 5–10-minute walk	To achieve 13 priorities and a series of actions to achieve the vision	Growth in cycling and walking activity at key locations around the city	Yes
Montrose, Houston (Montrose TIRZ 27 2020)	Action plan	Target goal, detailed plans	Four pillars define a successful 20-minute Neighborhood as (1) Safe, (2) Connected, (3) Affordable, and with (4) Enduring livability	To achieve the five goals of the plan	Sidewalk quality assessment	Yes
Houston (City of Houston 2020)	Action plan & documents	General discussion	A more equitable and prosperous city so that all of residents can have access to quality services and amenities.		Bike share usage Length in miles of constructed bikeways	Yes
Melbourne (City of Melbourne 2016, Victoria State Government 2022)	Official plan & documents	Target goal, detailed plans	The ability to meet most of their daily needs within a 20-minute walk from home, with safe cycling and local transport options	To optimize active transport by having safe, accessible, and well-connected pedestrians and cyclists' networks	Achieve a minimum density of at least 25 dwellings per hectare.	Yes
Edmonton (City of Edmonton 2020, City of Edmonton 2020)	Official plan & documents	Target goal, detailed plans	A Community of Communities is about making big city life feel less anonymous and more personal	50% of trips are made by transit and active transportation, and districts that allow people to easily complete their daily needs	Number of daily trips using active modes by district, transit ridership, bicycle paths/lanes per population, population within 0.5 km of transit, population within reasonable distance to services	Yes
Vancouver (City of Vancouver 2012, City of Vancouver 2015)	Transportation Plan & Action Plan	General discussion	A complete community is one that provides the services we use all within a convenient distance from where we live	To ensure 90% of people live within an easy walk or roll of their daily needs by 2030.	None	Yes
Brampton (City of Brampton 2018)	Official plan & documents	Target goal, detailed plans	Clustering buildings and activities to bring origins and destinations closer together, mixing uses to foster links	Develop 5 new town centers	Complete neighbourhood audit to develop individual improvement action plans Neighbourhood audit committee members to remain active after plans are adopted to monitor implementation	Yes
Surrey (City of Surrey 2021, City of Surrey 2022)	Transportation Plan & documents	Target goal	Residents can meet their daily needs within a safe and easy walk, roll, or cycle trip from home	To have 75% to 90% of households by 2050 in 15-minute areas	None	Yes
Waterloo city (City of Waterloo 2021)	Transportation plan	Target goal, detailed plans	Residents have convenient access to everyday services within a 20-minute trip of their home	To have reasonable services within a 20-minute walking radius	Measure percentage of population within 250 m of a bikeway that connects to a given destination	Yes
Los Angeles (City of Los Angeles 2019)	Official plan	Target goal	Focus on neighborhoods within a 15-minute walk, or half-mile, of the transit stations or corridors.	To ensure all residents have access to high-quality mobility options by 2028, access to fresh food and parks for specific segments	Increase L.A.'s average Walk Score to 75 by 2025, and track park area per residents	Yes
San Antonio (City of San Antonio 2016, City of San Antonio 2022)	Official plan	Target goal, detailed plans	A neighborhood that provides residents safe and convenient access to the services they need on a daily or regular basis	To increase number of walkable neighborhoods (Walk Score over 50)	Measure access to schools, parks, grocery stores, sidewalks, and transit.	Yes

(continued on next page)

Table 3 (*continued*)

City	Document type	Incorporation	Definition/rationale	Key targets/goals	Measures/actions	Public feedback
Charlotte (City of Charlotte 2021, City of Charlotte 2021, City of Charlotte 2021)	Official plan	Target goal, detailed plans	All households should have access to essential amenities, goods, and services within a 10-minute walk, bike, or transit trip	To provide opportunities for people to live, work, and play and shift from single use neighborhoods	Use an app to identify critical areas and measure 4 equity metrics: access to essential amenities, goods, and services, access to housing opportunities, access to employment opportunities, environmental justice	Yes
Greater Newcastle (State of New South Wales 2021)	Regional plan	Target goal, detailed plans	Mixed neighborhoods where people can access their everyday needs within a 15-minute walk or cycle from where they live.	To consider three elements: Time of travel, mode, and types of services or uses	Split measures into rural, suburban, and urban center contexts	Yes
Launceston (City of Launceston 2021)	Transport strategy	Target goal, detailed plans	To provide residents, workers, students, and visitors with 15-minute access to their nearest activity centers and health and education facilities via active modes and transit.	To achieve three key themes: A livable, healthy, and connected Launceston	Use of a customer connectivity tool to measure how many activity centers, health facilities and education facilities people can access	Yes

in the city by sustainable transportation by 2046. It should be noted that the goals and targets were different according to the document type. For example, regional plans focused more on general goals than city comprehensive plans and transportation plans. In some transportation documents, it was common to see the goal of improving accessibility to high-quality mobility options. In contrast, other cities such as Sydney and Montrose targeted to achieve several priorities and goals.

4.1.4. *Measures and actions*

Several actions and measures were discussed in the documents in regards to how they will track the progress towards achieving the success of their 15-minute city implementation. In total, ten cities out of the 15 cities provided in-depth and detailed measures and actions, while discussing the use of key indicators and framework of measurements. For example, Ottawa provides supporting implementation policies through their new official plan, with metrics benchmarking the success of their plan using a cumulative opportunities approach to amenities and services. Portland provides a list of the percentage of their population within a certain distance to amenities and services as a measure of the success of their 20-minute city concept. Sydney measures the success of their plan through the growth in active transportation at key locations and intersections. Melbourne provides a minimum dwelling density as a measure of success. Edmonton offers a transit ridership per capita value and number of daily trips using transit and active transportation as a measure of success. Brampton provides a standard evaluation framework addressing distance parameters to amenities and services as a measure of success. San Antonio also measures residents' local access to schools, parks, grocery stores, sidewalks, and transit.

Other cities incorporated using online datasets and tools in the measurement. For example, Los Angeles used the idea of measuring the changes in Walk Score (Walk Score® 2022), by targeting to increase the city Walk Score to 75 by 2025, while tracking other indicators such as park area per resident. Walk Score is a common land use accessibility measure that is commonly used to understand land use mix (Diab et al., 2021). In contrast, Charlotte (City of Charlotte 2021) provides a community resource center connection tool to identify critical areas through four equity metrics, while Launceston (City of Launceston 2021) offers a customer connectivity tool as a way to measure how many specific services and amenities residents can access within a set time.

4.1.5. *Public feedback*

This section discusses the extent to which public feedback was explicitly mentioned in the planning document while discussing the development of the 15-minute city policies. As seen in Table 3, all the analyzed documents stressed the use of public feedback. Different public engagement tools were used to incorporate the 15-minute city concept, which includes social surveys, in-person community workshops, online workshops, community feedback forums, and more. This shows the alignment of the concept with the community feedback.

Some cities were more explicit about using public feedback in order to define some of the parameters of the concept. For example, public feedback was used by Ottawa, Edmonton, and Surrey (City of Ottawa 2021, City of Edmonton 2020, City of Surrey 2021, City of Ottawa 2021) to identify what type of destinations that are more important within x-minute neighborhoods for residents. To do that, a public survey was conducted in Ottawa to determine the priority score of different destinations. Using this information, cities were able to determine destination weighting to be incorporated while operationalizing the concept.

4.2. *x-minute city concept related goals*

This section focuses on the x-minute city concept intersection with different goals that have been discussed frequently in the documents. It should be noted that some of these goals (such as equity) will not be exclusively achieved by the adaptation of 15-minute city concept, but rather their implementation will be fostered by the concept. Table 4 provides a summary of goals that intersected with the concept. In this section, when plans state them as a goal or objective in relationship to the x-minute city concept, they were marked as addressed, if the documents went beyond this and provided tangible actions or policies to achieve them, they were deemed to have operationalized them.

4.2.1. *Equity*

Equity was a major concern that was frequently cited by cities as a desirable outcome of their "complete" or "x-minute" neighborhoods. In fact, all the reviewed plans addressed equity in relation to the concept definition or implementation. For instance, Charlotte states for their 10-minute neighborhood goal that "all Charlotte households should have access to essential amenities, goods, and services" as a response to what they received from community comments, in particular that the city should "address disparities and inequity in access to basic daily households needs" (City of Charlotte 2021). A fewer number of cities discussed how equity can be operationalized by providing measures or actions addressing equity. In total, 10 cities operationalized the concept. Ottawa is a good example. It operationalized the inclusion of equity using a Neighborhood Equity Index, an index that provides a composite equity

Table 4
15-minute city concept intersection with other goals.

City	Equity	Safety and personal security	Gentrification/ Segregation	Funding	Perception of inhabitants	Mobility hubs (multi-modal)
Ottawa (City of Ottawa 2021)	A, O	A, O	A, O	A	A, O	A, O
Portland (City of Portland 2012)	A, O	A, O	A, O	A, O	A, O	A, O
Sydney (City of Sydney 2020)	A	A				
Montrose, Houston (Montrose TIRZ 27 2020)	A, O	A, O	A	A, O	A, O	
Houston (City of Houston 2020)	A, O	A, O		A, O		
Melbourne (City of Melbourne 2016, Victoria State Government 2022)	A	A	A	A, O	A, O	A, O
Edmonton (City of Edmonton 2020, City of Edmonton 2020)	A, O			A	A, O	A, O
Vancouver (City of Vancouver 2012, City of Vancouver 2015)	A			A, O		A
Brampton (City of Brampton 2018)	A, O	A			A	A, O
Surrey (City of Surrey 2021, City of Surrey 2022)	A	A, O	A, O	A	A, O	
Waterloo city (City of Waterloo 2021)	A, O		A, O	A		
Los Angeles (City of Los Angeles 2019)	A	A, O	A, O	A		A, O
San Antonio (City of San Antonio 2016, City of San Antonio 2022)	A, O	A	A		A	A
Charlotte (City of Charlotte 2021, City of Charlotte 2021, City of Charlotte 2021)	A, O	A	A, O	A, O		
Greater Newcastle (State of New South Wales 2021)	A	A	A		A	
Launceston (City of Launceston 2021)	A, O	A		A	A, O	A

Notes: *A* = Addressed; *O* = Operationalised.

score through 28 indicators and geographically defines vulnerable areas. Based on the index, they can address specific land use, transportation, and infrastructure needs for different neighborhoods (City of Ottawa 2021).

4.2.2. Safety and personal security

Cities also addressed the safety and personal security of residents in relation to their 15-minute city plans. A total of 13 different city plans addressed this. For example, Melbourne addressed this in their plan by stating that they want to “create neighborhoods that support safe communities and healthy lifestyles” (City of Melbourne 2016). Another example was the neighborhood of Montrose, which offered dedicated bike lanes as a method of security from vehicle traffic (Montrose TIRZ 27 2020). Six cities provided solid measures on how to operationalize this. These cities include Ottawa, Portland, Montrose, Houston, Surrey, and Los Angeles. To give an example, Ottawa operationalizes this through the principle of Crime Prevention Through Environmental Design, as well as community safety audits by community associations to supplement the safety assessments of specific locations to foster their x-city implementation (City of Ottawa 2021).

4.2.3. Gentrification and segregation

Cities also discussed gentrification concerns regarding improvements to existing neighborhoods. Gentrification is related to low-income populations displacement due to the arrival of more affluent residents and businesses. An associated term that was discussed in some of the planning documents is segregation, which is related to the physical separation of different groups of residents based on race, income, or both. In total, 10 different cities addressed one or both issues. One example is Montrose, which addressed this by acknowledging that they “should remain affordable for people in all stages of life, from student to new families and aging retirees” (Montrose TIRZ 27 2020). Only five cities provided actions and measures that would combat this. These cities include Ottawa, Portland, Surrey, Los Angeles, and Charlotte. For example, Portland operationalizes this through “investments, incentives, and other policy tools to minimize or mitigate involuntary displacement resulting from new development and economic change in established communities” (City of Portland 2012).

4.2.4. Dedicated funding

Several cities talked about where funding specific to the concept would come from. In total, 12 different cities addressed this. These cities include Ottawa, Portland, Montrose, Houston, Melbourne, Edmonton, Vancouver, Surrey, Waterloo, Los Angeles, Charlotte, and Launceston. Ottawa as an example stressed that their 15-minute neighborhoods will be supported by funding for transit and infrastructure (City of Ottawa 2021). Six cities provided plans on how their plans can be supported, these cities include Portland, Montrose, Houston, Vancouver, Waterloo, and Charlotte. For example, Charlotte uses their Community Benefits Agreement to provide funding for complete neighborhood development (City of Charlotte 2021). One notable city regarding funding is Brampton, where there is a current discussion on-going to ultimately make transit free to everyone (City of Brampton 2018).

4.2.5. Perception of inhabitants

A total of 10 cities discussed addressing the mental and emotional state of residents by implementing the concept. These cities include Ottawa, Portland, Montrose, Melbourne, Edmonton, Brampton, Surrey, San Antonio, Greater Newcastle, and Launceston. A good example is Waterloo, as it stresses that residents in 20-minute city using active transportation are “getting exercise and lowering their risk of cardiovascular disease, cancer, and have improved mental health” (City of Waterloo 2021). Another example is Launceston, who suggested a gap between people’s desires and current actions regarding commuting by walking and their social and mental health. They found that although 76% of respondents considered walking as their most-preferred or second most-preferred transport mode, only 7% currently commute by walking (City of Launceston 2021). About half of the cities (seven out of 15) provided actions on how to operationalize this, they include Ottawa, Portland, Montrose, Melbourne, Edmonton, Surrey, and Launceston. For example, Melbourne operationalized this by providing a wide array of urban and social services to promote mental health, social inclusion, sense of belonging, and participation (City of Melbourne 2016).

4.2.6. Mobility hubs

Mobility hubs can be defined as locations that “bring together public, shared and active travel modes with some public realm improvement and an identifying sign” (Dilks, 2021). Nine different cities discussed the link or the inclusion of mobility hubs in their x-minute plans. These cities include Ottawa, Portland, Melbourne, Edmonton, Vancouver, Brampton, Los Angeles, San Antonio, and Launceston. To give an example, San Antonio mentioned that "our transportation corridors should serve multiple modes of transportation and better balance the needs of pedestrians, cyclists, transit patrons, motorists and freight vehicles" (City of San Antonio 2016). Another example comes from the City of Edmonton with their nodes and corridors policies, which provide connections within and across districts and are destinations in themselves (City of Edmonton 2020). Only six cities provided actions on how to operationalize this, they include Ottawa, Portland, Melbourne, Edmonton, Brampton, and Los Angeles. Portland operationalizes this by linking neighborhood centers, employment areas, the central city, and the broader city through a multi-modal transit system, ensuring places prioritize safe and attractive frequent transit service, bikeways, and accessible pedestrian connections (City of Portland 2012).

4.3. Operationalization of x-minute city concept

This section explores how cities operationalized the concept of 15-minute city and present it to the public. More specially, it looks at the different technical aspects of the concept in terms of the used modes of transportation, cut-off value, destinations, destination weighting, spatial scale, and public dissemination. A summary of findings for all plans is presented in Table 5.

4.3.1. Modes of transportation

Cities incorporated different modes while operationalizing the concept. All the cities included walking as the main mode of transportation which residents will use to access nearby destinations, which is expected. It should be noted that all plans considered walking from home locations, while only one plan considered walking from home and work locations (i.e., Launceston). Similarly, all the cities except for one (i.e., Vancouver) included cycling as a mode of access in their approach. In contrast to the previous two active transportation modes, using transit was less common. In total, only nine cities out of 15 cities included transit as a mode of access. Interestingly, three cities included driving vehicles into their plans as a mode of transportation, namely Houston, Brampton, and Greater Newcastle. While Brampton included vehicles in their plan, Greater Newcastle included vehicles for rural areas whereas Houston simply mentioned roadway improvements for all modes, including vehicles. Only one city (i.e., Brampton) incorporated the use of ridesharing as a mode of transportation.

4.3.2. Cut-off values

Regarding the used cut-off values, cities utilized different cut-off values to realize the boundaries of the x-minute city concept. Montrose, Melbourne, and Waterloo used a 20-minute cut-off value, while Newcastle, Launceston, Ottawa, and Edmonton used a 15-minute cut-off value. It should be noted that while some of the cities used temporal boundaries in terms of time such as 15 or 20 min, other cities used spatial boundaries in terms of distance such as $\frac{1}{2}$ mile, 1 mile, or 2 miles. Some cities used a combination of both temporal and spatial boundaries. For example, Los Angeles used 10 min, or 1/2 mile cut-off value of access by walking and cycling. Some cities were very specific about the difference in the distance using straight-line vs network measurements. Ottawa is a good example as it was very specific in term of using 15 min to be equivalent to a radius of 900 metres or 1200 metres on the pedestrian network. Only two cities, namely Waterloo and Charlotte, clearly distinguished the difference between trip time by walking, biking and transit. For Waterloo (City of Waterloo 2021), they used a 20-minute walk or 5-minute bike ride. Charlotte (City of Charlotte 2021) used a 10-minute or $\frac{1}{2}$ mile walk or a 2-mile bike or transit ride. The use of different modes of transportation and different cut-off values, while realizing the concept will make it harder to compare cities progress.

4.3.3. Destinations and destination weighting

Within the desired cut-off values, all plans included a variety of services and amenities as destinations. These destinations included recreational and shopping opportunities, educational services, recreational facilities, public transit options, healthy foods and grocery stores, and open spaces and parks. While all these destinations are expected to be included to fulfill the promise of living locally, job destinations were not common to see. In fact, only two cities, namely Edmonton and San Antonio, included jobs as a destination (City of Edmonton 2020, City of Edmonton 2020, City of San Antonio 2016, City of San Antonio 2022). This may show the challenge of bringing appropriate employment opportunities locally.

Instead of treating all destinations equally in importance, a few cities placed more emphasis on one destination over the another. Ottawa, Edmonton, and Surrey were explicit about using public feedback in order to do that (City of Ottawa 2021, City of Edmonton 2020, City of Surrey 2021, City of Ottawa 2021). Cities such as Portland, Sydney, San Antonio, and Greater Newcastle identified the most important needs or prioritized some key services or amenities within neighborhoods. However, it was not clear from the documents how this was achieved. Nevertheless, all the rest of cities treated destinations equally or did not offer any discussion of how different destinations are prioritized.

4.3.4. Spatial scale and public dissemination

Different spatial scales were utilized in different plans. The most common spatial scale of measurement was at the neighborhood level. Cities that had a neighborhood spatial scale primarily focused on local accessibility measures include Waterloo, Los Angeles, Surrey, Brampton, and others. Whereas cities such as Sydney, Edmonton, Brampton, San Antonio, and Greater Newcastle focused on a larger scale (City of Brampton 2018, City of Edmonton 2020, City of San Antonio 2016, City of Sydney 2020, State of New South Wales 2021) that varies from district level to regional centers. It should be noted that only one city distinguished between rural and urban center contexts, while none of the cities focused on smaller scales of residential blocks, for example.

Regarding how each city communicated the x-city concept to the public, the most common method was the creation of maps of 15-minute neighborhoods. Using visual communication approaches is essential to provide higher accessibility to different individuals (Diaz et al., 2021). Only four cities out of the 15 cities used video and animations to communicate important information regarding the meaning and relevance of the concept to the public. By providing tangible practices for addressing the concept, cities can provide viewers a visual representation of how they plan on operationalizing the concept. As seen in Fig. 1, Portland provides their 20-minute neighborhood index (City of Portland 2012), while Waterloo visualize the concept (City of Waterloo 2021).

Finally, Table 6 shows a summary of the discussed aspects of the concept for each city, which are not only related to how to operationalize the concept, but also how it was incorporated, defined, and measured. The purpose of this table is not to rank cities, but rather to highlight which city incorporated more comprehensive information regarding the concept measurement, operationalization, intersection with different goals, and communication. As seen in the table, cities including Ottawa, Portland, and Melbourne are one of the current most comprehensive examples in terms of implementing the concept. From the table, it seems that the scale of the city was not necessarily related to the amount of information provided regarding the concept. Additionally, fewer cities provided detailed information regarding how the concept can be operationalized in comparison with providing detailed information regarding the concept elements and related goals.

5. Discussion and conclusion

The paper aims at exploring how North American and Australian cities incorporated, measured, and used the concept of an x-minute city (or a 15-minute city). To achieve this goal, cities that introduced or are

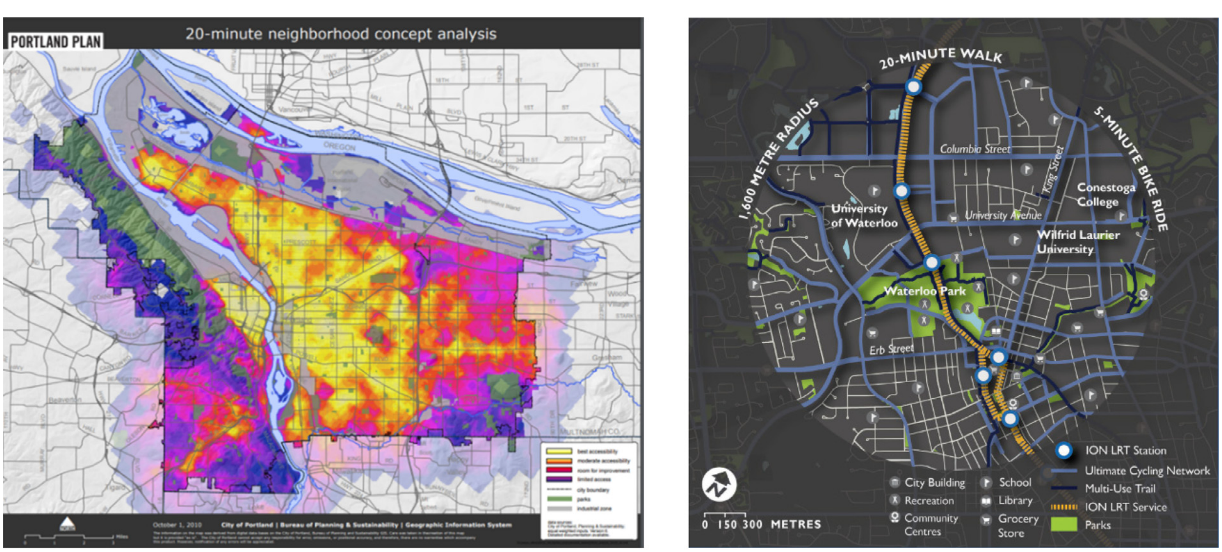
Table 5
Operationalization of the x-minute city concept.

City	Modes	Cut off value (Temporal or spatial boundary)	Destinations	Destination weighting	Analysis scale	Communication to the public
Ottawa (City of Ottawa 2021)	Walking, cycling, transit	15 min equivalent to a radius of 900 metres or 1200 metres on the pedestrian network.	• Transit • Schools • Childcare • Community centers • Parks/Greenspace • Community services • General retail • Grocery stores	Yes	Neighborhood	Diagrams, Maps
Portland (City of Portland 2012)	Walking, cycling, transit	Half mile & 20 min	• Businesses • Services • Accessible housing • Healthy food • Parks/gathering places	Yes	Neighborhood	Maps, Tables
Sydney (City of Sydney 2020)	Walking, cycling, transit	5–10 min	• Daily needs • Open spaces • Community and cultural facilities • Healthcare • Education • Emergency services	Yes	City villages	Maps
Montrose, Houston (Montrose TIRZ 27 2020)	Walking, cycling	20 min	• Schools • Grocery stores • Park • Transit routes • Restaurants • Health clinics • Commercial corridors • museums and libraries • community centers • places of worship	No	Neighborhood	Maps, Figures
Houston (City of Houston 2020)	walking, cycling, vehicles	Not clear	• Not clear	No	Neighborhoods	
Melbourne (City of Melbourne 2016, Victoria State Government 2022)	walking, cycling, transit	20 min & 800 m	• Activity centers • Still need to commute out of their area for work	No	Neighborhood, 3 pilot projects in 3 neighborhoods	Video and Figures
Edmonton (City of Edmonton 2020, City of Edmonton 2020)	walking, cycling, transit, roll	15 min	• Work • Groceries • Parks • Errands • Stores	Yes	District level	Videos, Diagrams, Maps
Vancouver (City of Vancouver 2012, City of Vancouver 2015)	Walking	10 min	• Grocery stores • Shops • Post offices	No	Neighborhoods	Graphs
Brampton (City of Brampton 2018)	Walking, cycling, transit, vehicles, rideshare	625 m	• Commerce • mixed housing • retail center • good local and regional transit connections	No	Town Centers	Concept maps, Diagrams
Surrey (City of Surrey 2021, City of Surrey 2022)	Walking, cycling, roll	15 min equivalent to a radius of 900 m or 1200 m on the pedestrian network.	• Neighborhood Park • Grocery store • Frequent transit • Public facility • Pharmacy • Education • Health care • Retail shopping • Childcare	Yes	Neighborhoods	Video, Graphics

(*continued on next page*)

Table 5 (*continued*)

City	Modes	Cut off value (Temporal or spatial boundary)	Destinations	Destination weighting	Analysis scale	Communication to the public
Waterloo city (City of Waterloo 2021)	Walking, cycling, transit	20-minute walk, 5-minute bike, 1600 meter radius	• Recreation • Community centers • School • Library • Grocery store • Parks • Cycling network • LRT service	No	Neighborhoods	Maps, Graphics
Los Angeles (City of Los Angeles 2019)	Walking, cycling	10 min & 1/2 mile	• High-quality mobility options • Fresh food • Parks	No	Neighborhoods	Tables, Graphics
San Antonio (City of San Antonio 2016, City of San Antonio 2022)	Walking, cycling, transit	1/2 mile	• Housing options • Grocery stores • Commercial services • Schools • Open spaces • Recreational facilities • Frequent transit	Yes	13 regional centers, contains 50% of all jobs	Graphics
Charlotte (City of Charlotte 2021, City of Charlotte 2021, City of Charlotte 2021)	Walking, cycling, transit	10 min or a $\frac{1}{2}$ mile walk or a 2-mile bike or transit ride	• Childcare • Parks and open space • Community facilities • Fresh Food • Health care & pharmacies • Financial services	No	Neighborhood	Graphics, Maps
Greater Newcastle (State of New South Wales 2021)	Walking, cycling, vehicle	15 min	• Cafe and restaurants • Gathering space • Community markets • Recreation facility • Schools • Daycare centers • Local shops & services • Health services • Natural green space • Open spaces	Split in 15-minute neighbor-hoods and 30-minute strategic centers	Rural to urban center contexts	Video, Maps
Launceston (City of Launceston 2021)	walking, cycling, transit	15 min	• Health services • Education services • Activity centers	No	Neighborhoods	Maps, Graphics



A. B.

Fig. 1. A. Portland 20-minute neighborhood concept (City of Portland 2012), and B. 20-minute city concept in Waterloo (City of Waterloo 2021).

Table 6
Documents' provided information.

City	Concept elements					Concept related goals						Concept determinants					
	Incorporation	Definition/ Rationale	Target/goals	Measures/ Actions	Public Feedback	Equity	Safety and personal security	Gentrification/ Segregation	Funding	Psychological	Mobility hubs	Modes	Cut off value	Destinations	Destination weighting	Analysis scale	Communication
Ottawa	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green	Yellow
Portland	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Yellow
Melbourne	Green	Green	Green	Green	Green	Yellow	Yellow	Grey	Grey	Grey	Grey	Green	Green	Green	Yellow	Yellow	Yellow
Montrose	Green	Green	Green	Yellow	Green	Green	Green	Yellow	Green	Green	Grey	Green	Green	Green	Grey	Green	Yellow
Edmonton	Grey	Yellow	Grey	Green	Green	Green	Green	Grey	Green	Grey	Grey	Green	Grey	Yellow	Grey	Green	Grey
Charlotte	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Green	Green	Green	Green	Yellow	Grey	Green	Green
Los Angeles	Green	Yellow	Green	Green	Green	Green	Grey	Grey	Yellow	Green	Green	Green	Green	Green	Green	Yellow	Green
Launceston	Grey	Green	Green	Grey	Green	Yellow	Grey	Grey	Green	Grey	Yellow	Yellow	Green	Yellow	Grey	Green	Yellow
Surrey	Green	Green	Green	Green	Green	Green	Yellow	Grey	Grey	Yellow	Green	Green	Green	Green	Grey	Yellow	Yellow
Brampton	Yellow	Green	Green	Grey	Green	Yellow	Green	Green	Yellow	Green	Grey	Green	Green	Green	Green	Green	Green
Waterloo City	Green	Green	Green	Green	Green	Green	Grey	Green	Yellow	Grey	Grey	Green	Green	Green	Grey	Green	Yellow
San Antonio	Yellow	Green	Green	Green	Green	Yellow	Green	Green	Yellow	Grey	Green	Green	Green	Yellow	Grey	Green	Yellow
Greater Newcastle	Green	Yellow	Green	Green	Green	Green	Yellow	Yellow	Grey	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Yellow
Sydney	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Grey	Grey	Green	Green	Green	Grey	Green	Yellow
Vancouver	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Grey	Yellow	Grey	Green	Green	Green	Yellow	Yellow	Green
Houston	Green	Green	Green	Green	Green	Green	Yellow	Grey	Yellow	Green	Yellow	Green	Green	Yellow	Grey	Green	Yellow

Notes: City plans level of detail scored by color. The green indicates detailed information for a certain aspect. The Yellow indicates an introduction to the information was available. The grey indicates that no information was found for that topic within the reviewed documents and webpages.

in the process of introducing the concept were identified from news articles, reports, and other resources, and then a search strategy involving the Google search engine was utilized to extend the list by incorporating more cities from the top 20 most populous cities in Canada, Australia, and the United States. After identifying the cities, their official plans and websites were reviewed to understand how the concept was incorporated, operationalized, communicated, and intersected with different goals such as equity and safety. Of the original 63 cities either identified or run through the Google search strategy, 10 had the concept emerging, with public engagement and elected officials pledging they are moving forward towards the implementation of the concept, with no official documents yet. This shows the current significance of the concept. A total of 15 cities were identified with very recent plans and documents, which were reviewed in depth.

Having first been proposed in 2016, the concept of "15-minute" cities has gained traction in recent years. One of the key aspects of this concept is its emphasis on proximity-based planning, where within a 15-minute walking or cycling distance, residents would have a higher quality of life as they would be able to travel less to access key desired services and amenities. This study showcases how common practice has somewhat deviated from the original concept, with cities such as Houston, Brampton, and Greater Newcastle including vehicles within their plans as a mode of travel. While their reasoning is sound, with Brampton considering vehicles in the format of ridesharing, and Greater Newcastle included it as consideration for rural areas, it still goes against the objective of reducing the reliance of automobiles. Another important deviation is the scale that different cities used when planning for 15-minute cities. One of the dimensions of this concept is that of proximity, focusing on residents at a neighbourhood scale. However, some cities are implementing it at a larger scale, for example Edmonton uses districts that are made up of a collection of neighborhoods to include work as a destination.

Cities also used different wordings to incorporate the concept ranging from "complete neighborhoods" to "20-minute and walkable neighborhoods." Using different types of wordings to incorporate the concept in a planning document may make it harder for professionals and researchers to identify it, without a systematic multi-stage research approach similar to the one used in this paper. Nevertheless, while using different wordings, there is an agreement between cities in terms of using the concept to achieve complete living and communities. The concept was also introduced in different types of plans including cities' comprehensive plans, regional plans, and transportation plans. This resulted in presenting various targets, goals, and measures. Although these differences in scopes may seem insignificant, it can make it harder for policy makers and cities to pinpoint best practices from other cities.

Furthermore, while most of the cities offered several spatial indicators to measure the success of their x-minute city frameworks, only very few cities incorporated using interactive tools in measurement. For example, Portland provides a list of the percentage of its population within a certain distance to amenities and services as a measure of the success of its 15-minute city concept. Similarly, Los Angeles used the idea of measuring the changes in Walk Score, by targeting to increase the city's average Walk Score to 75 by 2025. In contrast, Charlotte uses a customer connectivity tool to measure how many specific services and amenities residents can access within a set time. The use of these emerging options, which can help in obtaining residents feedback, while measuring the success of 15-minute city policies opens the door for more creative approaches that not only include the spatial component of the concept, but also captures residents' changing needs and preferences.

Cities operationalized the concept of x-minute city in several ways. Most of the cities included walking and cycling as the main mode of transportation. Additionally, several cities also included public transit. In contrast, other cities included car driving as a mode of transportation. While including car driving seems against the idea of "living locally", which is the central principle of x-minute city concept, it could be relevant to more rural areas. On the other hand, only one city explicitly included the use of ridesharing as a mode of transportation. This indicated an important adjustment to the original concept. Indeed, including more motorized transportation modes (i.e., transit and driving) within the idea of x-minute city, while it may help in making it more feasible for a wide array of residents, can lead to undesirable outcomes regarding the local proximity of amenities. Therefore, placing more emphasis on the use of active transportation modes can be required.

Cities used a wide array of temporal and spatial cut-off values to realize the concept of x-minute cities. However, it was rare to see cities using different cut-off values for different modes. A good example of this was presented by Waterloo as they used a 20-minute walk or 5-minute bike ride and by Charlotte as they used a 10-minute or $\frac{1}{2}$ mile walk or a 2-mile bike or transit ride. Additionally, while most of the cities included a variety of educational, health, leisure, and recreational services and amenities as destinations, it was less common to see employment opportunities. In fact, only two cities (i.e., Edmonton and San Antonio) included employments as a destination. The use of different types of modes of transportation, different cut-off values, and destinations while realizing the concept will make it harder to compare cities progress.

Overall, Ottawa, Portland, and Melbourne have emerged as one of the current most comprehensive examples in terms of implementing the concept. In fact, all the three cities provided detailed information regarding the concept's determinants, operationalization, with a good discussion of the concept's intersections with different goals and issues. After reviewing cities' web pages and links provided in their planning documents, it was found that the most common approach to communicate the concept is using maps and diagrams. However, only very few cities used animation and videos. Videos present an important opportunity to explain concepts by bringing them to life and making them easy to comprehend for a wider array of residents, while gaining public buy-in and improving public input. This study did not identify any clear patterns of how cities of different sizes implement the concept differently. This can be attributed that the main idea of the concept is related to living locally and improving local accessibility to desired destinations at the neighborhood level. Nevertheless, future studies can explore the relationship between cities' scale and current developed plans and their standing in adapting and incorporating the 15-minute city concept in their planning process. This study can focus not only on North American and Australian cities, but also on cities across the globe, using the developed methodology in this paper.

With more and more cities starting to embrace and use this concept and with the emergence of more academic studies in this area, lessons from the literature and practice could be organized to assist in developing a policy guide. This guide will aid in directing cities future practices, while encouraging more cities to implement the concept. The success of concept implementation is yet to be explored by the academic community and researcher as most of the cities are still in the planning process or have just completed their plans. Finally, as this concept focuses on bringing active transportation back to cities as a major element for designing the city, by adopting this concept cities will have more incentives to move away from developing vehicle infrastructure and spreading urban developments, stirring our cities to a more sustainable future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Walkability for children in Bologna: Beyond the 15-minute city framework☆

Andrea Gorrini [a,*], Dante Presicce [a], Federico Messa [a], Rawad Choubassi [a]

Fondazione Transform Transport ETS, Via Lovanio 8, Milan, 20121, Italy

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A B S T R A C T

The current research work is based on an extended spatial analysis executed through the application of GIS, aiming at assessing the level of walkability in the city of Bologna (Italy). In particular, the research focused on walkability for children (aged between 5 to 13 years old), as they experience the city differently than adult pedestrians, since they are more vulnerable to road accidents and they need proper infrastructures to freely play outdoors and walk independently. The GIS analysis was based on a series of location-based data retrieved from different open source repositories and focused on the level of usefulness, comfort, safety, and attractiveness of Bologna for child pedestrians. The proposed Walkability for Children Index was aimed at identifying the neighborhoods characterized by the lowest level of pedestrian friendliness in relation to the childrens needs while walking. Results helped to identify and characterize a short list of suitable areas where to prioritize interventions focusing, for example, on guaranteeing the presence of relevant public services within a walkable distance of 15 minutes from place of residence and on the implementation of urban regeneration projects through the tactical urbanism approach.

1. Introduction

Encouraging the shift towards Sustainable Urban Mobility Plans (i.e., *SUMPs*) based on public transport, shared-micro mobility, and active modes of travel such us walking and cycling is one of the main challenges of European cities (Buhrmann et al., 2019), since they are increasingly facing problems of traffic congestion, road safety, energy dependency, and air pollution linked to the urbanisation global trend (United Nations, 2016).

In this context, the activities of urban mobility planners are shifting towards a focus on walkability, namely how friendly the urban environment is for walking, living, visiting, or spending time in public spaces (Abley and Hill, 2005; Annunziata and Garau, 2020; Forsyth, 2015). Walkability contributes to the quality of life of citizens by enhancing physical activity, road safety, well-being, air quality, and social inclusion (Forum, 2012). Improving pedestrian mobility implies barrier-free and safe sidewalks, but also human-scale environments which allow people to enjoy walking and gather in comfort (Gehl, 2013). In this regard, the General Theory of Walkability proposed by Speck (2013) explains the essential elements for evaluating the level of walkability of an urban environment, such as: the presence of public services within a walkable distance, the level of comfort and road safety experienced by people while walking, and the attractiveness of the urban areas in terms of architectural design and social context.

The attention to pedestrian mobility started with the principles highlighted by the European Charter of Pedestrian Rights issued by the European Parliament in 1988[1], that focused on the need to ensure the comfort and safety of all pedestrians in urban areas:

> Article I: "*The pedestrian has the right to live in a healthy environment and freely to enjoy the amenities offered by public areas under conditions that adequately safeguard his physical and psychological well-being.*"

[1] See: https://goo.gl/0vKTJ9

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* Corresponding author.
E-mail addresses: a.gorrini@transformtransport.org (A. Gorrini), d.presicce@transformtransport.org (D. Presicce), f.messa@transformtransport.org (F. Messa), r.choubassi@transformtransport.org (R. Choubassi).

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Since then, walkability has become even more crucial considering the unprecedented effects of the Covid-19 pandemic on urban mobility (Gargiulo et al., 2021; Hayrullahoğlu and Varol, 2022; Rahman and Thill, 2022; Transport, 2022). In July 2020, the European Commission (European Platform on Sustainable Urban Mobility Plans, 2020) provided *ad hoc* guidelines for implementing short-term transport planning interventions to face the current critical situation. Among the principles included in the document, the section "Active Mobility" has a specific focus on pedestrian mobility.

In this regard, the activity of transport planners and decision makers is projected ahead towards sustainable, healthy, and equitable urban development solutions, which could enhance the social, environmental and economic resilience. This includes a reorganization of the urban system as a whole, focusing on its physical and functional characteristics (e.g., land use, road network, transport infrastructures, etc.) and the mobility demand of the users, in order to guarantee the possibility to access necessary goods, services, and amenities within a comfortable walking distance from any residential area.

In this framework, the goal of a *15-minute city* (Moreno et al., 2021) is to create a more livable and sustainable urban environment by reducing the need for car travel and promoting the use of more active and environmentally friendly modes of transportation. This can help to reduce traffic congestion, air pollution, and carbon emissions, and make it easier for people to access the things they need on a daily basis.

Although traditional approaches about pedestrian mobility tend to focus on the spatial dimension (Annunziata and Garau, 2020) and on universal design indicators (Steinfeld, 2011), individual characteristics of pedestrians have a significant impact on the perceived level of walkability. As highlighted by the 2030 Agenda for Sustainable Development adopted by all United Nations Member States (United Nations, 2016) (i.e., *SDG 11.2-Sustainable Transport for All*), urban mobility should be designed to be more inclusive to the needs of those in vulnerable situations, such as women, children, persons with disabilities and older persons:

> "*By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.*" (United Nations, 2016, p. 24)

Within the investigation of vulnerable city users' needs for walkability assessment, the current research work focuses on child pedestrians aged between 5 to 13 years old (primary and secondary schools students). Despite recent efforts in the design of safe, comfortable, and livable streets and public spaces for children (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019), there is still a lack of knowledge regarding walkability for children, especially due to the lack of available data.

Research about this topic has often been motivated by the necessity to contrasts the social costs of child pedestrian crashes. Compared to adults, children are indeed more vulnerable to road traffic collisions (World Health Organization, 2018), due to poor knowledge of regulations and the complex interaction of psychological and contextual factors, such as the coordination of attention and motor functions, and the individual perception of road risk (Evans and Norman, 2003; Rosenbloom et al., 2008; Sisiopiku and Akin, 2003).

However, various bodies of research point to the necessity of adopting a more comprehensive child-friendly urban planning approach (Korpela, 2003), taking into account social facets of public space starting from a broader understanding of walkability. This means understanding opportunities for urban areas to provide comfort and joy as well as safe and inclusive experiences through public spaces, playgrounds, and green areas (Voce, 2018). Walkability for children includes, in fact, opportunities to freely play outdoors, walk independently and safe, and feel a sense of belonging within their neighbourhoods (Krysiak, 2020).

In this framework, the current study was conducted in collaboration with the Department of Urban Planning of the Municipality of Bologna and the Foundation for Urban Innovations, aiming at supporting the planning of future sustainable and inclusive mobility strategies in the city of Bologna. In particular, the research started from the theoretical background about the evaluation of the level of walkability for children (see Section 2). According to the proposed methodology (see Section 3), a series of location-based open data were analysed by using Geographic Information Systems (see Section 4) to assess the level of usefulness, comfort, safety, attractiveness, and accessibility of the city for child pedestrians. The analyses were particularly focused on the neighborhood Navile of the City Bologna, which was selected by the Department of Urban Planning for the future implementation of an interim public space by using the tactical urbanism approach[2] (Peyton, 2019). The paper concludes with final remarks about results and future works.

2. Related works

Starting from to the General Theory of Walkability (Speck, 2013), and taking advantage of previous works already presented by the authors about this topic (Abdelfattah et al., 2021; Gorrini et al., 2021), the current Section presents some of the most relevant contributions about walkability assessment for children. The considered scientific contributions were organized in a tabular structure considering a series of walkability assessment criteria and methods (see Table 1).

2.1. Walkability assessment criteria

The proposed walkability assessment criteria are focused on the accessibility of public services within a walkable distance and on the level of comfort, road safety, and attractiveness of urban areas (see Table 1):

- *Usefulness* (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019): the urban territory should be designed and planned with an adequate level of land-use mix, street connectivity and commercial density, to guarantee the accessibility of relevant services for children (e.g., local shops, schools, libraries, health services, etc.) within a walkable distance from their place of residence;
- *Comfort* (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019; Rothman et al., 2014; Sisiopiku and Akin, 2003; Voce, 2018): streets should be designed according to a series of standard criteria of quality (e.g., pavement type and continuity on side-walks, adequate width of side-walks to avoid crowding in case of intense pedestrian flows, etc.), but also according to a set of highly recommended elements for the comfort of children while walking (e.g., playgrounds, green areas, benches, fountains, etc.);
- *Safety* (Aerts, 2018; Danenberg et al., 2018; Evans and Norman, 2003; Peyton, 2019; Rosenbloom et al., 2008; Rothman et al., 2014; Sisiopiku and Akin, 2003; Voce, 2018): streets should be designed to guarantee the safety of children while crossing during day and nighttime (e.g., speed bumpers in proximity of the zebra crossings, illumination systems at intersections to guarantee visibility, legible horizontal and vertical traffic signage, etc.);
- *Attractiveness* (Peyton, 2019): the city should be designed to have a polycentric structure, with several and distinctive areas of attraction for children (e.g., points of interest, events, quality of the architectural streetscape, vitality of the social context, etc.).

2.2. Walkability assessment tools

The proposed walkability assessment tools include a wide range of methodologies and techniques that have been developed to empirically measure walkability (see Table 1):

[2] As part of the EN-UAC research project EX-TRA "EXperimenting with city streets to TRAnsform urban mobility" (No. 99950032).

Table 1
Theoretical background about walkability for children, focusing on assessment criteria and tools.

	Walkability Assessment Criteria				Walkability Assessment Tools		
References	Usefulness	Comfort	Safety	Attractiveness	GIS analysis, Space Syntax	Observations, Sensors, Apps	Audit Tools, Co-creation
Aerts (2018)	•	•	•		•		•
Danenberg et al. (2018)	•	•	•				•
Evans and Norman (2003)			•				•
Peyton (2019)	•	•	•	•	•	•	
Sisiopiku and Akin (2003)		•	•			•	•
Rosenbloom et al. (2008)			•			•	
Rothman et al. (2014)		•	•			•	
Voce (2018)		•	•		•		•

- *Geographic Information Systems and Space Syntax* (Aerts, 2018; Peyton, 2019; Voce, 2018): these methods can be applied for characterizing a neighbourhoods suitability for walking activity among children through the analysis of location-based data related to the topographical, cadastral, infrastructural, and architectural features of urban areas (e.g., presence of public services, quality of road infrastructures, census indicators about the socio-demographic characteristics of the inhabitants, etc.). As an example, the use of GIS offer the possibility to evaluate if necessary goods, services, and amenities are within a 15-minute walk, bike ride, or public transit trip from any residential area through isometric and isochronal analyses. The use of Space Syntax allows to combine different attributes of the sidewalk network (e.g., level of integration of streets, shortest paths, type of land use, etc.);
- *Observations, Sensors and Smartphone Apps* (Peyton, 2019; Rosenbloom et al., 2008; Rothman et al., 2014; Sisiopiku and Akin, 2003): on-site observations can support the visual detection of the actual behaviour of children while walking and crossing in a certain street and public space (e.g., desired lines, jaywalking, impact of spatial elements, etc.). When supported by video analytics, observations can be applied to produce behavioural maps by systematically annotating where movements occur in a certain environment (e.g., people counting, pedestrian trajectories, pedestrian-vehicle interactions, etc.). Wi-Fi sensors, GPS tools, and smartphone applications can support, instead, the collection of disaggregated data about footfall activity patterns and OD matrices in large scale scenarios with high spatial and temporal granularity;
- *Audit Tools and Co-creation* (Aerts, 2018; Danenberg et al., 2018; Evans and Norman, 2003; Sisiopiku and Akin, 2003; Voce, 2018): audit tools are based on the use of validated measures, self-report, survey questionnaires, and interviews to study the subjective perception of children about the level of walkability of a determined urban area. Co-creation methods, such as focus groups and design laboratories, can be also applied to directly engage children into a participatory design process through interactive workshops.

3. Enabling data and methodology

The methodological approach which sets the current research is based on the application of GIS[3] for the analysis of a series of location-based data, which were select in collaboration with the Department of Urban Planning of the Municipality of Bologna and the team of Foundation for Urban Innovations and retrieved from several open-data repositories (see Table 2). According to the proposed theoretical background, the considered dataset spans several domains related to the study of walkability for children (i.e., *usefulness, comfort, safety, attractiveness*).

The analysis was focused on the territory of the City of Bologna (i.e., *macro scale*), aiming at identifying and characterizing the urban areas where to prioritize interventions for enhancing the level of walkability for children. In particular, a series of multi-layer thematic maps were produced according to the proposed walkability assessment criteria. The analysis was aimed at developing and testing an innovative walkability metric, against already available standard (i.e., Walk Score®).

As a preliminary step for the analysis of the retrieved location-based data, an *ad hoc* designed grid was implemented to calculate the spatial distribution of punctual, linear, and areal vectors on every cell (250 m x 250 m). In order to ensure a homogeneous dataset and a robust comparative basis, data was harmonized and normalized on cells level through a 0–1 scale (creating Z-scores that follow the normal distribution of the values).

The indicators were then included in the calculation of the Level of Usefulness Index (LUI), Level Comfort Index (LCI), Level Safety Index (LSI), and Level of Attractiveness Index (LAI). This was essentially based on weighted summations of the Z-scores of the variables proposed in this study (see Table 2).

The weights definition (Kalton and Flores-Cervantes, 2003) was based on a three-step process: (*i*) assigning a reference magnitude for the weights based on the proposed theoretical background, in order to strengthen the impact of the indicators and criteria which were defined by previous research works as more relevant considering the needs of children while walking; (*ii*) adjust the magnitude of the weights using information provided by the Department of Urban Planning of the Municipality of Bologna and the team of Foundation for Urban Innovations; and (*iii*) varying the definition of the weights through a sensitivity analysis to see how sensitive the results of the analysis were to changes in the definition of the indexes and to optimize the calculation of the proposed multidimensional data analysis.

Percentile frequency distribution of results made possible the identification of the cells (ce) characterized by the lowest level of Walkability for Children Index (WCI) of the City of Bologna, which represents a synthesis of four proposed indexes. The results of the analysis are visualized considering the administrative boundaries of the neighborhoods and the urban sub-areas of Bologna (namely *Areali*, a geographical unit between the statistical areas and the neighborhoods).

3.1. Level of Usefulness Index

The calculation of the Level of Usefulness Index (LUI) was focused on the local services that impact neighborhood quality for children and are owned, operated, and certified by the Municipality of Bologna. The considered dataset spans several domains, as follows: Education Services (Ed) (e.g., public kindergarten, nursery school, primary school, secondary school, etc.); Health Services (He) (e.g., hospital, local health service, clinic, consulting service, pharmacy, etc.); Local Shops (Sh) (e.g., grocery, local market, non-food local shop, tobacconist, newsstand, etc.); and Neighborhood Services (Ne) (e.g., bank and ATM, post office, personal service such as hairdresser, bar, local public administration office, etc.).

Data analysis was based on a series of isochrone maps showing lines of travel time by walking on the road network to reach each service on a 0–3 scale (considered walking speed of children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 1; > 15

[3] GIS analysis has been performed by using the software QGIS v.3.20.1.

Table 2
The open data that were retrieved and analyzed through GIS.

Criteria	Indicators	Label	Weight	Data Source	Year
Preliminary data	City of Bologna	-	-	Open Data Bologna	2021
	Neighborhoods	-	-	Open Data Bologna	2021
	Urban Sub-areas	-	-	PUG City of Bologna	2021
	Children Population	Ch	-	ISTAT	2011
	Road Network	Ro	-	Open Data Bologna	2021
	Land Use	La	-	Copernicus Service	2018
Usefulness	Education Services	Ed	0.25	PUG City of Bologna	2020
	Health Services	He	0.25	PUG City of Bologna	2020
	Local Shops	Sh	0.25	PUG City of Bologna	2019
	Neighborhood Services	Ne	0.25	PUG City of Bologna	2019
Comfort	Covered Walkways	Co	0.2	Open Data Bologna	2016
	Green Areas	Gr	0.3	PUG City of Bologna	2020
	Pedestrian Paths and Squares	Pe	0.4	PUG City of Bologna	2020
	Urban Furniture	Ur	0.1	Open Data Bologna	2017
Safety	Environmental Islands	Ei	0.4	Open Data Bologna	2017
	Pedestrian Road Accidents	Pr	-0.6	ISTAT	2018-20
Attractiveness	Community Services	Cm	0.33	PUG City of Bologna	2020
	Cultural Services	Cu	0.33	PUG City of Bologna	2020
	Sport Services	Sp	0.33	PUG City of Bologna	2020

minutes = 0), which were combined to the calculation of the distribution of each dataset on cells (ce). The calculation of the LUI was based on the weighted summation of the Z-scores of each indicator (see Eq. 1). The constant parameters KEd, KHe, KSh, and KNe were equally balanced ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Ed}} Z\_Ed_{ce} + {}_{K_{He}} Z\_He_{ce} + {}_{K_{Sh}} Z\_Sh_{ce} + {}_{K_{Ne}} Z\_Ne_{ce} \quad (1)$$

3.2. Level of Comfort Index

The calculation of the Level of Comfort Index (LCI) was focused on pedestrian infrastructures and facilities, as follows: Covered Walkways (Co); Green Areas (Gr), Pedestrian Paths and Squares (Pe); and Urban Furniture (Ur). This allowed to consider the planimetric base map containing sidewalks area, historical porticoes area (a landmark of the city center of Bologna, which was recently recognized as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization[4]), open space features, urban parks (entry points), urban community gardens (entry points), and the localization of urban furniture for sitting, resting, reading, and studying (e.g., benches, tables, bike parking racks, drinking fountains, etc.).

Regarding green areas, data analysis was based on an isochrone map showing lines of travel time by walking on the road network to reach them on a 0–3 scale (considered walking speed of children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 3; > 15 minutes = 0), which was combined to the calculation of the distribution of data on cells (ce). Regarding the other indicators, instead, data analysis was based on calculating the spatial distribution of each dataset on cell (ce). The calculation of the LCI was based on a weighted summation of the Z-scores of each indicator (see Eq. 2 and Fig. 1). According to the proposed theoretical background, the constant parameters KCo (corresponding to 0.2), KGr (corresponding to 0.3), KPe (corresponding to 0.4), and KUr (corresponding to 0.1) were weighted to accentuate the impact of sidewalk infrastructures on LCI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Co}} Z\_Co_{ce} + {}_{K_{Gr}} Z\_Gr_{ce} + {}_{K_{Pe}} Z\_Pe_{ce} + {}_{K_{Ur}} Z\_Ur_{ce} \quad (2)$$

[4] See: https://whc.unesco.org/en/list/1650

3.3. Level of Safety Index

The calculation of the Level of Safety Index (LSI) was focused on pedestrian road safety issues, as follows: Environmental Islands (Ei) and Pedestrian Road Accidents (Pr). The first dataset allowed to consider the localization of the urban areas in which a series of interventions were carried out by the Municipality of Bologna to improve the functionality and safety of the roads (e.g., 30 Km/h maximum speed limit, moderated traffic volumes, containment of crossing flows, etc.), but also to reduce atmospheric, acoustic and visual pollution. The second dataset allowed to consider the streets and road intersections with the highest number of pedestrians killed and severely injured due to road accidents during the period 2018-20[5]

Data analysis was based on calculating the distribution of the dataset on cell (ce). Moreover, the dataset related the pedestrian road accidents was also combined to the number of road intersections on cell (ce). The calculation of the LSI was based on a weighted summation of the Z-scores of each indicator (see Eq. 3). According to the proposed theoretical background, the constant parameters KEi (corresponding to 0.4) and KPr (corresponding to - 0.6) were weighted to accentuate the impact of road accidents on LSI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Ei}} Z\_Ei_{ce} + {}_{K_{Pr}} Z\_Pr_{ce} \quad (3)$$

3.4. Level of Attractiveness Index

The calculation of the Level of Attractiveness Index (LAI) was focused on the local services and facilities that impact neighborhood attractiveness for children and are owned, operated, and certified by the Municipality of Bologna, as follows: Community Services (Cm) (e.g., community centers, association centers, civic and multipurpose centers, neighborhood centers, places of worship, etc.); Cultural Services (Cu) (e.g., libraries, etc.); Sport Services (Sp) (e.g., gyms, sport facilities, etc.).

[5] A preliminary analysis showed 733 pedestrian road accidents (15 killed pedestrians, 820 seriously injured pedestrians), which were characterized for the large majority by the following circumstances: “He/She crossed the street at a pedestrian crossing not protected by traffic lights or by agents” (27%); ”He/She crossed the street at a pedestrian crossing protected by a traffic light or by an agent, respecting the signs” (17%); and “He/She crossed the road irregularly” (16%).

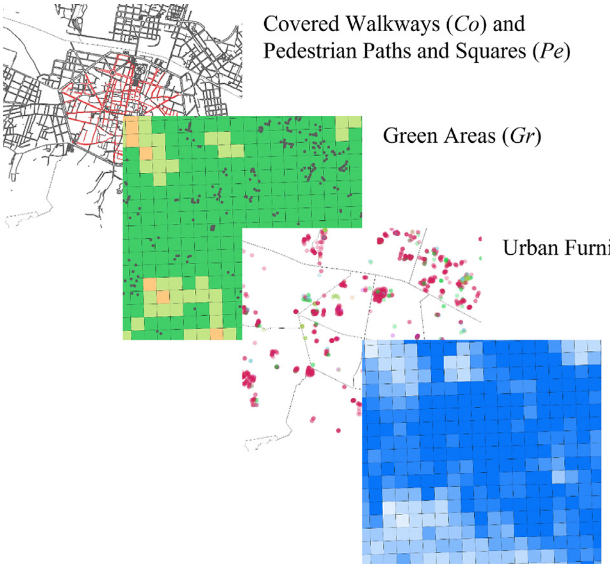

Fig. 1. An example of the proposed cartographic analysis, based on the spatial distribution of each dataset included in the analysis of the Level of Comfort Index (LCI).

Table 3
Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), Level of Attractiveness (LAI), and the Walkability for Children Index (WCI) of the Neighborhoods and urban sub-areas of the City of Bologna.

Neighborhoods	Urban Sub-areas	Z_LUI	Z_LCI	Z_LSI	Z_LAI	Z_WCI
Borgo Panigale - Reno	Borgo Panigale	0.390	0.360	0.471	0.354	0.385
	San Viola	0.807	0.766	0.623	0.750	0.795
	Barca	0.821	0.819	0.486	0.787	0.781
Navile	Lame	0.461	0.460	0.435	0.469	0.462
	Corticella	0.513	0.463	0.441	0.456	0.470
	Bolognina	0.819	0.733	0.444	0.830	0.761
Porto Saragozza	Costa Saragozza	0.395	0.394	0.493	0.406	0.400
	Saffi	0.788	0.755	0.534	0.758	0.763
	Marconi	0.925	0.965	0.803	0.938	0.893
	Malpighi	0.928	0.904	0.806	0.949	0.875
San Donato - San Vitale	San Donato	0.453	0.436	0.484	0.525	0.463
	San Vitale	0.625	0.585	0.427	0.615	0.569
Santo Stefano	Colli	0.240	0.262	0.454	0.273	0.274
	Murri	0.887	0.814	0.365	0.821	0.702
	Irnerio	0.917	0.928	0.782	0.943	0.893
	Galvani	0.923	0.923	0.872	0.954	0.885
Savena	San Ruffillo	0.573	0.439	0.518	0.529	0.468
	Mazzini	0.762	0.768	0.448	0.719	0.711

Data analysis was based on a series of isochrone maps showing lines of travel time by walking on the road netowrk to reach each service on a 0–3 scale (considered walking speed or children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 3; > 15 minutes = 0), which were combined to the calculation of the distribution of each dataset on cells (ce). The calculation of the LAI was based on the weighted summation of the Z-scores of each indicator (see Eq. 4). The constant parameters KCm, KCu, and KSp were equally balanced ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = K_{Cm} Z\_Cm_{ce} + K_{Cu} Z\_Cu_{ce} + K_{Sp} Z\_Sp_{ce} \tag{4}$$

3.5. Walkability for Children Index

The results related to LUI, LCI, LSI, and LAI were further analyzed to calculate the proposed Walkability for Children Index (WCI). This was essentially based on a weighted summation of the Z-scores of each index proposed in this study (see Eq. 5). According to the results of the proposed theoretical background, the constant parameters $KLUI$ (corresponding to 0.15), $KLCI$ (corresponding to 0.3), $KLSI$ (corresponding to 0.4), and KAI (corresponding to 0.15) were weighted to accentuate the impact of the level of comfort and safety on WCI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values. Finally, the results of the analysis were further filtered taking into account additional information related to census data. In particular, the cells characterized by the lower population density of children aged between 5 to 13 years old ($Ch \leq 4.310$ children/Km^2 - 20th percentile) were not considered for presenting the results of the analysis[6].

$$\sum_{k=1}^{0} = K_{LUI} Z\_LUI_{ce} + K_{LCI} Z\_LCI_{ce} + K_{LSI} Z\_LSI_{ce} + K_{LAI} Z\_LAI_{ce} \tag{5}$$

[6] According to the latest available data from the Italian National Institute of Statistics (ISTAT) in 2021, the population of Bologna was approximately 400,000 people. Approximately 7.6% of the population are aged between 5 to 13 years old.

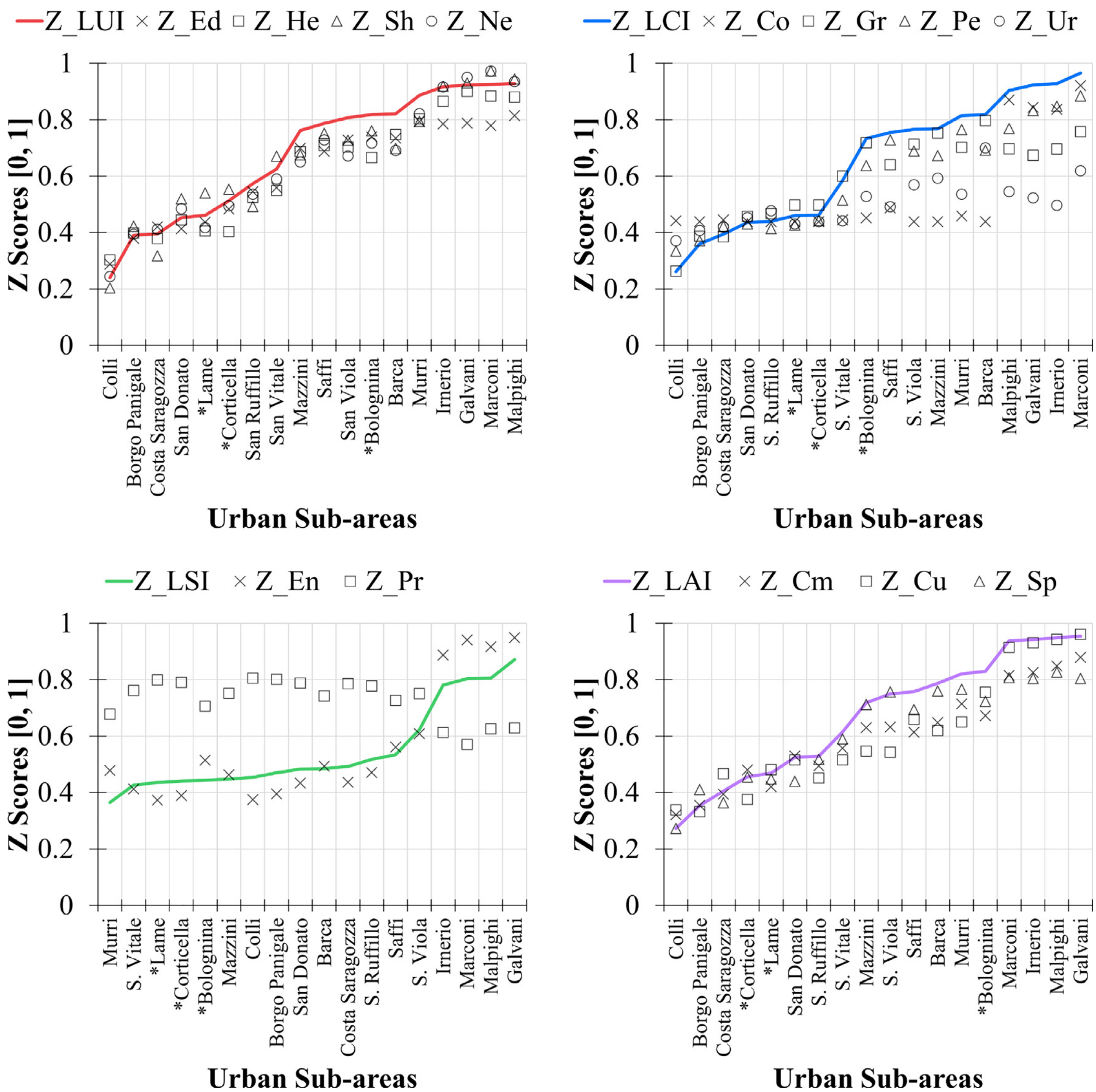

Fig. 2. Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), and Level of Attractiveness (LAI) of the urban sub-areas of the City of Bologna. The sub-areas marked with ∗ are those belonging to the neighborhood Navile.

4. Results

The proposed GIS-based analysis was applied to produce a cartographic analysis and a series of thematic maps focused on the proposed walkability assessment criteria (see Section 2). Results are visualized considering both the grid and the administrative boundaries of the neighborhoods and the urban sub-areas of Bologna, with a focus on the neighborhood Navile. In particular, results helped to identify the cells (ce) characterized by the lowest level of usefulness, comfort, safety, and attractiveness, as follows:

- Level of Usefulness Index ($LUI \leq 0.149$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas characterized by a scarce possibility for children to access relevant services within a comfortable walking distance;
- Level of Comfort Index ($LCI \leq 0.198$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas characterized by the lack of recommended elements for the comfort of children while walking (e.g., sidewalks, squares, green areas, etc.);
- Level of Safety Index ($LSI \leq 0.297$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the streets and intersections characterized by an insufficient level of road safety for pedestrians due to car accidents;
- Level of Attractiveness Index ($LAI \leq 0.128$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas character-

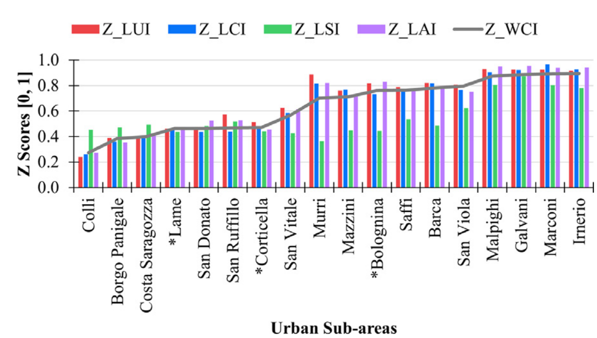

Fig. 3. Results of the Walkability for Children Index (WCI) of the City of Bologna. The urban sub-areas marked with ∗ are those belonging to the neighborhood Navile.

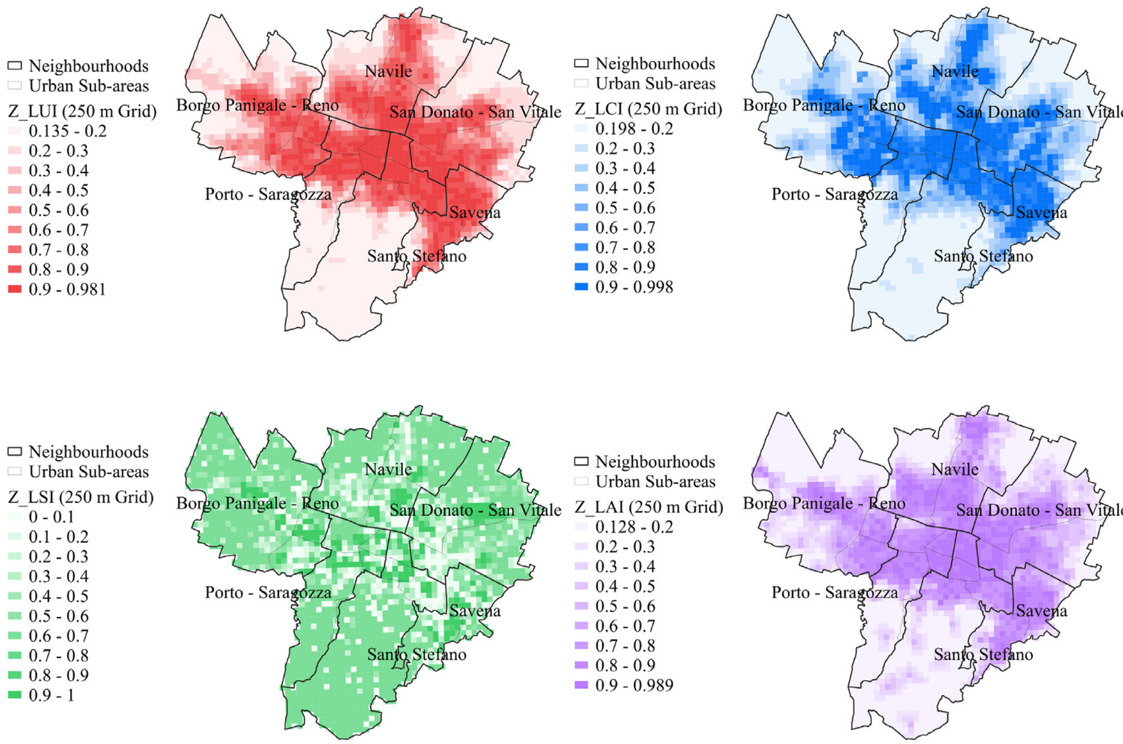

Fig. 4. Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), and Level of Attractiveness (LAI) of the neighborhoods of the City of Bologna.

ized by the lack of distinctive points of interest for children (e.g., community services, sport facilities, etc.).

In terms of walkability, Bologna is considered a highly walkable city, with narrow streets and a compact layout that make it easy to navigate on foot (Fonseca et al., 2022). The city center is particularly pedestrian-friendly, with a network of narrow streets and alleys, as well as numerous piazzas and squares that are popular destinations for locals and tourists alike. Bologna is also home to a well-developed public transportation system, which includes buses, trams, and a light rail network. Overall, Bologna is a city that is well-suited for walking and using public transportation, with a variety of options available to suit the needs of different age groups and mobility levels.

In this context, the results of the mapping analysis revealed that Bologna performs very well overall in terms of walkability for children (see Fig. 5). More in detail, results helped to identify and characterize a short list of suitable urban areas of the city of Bologna where to prioritize future interventions to enhance the level of walkability for children, as mainly located in the peripheral areas of the city ($WCI \leq 0.214$ 20^{th} percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 5). In particular, the maps related to the level of usefulness, comfort, safety, and attractiveness (see Fig. 4) demonstrates that most neighbourhoods are covered by essential services for children, although some southern neighbourhoods can benefit from a more diversified service supply to ensure a more balanced offering, as well as the implementation of additional infrastructures for pedestrians (e.g., green areas, urban furniture, community and sport services, etc.). Moreover, the streets in the city center of Bologna should be designed to guarantee an higher level of safety of children (e.g., speed bumpers in proximity of the zebra crossings, illumination systems at intersections to guarantee visibility, environmental islands, etc.).

The results of the analysis achieved through the proposed Walkability for Children Index have been compared to available standard walkability measures, with particular reference to the Walk Score® (see Fig. 6). A quantitative comparison was limited due to the different input data, considering that the Walk Score is based on the combination of three elements: the shortest distance to a group of pre-selected destinations (e.g., businesses, parks, theaters, schools, etc.), the block length, and the intersection density around the origin (Hall and Ram, 2018). However, the current study proposes a qualitative comparison between these two measures, in order to highlight the impact of individual characteristics of pedestrians, namely their age, on the perceived level of walkability. As an example, the central areas of the neighborhoods Navile, Santo Stefano, and Savena showed worse walkability scores in the WCI than in the Walk Score due to the lack of dedicated infrastructures (i.e., *comfort*) and pedestrian-car accidents in the areas (i.e., *safety*).

5. Conclusion and future work

Various bodies of research point to the necessity of adopting a user-centered approach for transport planning, that considers social facets of the city users (e.g., mobility impairments, age, gender, etc.) and a broader understanding of urban mobility. However, there is still a lack of knowledge about the needs and expectations of children regarding public spaces and walkability, primarily due to limitations in gathering data about this topic. In this framework, the current work was firstly aimed at presenting the theoretical background about the criteria and tools for the assessment of the level of walkability in urban environments, focusing on the specific needs of child pedestrians.

The objective of the research was the investigation of the level of walkability for children through the application of Geographic Information Systems. This was aimed at defining a novel Walkability for Children Index (WCI) through the analysis of a series of location-based open data about the city of Bologna (see Fig. 5). In particular, data analysis focused on the level of pedestrian friendliness of the city in terms of usefulness, comfort, safety, and attractiveness.

The results of the proposed GIS analysis revealed important insights about the possibility to assess the level of walkability for children. Our study found that neighborhoods with higher walkability scores tend to have more amenities, such as parks and playgrounds, which can encourage physical activity and outdoor play for children. These findings are

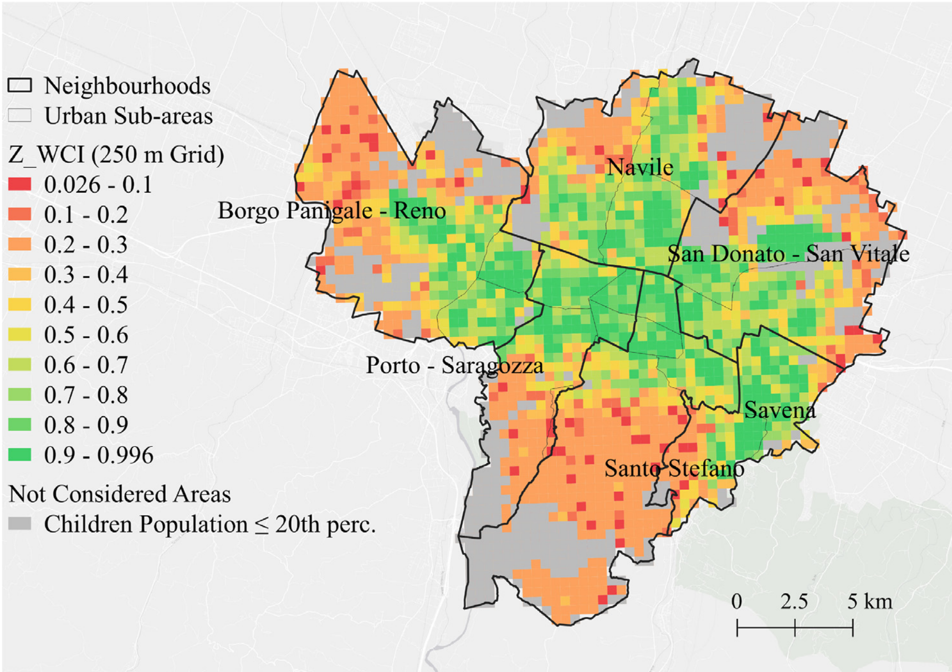

Fig. 5. Results of the Walkability for Children Index (WCI).

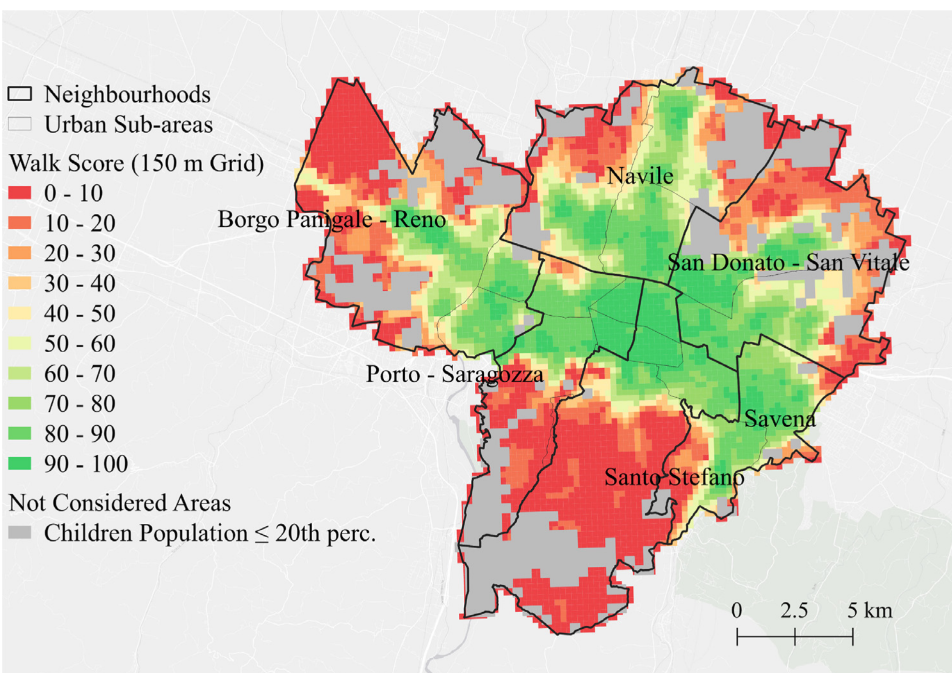

Fig. 6. Results of the Walk Score® analysis (< 60 poor, 60–80 moderate, > 80 high level).

consistent with previous research that has highlighted the importance of access to green spaces in promoting active lifestyles among children (Voce, 2018).

Moreover, our study found that neighborhoods with higher walkability scores tend to have lower traffic volumes and speed limits, which may contribute to safer pedestrian environments for children. This finding is particularly important given that pedestrian injuries are a leading cause of injury-related deaths among children (Evans and Norman, 2003; Rosenbloom et al., 2008). By identifying the characteristics of neighborhoods that support safe walking environments, our study can inform urban planning and policy efforts to create more child-friendly communities.

However, our study also highlighted disparities in walkability across different neighborhoods. Specifically, we found that neighborhoods with lower walkability scores tended to be located in peripheral and low-income areas. This finding is consistent with previous research that has shown that low-income and minority populations often face greater barriers to accessing safe and healthy environments (Gatrell et al., 2004). Thus, our study underscored the need for targeted interventions and policies that address these disparities and promote equitable access to walkable environments for all children.

Overall, this GIS analysis provided important insights into the walkability of neighborhoods for children, and highlights opportunities for improving the design and planning of child-friendly communities. By addressing disparities in walkability and promoting safe and accessible environments for all children, we can create healthier, more equitable communities that support the well-being and development of our youngest residents.

In particular, the final goal of the analysis was to identify and characterize a short list of suitable urban areas where to prioritize interventions to enhance the level of walkability for children (Peyton, 2019). This could be focused, for example, on innovative design elements for streets and public spaces focused on both the comfort and safety of children, and on differentiated urban planning strategies, such as: (*i*) inform decision makers and practitioners on the constraints and opportunities of the urban areas with regard to the street network and how it can attract or deter child pedestrian movements; (*ii*) offer insights on how the area can be optimised in its context regarding its viability, the design of sustainable development, and the creation of lively urban spaces; and (*iii*) test different strategic guidelines and design proposals.

The area identified by the Municipality of Bologna for the implementation of an interim public space was further investigated by the authors through onsite observations supported by video cameras and computer vision applications (Buch et al., 2011; Ceccarelli et al., 2023, *submitted*; Niu et al., 2022), aiming at producing *ex-ante* and *ex-post* intervention assessments related to level of comfort and safety for pedestrians. In particular, the analysis was aimed at producing behavioural maps by systematically noting specific pedestrians behaviours and movements occurring in the considered area (e.g., people counting and tracking, pedestrian flow patterns estimation, pedestrian-vehicle interactions, etc.), in order to support the iterative design process.

In conclusion, the research work represents a valuable example of the possibility to analyze digitally widespread open data sources to support decision-makers by unveiling specific target-users needs. According to the urban agenda for sustainability (e.g., SDG 11.2-Sustainable Transport for All, SDG 3.6-Reduced Road Deaths, Vision Zero Project, School Street Initiative, etc.), the presented results could be of notable interest for public institutions involved in the design of inclusive mobility strategies focused on the needs of children.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Andrea Gorrini: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Dante Presicce:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization. **Federico Messa:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Rawad Choubassi:** Conceptualization, Methodology, Investigation, Writing – review & editing.

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Dr. Andrea Gorrini He is Head of Research at Fondazione Transform Transport ETS, a non-profit research foundation launched by Systematica on April 2022 and focused on innovation in mobility and transport planning. He is an environmental psychologist with experience in human behavior in transport systems, pedestrian crowd dynamics and walkability. He oversees research and development activities related to the identification, collection and exploitation of different mobility data sources.

Dante Presicce He is Senior Researcher at Fondazione Transform Transport ETS and Senior Consultant at Systematica. He is an urban planner and GIS Specialist, with interest in urban and transport planning and data analysis and visualisation. He is involved in several international projects for which he works at multiple scale, from global to regional to urban to complex buildings. He is mainly focused on mobility strategy definition, territorial index creation and space regeneration.

Federico Messa He is Senior Researcher at Fondazione Transform Transport ETS and Senior Consultant at Systematica. He is an Architect and he has been active as a transport consultant on a diverse set of projects, ranging from territorial studies to masterplans and complex buildings mobility strategies. He is also involved in architecture and mobility research studies, mainly related to urban dynamics, mobility data analysis and visualization, project performance analysis and spatial analysis.

Rawad Choubassi He is Member of the Board of Directors of Fondazione Transform Transport ETS and Director and Board Member of Systematica. He leads research projects on mobility in urban environments. He leads a team of multi-disciplinary consultants for expanding the limits of the science behind mobility engineering dynamics on every scale. He has also been leading major urban planning and design projects, challenging the traditional approach to transportation planning.

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A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities – A case study in Utrecht, the Netherlands

Elizabeth Knap[a], Mehmet Baran Ulak[a,*], Karst T. Geurs[a], Alex Mulders[b], Sander van der Drift[b]

[a] Department of Civil Engineering, Faculty of Engineering Technology, University of Twente, Horst Complex Z218, P.O. Box 217, AE Enschede 7500, the Netherlands
[b] Goudappel BV, Snipperlingsdijk 4, BJ Deventer 7417, the Netherlands

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ABSTRACT

The 15 min city (or "X-minute city" in general) concept aims to give people access to all essential services and daily needs (e.g., healthcare, education, etc.) within X minutes of active transportation, to improve transport equity, sustainability, and traffic safety. To date, there is a lack of methods and tools to assess to what degree cities currently, or after implementing policies, comply with the X-minute city concept. This research aims to develop a methodology for quantifying the X-minute city through a metric (CS_x) that was developed based on an accessibility framework and tested for cycling mode in the Utrecht region in the Netherlands as a study area. Travel data from the Netherlands mobility panel were analysed to determine input characteristics of the metric, such as the weight of destination types. Standardized gravity-based 2-step floating catchment area (2SFCA) accessibility scores for all destination types were weighted and aggregated into a composite metric that shows relative scores as an X-minute city. The results of the analysis show that 100% of the population in the Utrecht region has access to at least one destination for all 9 destination types within 15 min, whereas this number reduces to 94% within a 10 min cycling threshold; indicating the status of Utrecht as a cycling city with cycling-friendly infrastructure. Furthermore, low-income groups do not have lower cycling accessibility to the services in the 15 min city in the study area, reinforcing the notion that cycling can be an effective solution to reduce transport inequalities. The developed metric can be used to assess cities on their way towards becoming X-minute city, prioritise neighbourhoods to develop, set quantifiable goals, and evaluate planning scenarios.

1. Introduction

Urban population is increasing all over the world and this increase causes problems such as overcrowded streets, increased traffic demand, and increased travel time to essential services. Road space has to be shared by more people causing more frequent traffic jams and crashes, coupled with polluted air and a diminished environment in cities. Covid-19 lockdowns showed that it is possible to improve the overall urban quality by decreasing motorised-vehicle travel in cities (Albayati et al., 2021; Goenaga et al., 2021; Liu & Stern, 2021; van der Drift et al., 2021; Wang & Li, 2021). However, the lockdowns also exposed weaknesses of current city planning: not all essential services can be found close to everyone's home; sidewalks are often too narrow for social distancing; and with public transit largely restricted or deemed unsafe, some locations can be hard to reach, especially for those without a car.

The 15 min city (or "X-minute city" in general), a concept first defined by Carlos Moreno in 2015 and discussed in more detail in Moreno et al. (2021), gained popularity during the pandemic. The concept's goal is to give people access to all essential services and daily needs (e.g., healthcare, education, etc.) within X minutes of active transportation (walking, cycling), thus reducing traffic demand, overall time spent in traffic, congestion, and pollution. Note that the early X-minute city concept as developed by Moreno focuses on proximity to basic amenities and public transport is not included. Others have excluded public transport as public transport travel times depend on external factors such as delays and access/egress connections (Duany & Steuteville, 2021).

Services that may be included in the X-minute city encompass public schools, parks, libraries, grocery stores, retail, employment places, basic healthcare, and places for entertainment or recreation. The concept is proposed to create lively and liveable neighbourhoods, promote economic growth, support social cohesion and sustainability (Moreno et al., 2021), and improve the health and well-being of residents (Boulange et al., 2017; Gao et al., 2020; Riggs & Sethi, 2019; Weng et al., 2019). Advocates of the concept argue that the X-minute cities are a potent solution for encouraging deep decarbonisation

* Corresponding author.
E-mail address: m.b.ulak@utwente.nl (M.B. Ulak).

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(Allam et al., 2022) and that it contributes to building safer, more resilient, sustainable and inclusive cities, as depicted in the Sustainable Development Goal 11 of the United Nations (Moreno et al., 2021). The X-minute city can help to mitigate the impacts of societal shocks such as Covid-19 and fuel price fluctuations as its residents are less reliant on motorised transport to fulfil their daily needs.

Several cities around the world such as Paris, Barcelona, Melbourne, Portland, Shanghai, and more are now adjusting their transport policies to fit the X-minute city concept (Pozoukidou & Chatziyiannaki, 2021). Implementation of the 15 min city concept not only calls for walkability and safe bicycle infrastructure, but also mixed land use, appropriate density, and adequate spatial distribution of services, commerce, and green spaces. The 15 min city can be a possible solution in urban planning to reduce energy use in cities and reduce emissions to mitigate climate change (IPCC, 2022). In the Netherlands, Utrecht is the first city that has stated they want to become a 10 min city with services such as healthcare, sports, education, shopping, and more within a 10 min walk or bike ride from people's homes. Although several neighbourhoods in Dutch cities might already meet some of the requirements of 15 min cities, these requirements have never been quantified nor measured.

Literature on the 15 min city introduced and defined the concept (Moreno et al., 2021); reviewed city plans for becoming a 15 min city (Pozoukidou & Chatziyiannaki, 2021); measured neighbourhood characteristics and travel behaviour (Carpio-Pinedo et al., 2021; Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Weng et al., 2019); and measured the potential for the 15 min by walking (Abdelfattaha et al., 2022; Caselli et al., 2021). This paper addresses three knowledge gaps in the literature. First, the concept of the X-minute city has been qualitatively defined and interpreted in many studies, but much less research has been done on how to measure the concept using accessibility metrics. Second, existing quantitative studies have focused on the role of walking in the x—minute city (e.g., Ferrer-Ortiz et al. 2022). The role of cycling has received less attention, whereas cycling is one of the main modes of transport in Dutch cities. Third, there is scarce research on how X-minute city scores vary across socio-demographic groups at the neighbourhood level within cities. Therefore, this study aims to develop a composite metric to assess X-minute cities based on cycling accessibility measures, and assess the spatial and sociodemographic inequalities with regard to X-minute city scores of neighbourhoods in Utrecht and its surrounding towns in the Netherlands.

To achieve the objectives of the study, first, recorded travel data were used to determine mobility patterns, appropriate cycling distances, and the frequency of different daily activities in urbanised areas in the Netherlands. Then, the set of candidate services to be included in the calculation of the X-minute city metric was identified and the resultant metric was calculated. Finally, spatial and socio-demographic inequalities were investigated based on the current physical neighbourhood characteristics and the impacts of future transportation investments and changes on the X-minute city were assessed in two scenario analyses. Although the concept of the X-minute city concept considers all active transportation modes, only cycling was utilized in the development of the metric.

2. Literature review

2.1. Quantification of the X-minute city

Although the name of the concept suggests a straightforward and quantitative nature, there are many variations in the quantification of the metric such as using different threshold travel times and alternative modes (i.e., public transport). That is, the X-minute city has been adapted to fit different regional needs, such as 20 min neighbourhoods in Melbourne (Melbourne Government, 2017) and Portland (Portland, 2010), the 15 min city in Paris (Paris en Commun, 2020), and now the ambition of Utrecht for the 10 min city (Gemeente Utrecht, 2019). Furthermore, the types of services included in the development of X-minute city metrics differ drastically between plans and in the literature (Carpio-Pinedo et al., 2021; Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Moreno et al., 2021). In summary, the X-minute travel time is not rigid and can be adjusted in different cases or contexts (Duany & Steuteville, 2021).

The Netherlands is amongst the highest cycling countries and its cities are amongst the highest cycling cities across the globe (Goel et al., 2021). This dominance of cycling over walking makes the concept of X-minute cities in the Dutch context different from most other countries. Thus, this research focuses only on cycling and cycling accessibility.

2.2. Services in the X-minute city

Moreno et al. (2021) state that six main categories should be included in X-minute city quantification: living, working, commerce, healthcare, education, and entertainment. Graells-Garrido et al. (2021) add access to healthy food, government facilities, green spaces, and public transit to this list. Furthermore, green spaces in cities are important considering the effects of climate change and urban heat islands. Table 1 presents the services considered by literature that either define the X-minute city concept or use it in analysis or assessment.

The six main categories seem to be present in some way in most of the literature (Moreno et al., 2021). Employment is an important characteristic of the X-minute city because most workers commute to work each day. In the Netherlands, two-thirds of short-distance commuting trips (0-5 kilometres corresponding to 0-20 min based on 15 km/h average cycling speed) are done on foot or by bike, with the bicycle as the most important mode (55% mode share) (de Haas & Hamersma, 2020).

Table 1
Services in the academic literature on 15 min cities.

Source	Services	Use
(Moreno et al., 2021)	Categories: Living, Working, Commerce, Healthcare, Education, Entertainment	Definition
(Weng et al., 2019)	Services: Education (School or Training institution), Medical care (Hospital or Pharmacy), Municipal administration (Public transport; Park and square; Sports venue; Cultural venue), Finance and telecommunication (finance and post office), Commercial service (restaurant, shopping, entertainment venue), Elderly care (nursing home or elderly education)	Measuring walkable neighbourhoods
(Pozoukidou & Chatziyiannaki, 2021)	Categories: Work, Basic healthcare, Cultural and recreational opportunities, "key resources"	Assessing/evaluating transportation plans
(Carpio-Pinedo et al., 2021)	Land-use types: Industrial, Offices, Commercial, Sports, Show business, Leisure and hospitality, Health, Cultural, Religious	Measuring walkability
(Gaxiola-Beltrán et al., 2021)	Services: Schools (Preschool, Primary school, Secondary school, Technical secondary school, High school), Hospitals (General hospital, Addiction and psychiatric hospitals, other hospitals), Other (Supermarkets and Employment centres)	Assessing urban accessibility (walking and cycling)
(Graells-Garrido et al., 2021)	Categories: Education, Entertainment, Finance, Food, Government, Health, Professional, Recreation, Religion, Retail, Public transport	Measuring 15 min accessibility (walking)

Table 1 presents the services considered by papers that either define the 15 min city concept or use it in analysis or assessment. The *living* category is captured by the origin points and spatial unit used in the analysis, and the housing affordability category in Pozoukidou and Chatziyiannaki (2021). The *working* category is considered in Carpio-Pinedo et al. (2021) and Pozoukidou and Chatziyiannaki (2021) but no distinction is made between different types of jobs or different types of workers. Gaxiola-Beltrán et al. (2021) include employment centres and make a distinction in size (number of job positions). The *commerce* category is included in all other studies but in different ways. Gaxiola-Beltrán et al. (2021) only include supermarkets, which provide the most essential of daily needs, while Graells-Garrido et al. (2021) consider supermarkets in their retail category together with other shops and malls. *Health* is also considered in all of the other articles. While some consider several types of healthcare, others consider all healthcare grouped and do not distinguish between types such as hospitals, pharmacies, or general practitioners. However, these different health providers all have different amounts of people they need to service, and it is safe to assume that not every 15 min neighbourhood needs regional services such as a hospital. The *education* category is considered in 3 of the other articles. Gaxiola-Beltrán et al. (2021) and Weng et al. (2019) both distinguish different types and levels of education in their analysis, while Graells-Garrido et al. (2021) group all types together. Finally, there are some very distinctly different services included in the *entertainment* category in all articles. Gaxiola-Beltrán et al. (2021) do not consider entertainment at all, while in other articles a distinction is made between entertainment and recreation Graells-Garrido et al. (2021). Carpio-Pinedo et al. (2021) and Weng et al. (2019) include parks, sports venues, cultural venues, restaurants, entertainment venues, and leisure and hospitality types in their analysis that may all be considered part of the *entertainment* category.

2.3. Accessibility measures for active transportation

Different types of accessibility measures, such as distance-based, gravity-based, infrastructure-based, and Walk Score types are available (Vale et al., 2016). Distance-based measures only consider the travel time or distance from an origin to a destination within a threshold. These measures are relatively simple to compute but the distance threshold is arbitrarily chosen and may have a large influence on the number of opportunities that can be reached. Gravity-based measures, on the other hand, assign weights to opportunities based on their distance or travel time from the origin point, and possibly other factors such as floor space, or the number of employees (El-Geneidy & Manaugh, 2012; Kockelman, 1997). These measures are more realistic because destinations further away are less attractive than closer ones. The Shen index (1998) and its equivalent the two-step floating catchment area method (2SFCA) (Luo & Wang, 2003) combine two potential accessibility measures to into account the supply and demand of service. The enhanced 2SFCA index provides a ratio between the accessible opportunities and the population that can reach said opportunities using a decay or impedance function for both. It is a straightforward accessibility indicator to include competition effects into accessibility analysis. It is often used to measure accessibility to healthcare or other service providers with capacity constraints. The inclusion of competition effects is also relevant for measuring job accessibility and can reveal different spatial patterns and equity impacts than a standard potential accessibility measure (e.g., Cervero et al. 1995, Geurs & Eck 2003, Pritchard et al. 2019, Shen 1998). In this paper, including competition effects is particularly relevant as the spatial distribution of jobs (supply) at walking or cycling distance can be very different from the spatial distribution of workers (demand). Furthermore, the 2SFCA approach has also been used to examine disparities or inequalities in the distribution of urban parks and green spaces (Dony et al., 2015). In this paper, we apply the same accessibility index to all destinations to achieve consistent scores and allow comparisons between destinations.

Lastly, some composite measures such as Bike Score (Winters et al., 2013) which is based on Walk Score have been developed to capture both network qualities like the infrastructure-based measures, and travel time to opportunities much like the distance- or gravity-based measures. Other walkability and bikeability indexes may include topological characteristics of the network, such as intersection count and percentage of roads with sidewalks (Vargo et al., 2012) or even go as far as to include the quality, width, and maintenance of available sidewalks, as well as the slope, number of problematic intersections, speed limit, and more (Horacek et al., 2012).

2.4. Conclusions from the literature

The concept of the X-minute city has been qualitatively defined and interpreted in other studies (Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Moreno et al., 2021). Abdelfattaha et al. (2022) used Walk Score and density to map the potential for the 15 min city in Milan, and Gaglione et al. (2022) carried out an analysis for walking destinations to health centres and grocery stores in different districts in Naples. Accessibility analysis by Ferrer-Ortiz et al. (2022) to different urban services was focused on walking as well and labelled Barcelona as a 15 min city. Caselli et al. (2021) also investigate the walkability to different services in a single neighbourhood. The majority of the current literature focuses on walking, whereas X-minute city based on cycling has not been thoroughly studied. Moreover, dimensions such as density and land mix, the type of services to consider, the catchment areas and capacities of different services, and the comfortable biking distances have not yet been fully quantified (Chen & Crooks, 2021). Lastly, many accessibility studies including cycling often also include public transport (Mavoa et al., 2012; Yigitcanlar et al., 2007), or only consider one type of service (Apparicio et al., 2008; Apparicio et al., 2007; Páez et al., 2012). The X-minute city, on the other hand, is a holistic concept and cannot be properly captured by only considering one type of urban service.

3. Study area and data

3.1. Study area

This research focuses on the city of Utrecht and surrounding towns (Nieuwegein, Maarssen, Houten, Zeist, De Bilt, Bilthoven, and Bunnik) as shown in Fig. 1. These towns were chosen because they are represented in the 10 min city strategy as new or existing centres for the polycentric structure (Gemeente Utrecht, 2021). The city of Utrecht is well-known as a cycling city due to the cycling-friendly infrastructure, where 48.5% of all trips within the city of Utrecht are made by bike (in Amsterdam it is 42.6%). Furthermore, Utrecht is the first city in the Netherlands to express its ambitions to become a 10 min city

3.2. Data

Table 2 presents the data sources that are used in this study, and are described in more detail below.

3.2.1. Travel patterns

Recorded travel data from the Dutch Mobility Panel (DMP) (van der Drift et al., 2021) are used in this paper to develop the X-minute city cycling accessibility metric. The DMP started in 2019 with a panel of over 5.000 participants recruited from a large online access panel. The DMP is based on a smartphone app to collect travel data of the participants entirely GDPR proof 24/7 including background knowledge comparable with traditional repetitive household surveys (e.g. income, age, household size, residential location, gender, car ownership). Recorded travel data from the DMP were selected from all records based on several criteria. Trips were recorded between December 2019 and February 2020,

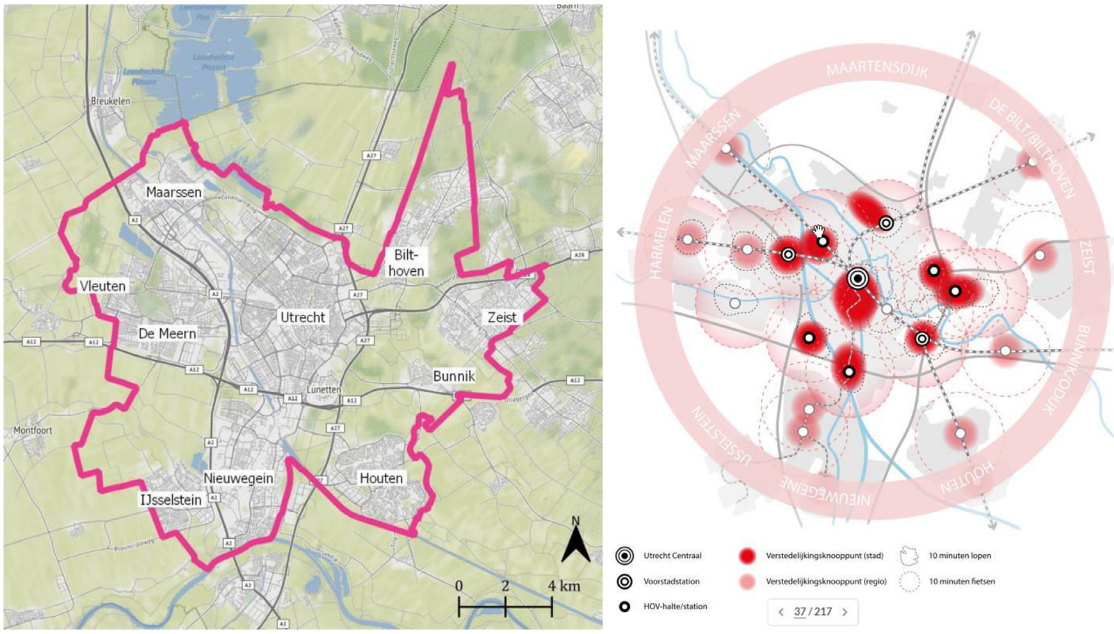

Fig. 1. Study area and Polycentric Structure of Utrecht (GemeenteUtrecht, 2021).

Table 2
Data sources.

Data	Description	Source	Year/time period
DMP subset	Recorded trips from individual panel members	Dat.mobility	Dec 2019 – Feb 2020 June – July 2020
CBS 500-by-500 m grid	Contains information on distance to services, socio-demographic information	CBS	2018 (v3)
Bicycle network	Created from roads in OSM	OpenStreetMap (OSM)	January 2022
POIs	Building (polygons) and point data from OSM containing many different POIs	OSM	January 2022
Parks and recreation areas	Land use (polygons) from OSM containing many different kinds of land-use	OSM	January 2022
Employment data	Point data, number of employment places per building	BAG, Dat.mobility	2021

as well as June and July 2021. Only trips made by people living in urbanisation levels 1, 2, or 3 (>1000 addresses/km2) to a destination type essential to the X-minute city were selected. Nine categories of destination types were considered: jobs, education, commercial, food, bars and restaurants, sports, entertainment, recreation, and healthcare. The selected DMP data consists of a dataset with trip records and one with user records. There are 233,273 trips in the trip dataset, and 21,556 records in the user dataset. After the removal of duplicate records, the user dataset consists of 8,214 users. Matching trip data with user data led to 225,958 trips with both trip and user information, excluding invalid trips with travel time 0 or travel mode unknown. Of these, 81,627 trips were made by bike.

3.2.2. Spatial data

For the spatial information on the region, the CBS 500-by-500 m grid was chosen since it consists of equal-sized squares, unlike the postcode polygons. A 100-by-100 m grid is also available, but too small for a study focusing on cycling, considering that 4 to 7 grid cells of 500-by-500 m can already be covered in 10 to 15 min. Note that, the average cycling distance in the Netherlands is about 4 kilometres (de Haas & Hamersma, 2020) Furthermore, the 500-by-500 m data set contains information on inhabitants such as age groups, household characteristics, gender, and income, while in the 100-by-100 m grid cell data set a lot of this data is missing due to privacy regulations. Thus, the 500-by-500 m dataset is considered the best available data set for this study. Note that for higher accuracy of the accessibility assessment, the population-weighted centroids of the cells in the 500-by-500 m grid are determined by using the mean coordinates tool in QGIS. The building types of *houses* or *apartments* in the Open Street Map (OSM) point data to increase the accuracy are used in this tool, which calculates a mean coordinate for each grid cell.

Destination data is filtered from OSM data as well. Table 3 presents the number of data points and the description of each destination type. The destination types were selected based on the assessed literature as presented in Table 1. Only general practitioners were selected as the "health service" component as they are the only health service providers addressing the daily needs of residents (except in emergencies) in the Netherlands. Parks are intentionally left as polygons, with points created along the edges connecting to the road network as entrances for areas larger than 0.2 km^2. Job data containing the number of jobs per building are available at the building level, in a BAG data file enriched by Dat.mobility (Table 2). The data sets for commercial, bars and restaurants, and jobs are each aggregated per grid cell with a point containing the number of facilities at the weighted centroid, based on the point locations of the activities. Note that, this aggregation was needed due to the complexity of the network analysis and may lead to slight inaccuracies. However, as the weighted centroids of locations were used, such inaccuracies are not expected to affect the overall outcome.

OSM road data was used to create the bicycle network by selecting roads with cycleway type, tertiary, living street, residential, unclassified, tracks, and secondary. Of this last one, only secondary roads with the attribute 'both ways' were included since one-way secondary roads in the Netherlands will usually have a separated bike path.

To address the boundary effect problem a 3 km buffer zone around the study area was created and all the destinations within this zone were also included in the analysis. This is because people living right at the edge of the study area can also travel to destinations just outside of the study area within X minutes.

Table 3
Destination data and description.

Destination type	Nr of points	Aggregated	Description of the destination type
Jobs	30,334	1,326	The exact number of jobs in each cell (2020)
Commercial	4,772	667	Number of shops in a cell excluding grocery stores, fresh produce, delis, and bakeries
Bars and restaurants	1,309	297	Number of bars, restaurants, cafés, and coffee shops in a cell
Education	573	-	School, high school, or higher education
Food	413	-	Grocery stores, delis, bakeries, fresh produce
Recreation	367	-	Playgrounds, picnic sites, attractions (such as theme parks and large playgrounds)
Parks	213	-	Green spaces
Entertainment	193	-	Museums, theatres, cinemas, community centres, libraries, nightclubs
Healthcare	191	-	General practitioners
Sports	162	-	Sports centres, gyms, pools, sports fields

4. Methodology

4.1. X-minute city cycling accessibility metric

In this paper, a composite metric is developed that combines accessibility scores with the frequency of different destinations (through weights as derived from DMP data). The developed 15 min city cycling accessibility metric consists of built environment factors and behavioural factors. Note that, the quality of the cycling network, road safety, and barriers such as crossing large roads were not considered in the development of the metric. The behavioural factor is captured in the average speed of cyclists as determined through analysis of recorded trip data, distance decay functions (see Appendix), and frequency of visits to different destination types. The conceptual model of the metric is presented in Fig. 2.

4.2. Accessibility score per destination type by 2-step floating catchment area approach

According to Penchansky and Thomas (1981), access to service has 5 dimensions; accessibility, availability, accommodation, affordability, and acceptability. 2-step Floating Catchment Area (2SFCA) takes into account two of these dimensions: accessibility and availability (i.e., supply and demand). This is important because more densely populated areas typically have more services and larger capacities; however, there are also more people using these. Due to this capability, several studies utilize 2SFCA for measuring spatial accessibility to services (Luo & Wang, 2003; Ye et al., 2018), sports facilities (Langford et al., 2017), green spaces (Wang & Wang, 2018), and jobs (Xiao et al., 2021).

The X-minute city metric in this study consists of gravity-based 2SFCA accessibility measures that take into account the age of the residents in the area (Qiu et al., 2019). The demand for a service is calculated using the distance decay functions (see Appendix) and the fraction of the population per age group. Accessibility for grid cell *i* for destination type *p* then becomes:

$$A_{i,p} = \sum_{j=1}^{J} \frac{S_j * f\left(c_{ij}\right)}{D_j} \tag{1}$$

where $A_{i,p}$ is the accessibility of cell *i* for destination type $p = \{1, \ldots, P\}$ (e.g., healthcare), $j = \{1, \ldots, J\}$ is one of the destinations of destination type *p*, $f(c_{ij})$ is the distance decay function for cell *i* to access destination *j*, S_j is the supply in destination *j*, and D_j is the demand *D* for every destination *j* being:

$$D_j = \sum_{k=1}^{K} \sum_{q=1}^{Q} P_{k,q} * f\left(c_{kj}\right)_q \tag{2}$$

where $q = \{1, \ldots, Q\}$ are the five age groups, $k = \{1, \ldots, K\}$ are the origin cells for the demand, and $f(c_{ij})_q$ is the distance decay function for age group *q* between cell *i* and destination *j*. The supply of the destination type is calculated using the distance decay function specific to each destination type. The demand D_j is calculated per age group and multiplied by the size of that group $P_{k,q}$ in cell *k*. Demand is taken from all cells *k* which can reach service *j* within the threshold time (e.g., 15 min). Supply is calculated for the study area and 3 km buffer zone. Demand

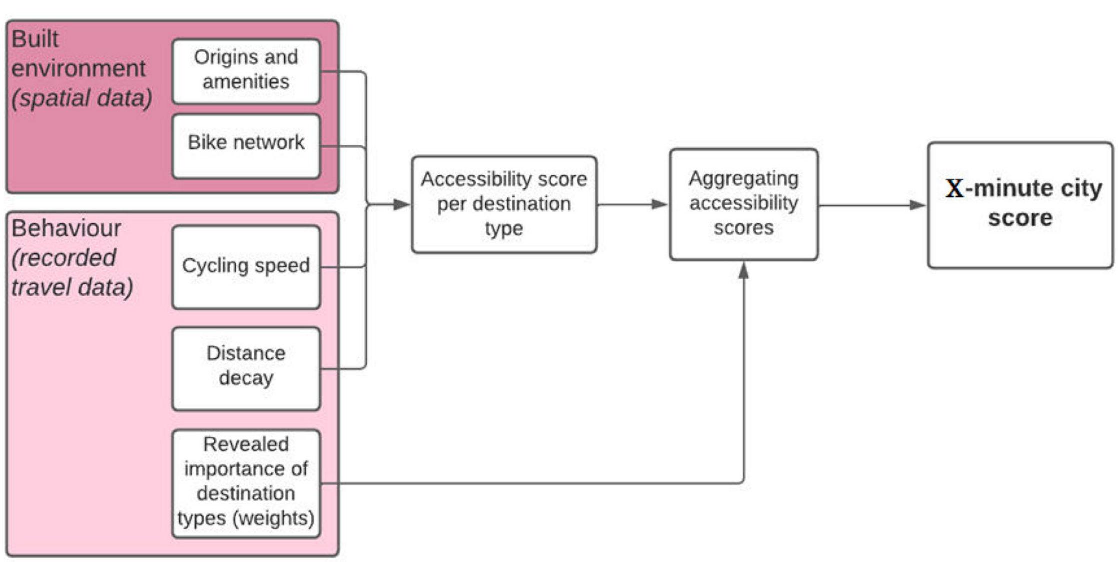

Fig. 2. Conceptual model of the X-minute city cycling accessibility metric.

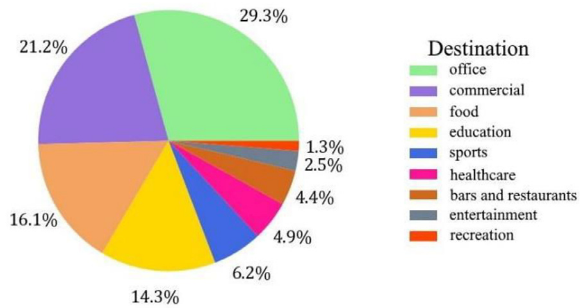

Fig. 3. Percentage of trips (all modes) per destination type.

is calculated for this area, including another buffer zone, since people living just outside the buffer zone can also travel to destinations in the 3 km buffer zone. Note that, for education, the demand is calculated for people aged 24 or lower only. Furthermore, for jobs, the demand is calculated only for people aged between 15 and 65. For all other destination types, demand from all age groups is considered. Consequently, the accessibility measure can be interpreted as the number of services of a specific destination type that are available for grid cell *i* per person, within the specified threshold time.

4.3. Aggregation of accessibility scores for the composite X-minute city metric

To aggregate the accessibility scores obtained for each service into a composite metric, the scores are needed to be normalized first to bring them on the same scale. The min-max normalization was used as follows:

$$X_{i,p} = \frac{A_{i,p} - min\left(A_{i,p}\right)}{max\left(A_p\right) - min\left(A_p\right)} \tag{3}$$

where $A_{i,p}$ is the accessibility of cell *i* for destination type *p*, $X_{i,p}$ is the normalized accessibility score of cell *i* for destination type *p*. Following the normalization, the accessibility scores were aggregated based on the frequency of trips to each destination type. The weights were derived from the trip distributions calculated based on travel patterns in the DMP dataset (Fig. 3). The final metric is then defined by the equation:

$$CS_{x,i} = \sum_{p=1}^{P} w_p * X_{i,p} \tag{4}$$

where $CS_{x,i}$ denotes the X-minute city score with travel time threshold *X* in cell *i*, w_p the weight of destination type p (i.e., percentage of trips to destination type *p*), and $X_{i,p}$ the normalized accessibility score of destination type *p* in cell *i*. The metric is calculated for three different travel time thresholds; 10, 15 and infinite minutes (in reality 130 min because no destinations were further than 130 min cycling within the study area). From here on denoted as CS_{10}, CS_{15}, and CS_{∞}.

4.4. Spatial statistics and analysis

In this study, first, an adjusted version of Local Moran's I called bivariate Local Moran's I (Lee, 2001; Weng et al., 2019) was used to analyse spatial relationships between calculated X-minute city metrics (CS_X) and socio-demographic variables. The bivariate local Moran's I identifies statistically significant clusters of high-high observations (i.e., both metric value and socio-demographic indicator are high), low-low observations as well as high-low and low-high observations. Next, spatial regression models were applied to gain insight into the relationship between the CS_X and some neighbourhood and population characteristics. Spatial regression modelling was adopted due to the spatial autocorrelation and spatial dependence identified in the score of CS_X (Anselin, 1988). There are alternative spatial regression models such as the spatial lag model (SAR), spatial error model (SEM), and combined spatially lagged and error models (SARMA) are available in the literature. To decide the best-fitting spatial regression model, Lagrange Multiplier tests are conducted (Chi & Zhu, 2020). The CS_{10} (excluding job accessibility) was chosen as the dependent variable because Utrecht has the ambition to become a 10 min city. Note that, two CS_{10} metrics, one including job accessibility and the other excluding it, were utilized for modelling. However, the difference between the two models was negligible; thus, the CS_{10} metric excluding the job accessibility was used in the final model.

The independent variables included in the model (Model A) are based on factors indicating the risk of transport poverty according to Kampert et al. (2019) and Jorritsma et al. (2018). Transport poverty entails the inability to access locations or opportunities and a disadvantage in partaking in society as a result (Kampert et al., 2019). The second model (Model B) consists of the same variables as Model A while also controlling for the built environment characteristics which might be also influential on the X-minute city metrics. This is because without addressing built environment characteristics, the effects of socio-demographic factors could simply act as proxies rather than genuine effects. To normalize the dependent variable (CS_{10}), log-scaled values were used in the regression models by taking the natural logarithm of the CS_{10}. Correlations between candidate independent variables were checked to avoid multicollinearity in the models. The variables that are included in the analyses are listed below in Table 4.

4.4.1. Spatial regression modelling

A spatial regression model is similar to a standard linear model but includes a spatial lag and/or error components introducing an autoregressive effect into the model. Thus, the prediction at a location is influenced by the dependent variable values of its neighbours, as specified

Table 4
Variables used in the regression models.

Variable	Description	Unit	Model
% soc. minimum	Percentage of households living under or just around the social minimum, households of which at least one person makes money all year round, but below the social minimum as defined by the government	%	A, B
% welfare	Percentage of people receiving benefits from the government because they are unemployed or unable to work	%	A, B
% > 65 years	Percentage of residents over 65 years of age	%	A, B
% < 15 years	Percentage of residents under 15 years of age	%	A, B
% immigrants	Percentage of residents that were born outside of the Netherlands or whose parents were born outside of the Netherlands	%	A, B
D train station	Distance to the nearest train station	km	A, B
% < 1945	Percentage of residencies built before 1945	%	B
% > 1994	Percentage of residencies built after 1994	%	B
% apartments	Percentage of residencies that house more than one family (i.e., apartment buildings)	%	B
Income	Mean yearly income per person (before tax)	[€ x 1000] / year	B
Pop. density	Residents per km2	[People x100]/km2	B

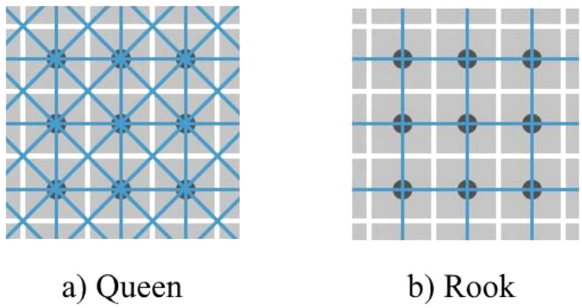

Fig. 4. Spatial weights matrices.

in a spatial weights matrix Anselin, 1988). The regression equation of a combined spatial lag and error model (SARMA) is composed of two parts which produce spatial lag (SAR) and spatial error models (SEM) individually. Eqs. (5)–(7) below show SAR, SEM, and SARMA models, respectively (Anselin & Bera, 1998):

$$Y = \alpha + \boldsymbol{X}\beta + \rho \boldsymbol{W} Y + \varepsilon \quad (5)$$

$$Y = \alpha + \boldsymbol{X}\beta + \lambda \boldsymbol{W} u + \varepsilon \quad (6)$$

$$Y = \alpha + \boldsymbol{X}\beta + \rho \boldsymbol{W} Y + \lambda \boldsymbol{W} u + \varepsilon \quad (7)$$

where Y is a vector of observations of the dependent variable, β is the set of coefficients of the independent variables *X, W* is the spatial weight matrix (i.e., contiguity matrix) involving the cost relations between observations (i.e., square grids), ρ and λ are the spatial autoregressive parameters, ε is a normally distributed error term with zero mean and non-zero variance, and u is a vector of error terms assumed to have an autocorrelation. Moreover, the type of spatial weights matrix can influence the model results (Chi & Zhu, 2020), therefore two different contiguities (Queen and Rook) were specified to develop spatial weights matrices for all models used. Queen spatial weights include every neighbour that a cell shares an edge or a vertex, while Rook spatial weights matrix only includes those that share an edge (Fig. 4).

4.5. Scenario analysis

Two scenarios were created to evaluate the effects of future developments on the X-minute city scores. These developments are based on some existing plans regarding new bridge or tunnel connections for cyclists in the study area and changes in the speeds on the cycling network due to e-bike penetration in the bike market. In the first scenario, 9 bridge/tunnel connections were added to the network, based on the report for new cycling connections from Gemeente Utrecht (Gemeente Utrecht, 2019). These nine bridges and tunnels are shown in Fig. 5 and were added to the network.

For scenario 2, the speeds on the cycling network are changed to simulate the effect of an increasing number of e-bike riders. A distinction is made between urbanisation levels, and the type of infrastructure. In urbanisation levels 4 and 5 (less than 1000 addresses/km2), speed is 20 km/h for cycleways (separated infrastructure), and 18 km/h otherwise. In urbanisation levels 1, 2, and 3 (more than 1000 addresses/km2), speed is 18 km/h on cycleways and 17 km/h otherwise. All origins and destinations were kept the same and the X-minute metrics were calculated again.

5. Results

5.1. X-minute city scores and accessibility analysis

The accessibility per destination type is calculated for 10 min and 15 min threshold travel time and without any time threshold. The results of the accessibility analysis for 10 min threshold are presented in Fig. 6 as an example. The scores in Fig. 6 are standardized according to the lowest and highest values; thus, the results of the analysis are comparable. Afterwards, the accessibility scores were weighted according to the weighing approach (see Section 4.3), and the results are calculated for the 10 min threshold, 15 min threshold, and no travel time boundary (Fig. 7). The final scores are standardized according to the distribution of 10 min scores (both highest and lowest outliers); hence, the results are all on the same scale and comparable.

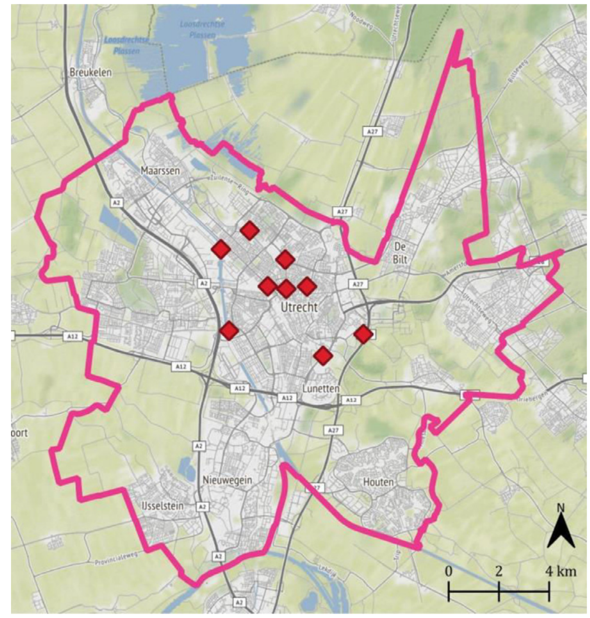

Fig. 5. Newly planned cycle bridges and tunnels in the study area.

The most prominent difference between the CS10 and the CS15 is the presence of grid cells which has no score in the CS10. This is because these grid cells do not have accessibility to one or more of the destination types such as sports, healthcare, and entertainment. On the other hand, in CS15, there is only one grid cell at the northeast of the study area (Bilthoven) that has no score. Based on this definition, a mere 5.76% of the population in the study area does not have access to at least one of the destination types within 10 min, whereas, within 15 min, this number drops to a marginal 0.03%. Nonetheless, further research on identifying proper thresholds for citizens and marginal benefits of having more than one facility or service within a given threshold is needed to better assess the cities.

The overall CS_{10} show high values in the city centre of Utrecht and Bunnik (the eastern part of the study area). Also, in the surrounding towns, the centres score higher than the peripheries. The CS_{15} results are more homogenous, but still, the highest scores can be found in the city centre of Utrecht and Bunnik. Lower values are found in peripheries (IJsselstein and Houten, southwestern Utrecht).

Furthermore, Fig. 8 shows the absolute difference between the scores with different thresholds. The difference between the CS_{15} and the CS_{∞} is relatively small, as can be seen in Fig. 8-c. Only in Bunnik is the difference in score more considerable, with CS_{15} being substantially higher than CS_{∞}. However, differences between CS_{15} and CS_{10}, and between CS_{10} and CS_{∞}, shown in Fig. 8-a and -b, are more substantial. People living in the peripheries of the city centre are especially disadvantaged due to a longer travel time, meaning they have to travel further to find the same number of opportunities as someone living in the city centre. CS_{10}, on the other hand, is substantially higher than CS_{15} and CS_{∞} in the city centre. People living here benefit from the shorter travel time, but only if people in the other neighbourhoods also stay in their neighbourhood – can find their daily needs within 10 min cycling – because otherwise,

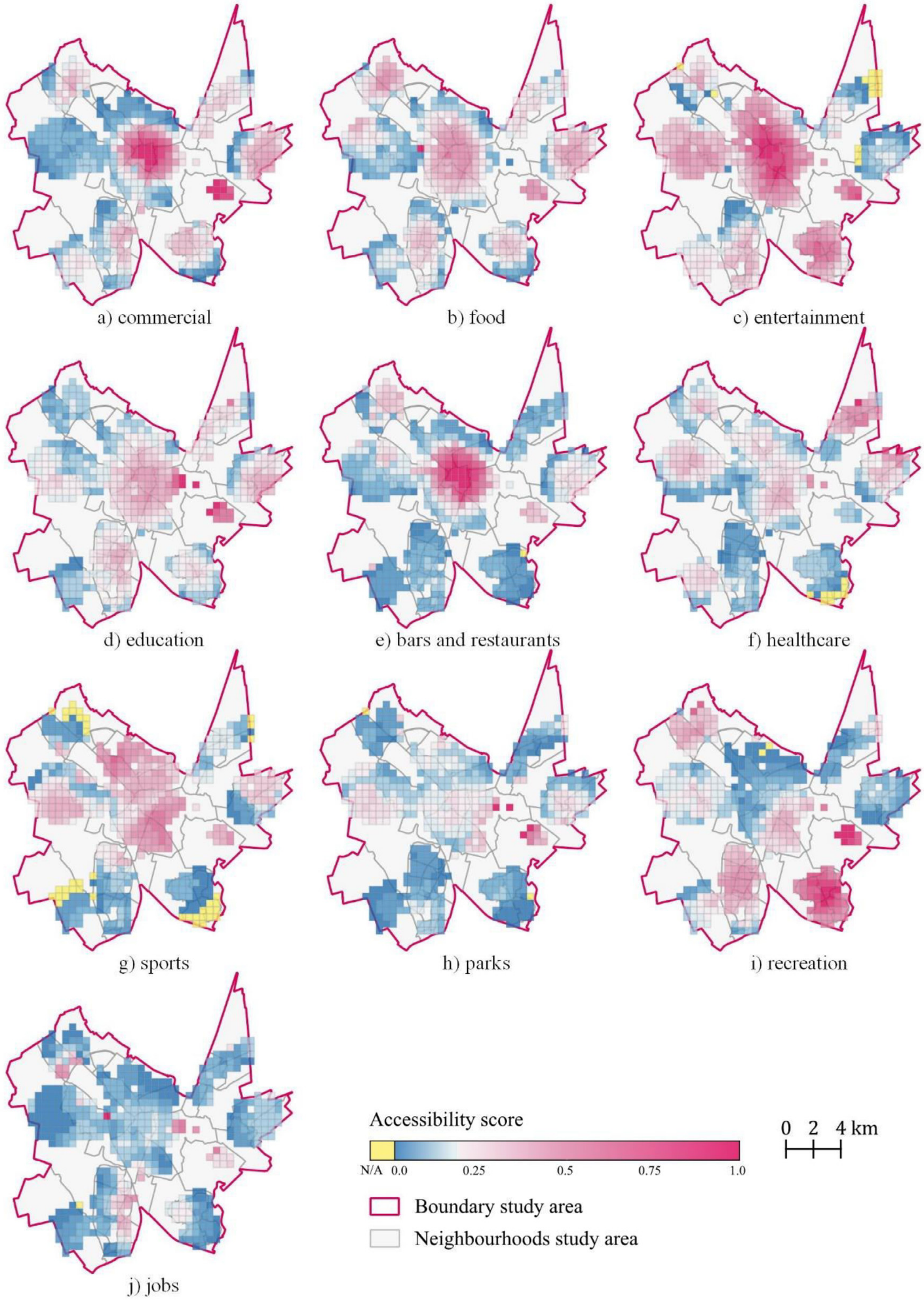

Fig. 6. Standardized accessibility scores per destination type, 10 min maximum travel time.

demand is too high. Thus, people living in the city centre might benefit from the other areas scoring higher as a 10 or 15 min city. Though it should be noted that the higher demand from the CS_{∞} may be showing a more realistic image for the commercial and entertainment categories for example because the city centre of Utrecht attracts people from much further than just the 10 or 15 min boundary.

5.2. Bivariate clustering of scores and the socio-demographic variables

Fig. 9 presents bivariate local Moran's I for the CS_{10} and key sociodemographic and neighbourhood characteristics hinting at the equity aspects. Results show that there is a low-high bivariate cluster of the CS_{10} and percentage of people with an immigration background, per-

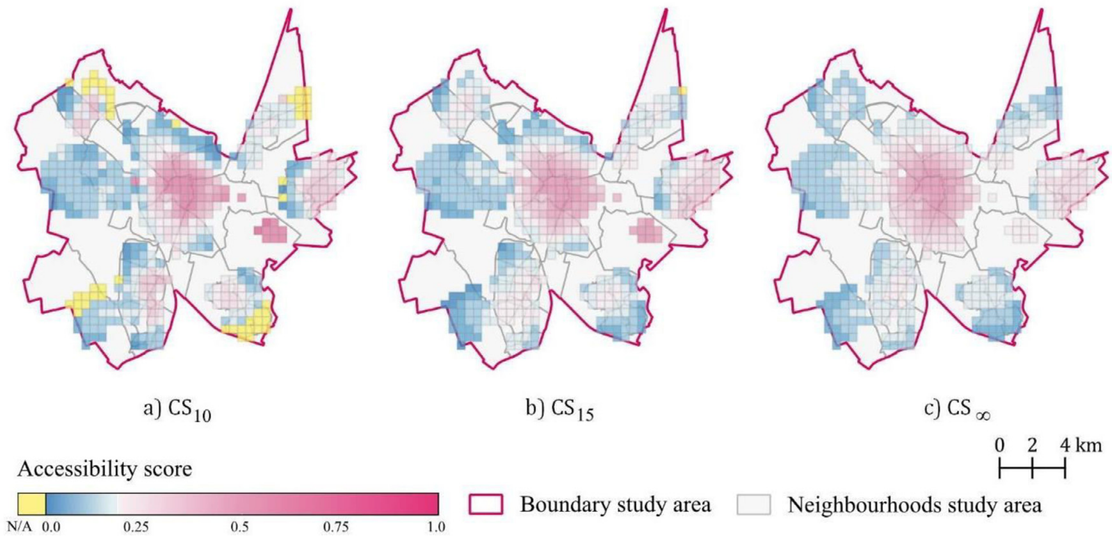

Fig. 7. CS10, CS15, and CS∞.

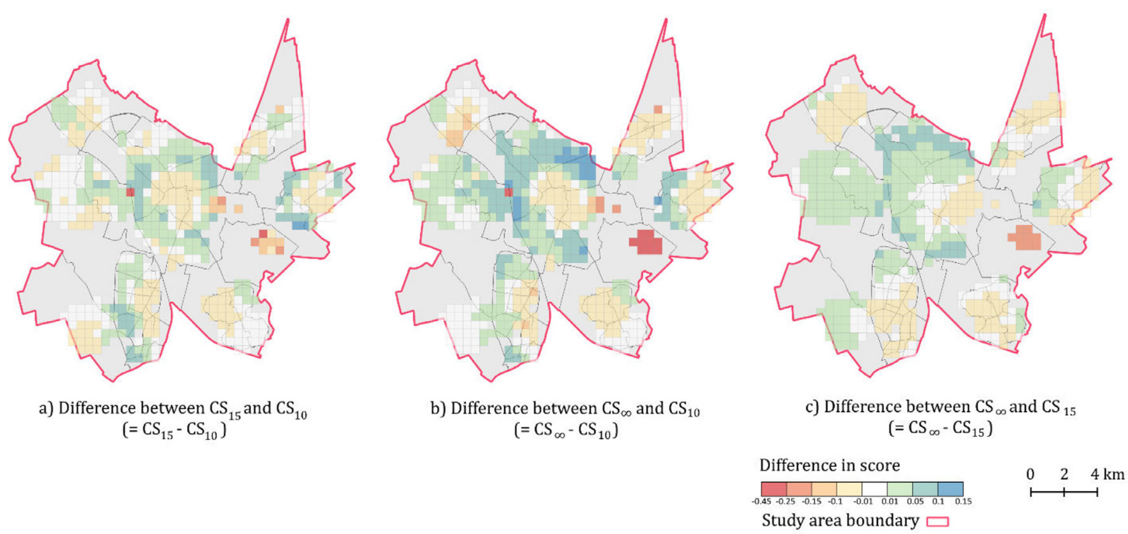

Fig. 8. Differences in CS10, CS15, and CS∞.

centage of people receiving welfare, and percentage of social housing in the neighbourhood Overvecht in Utrecht (centre-north). This indicates that the CS_{10} scores of these cells are low, while the number of people with an immigration background, the percentage of people receiving welfare, and the percentage of social housing are high. The people that live here are largely economically disadvantaged and have a greater risk of transport poverty (Kampert et al., 2019) and according to the CS_{10}, have less access to the services of the 10 min city. It should be noted that people with an immigration background generally cycle less than native Dutch people (Harms et al., 2014; Nello-Deakina & Harms, 2019) and an assessment based on the developed metric might overestimate the overall accessibility of areas with high immigrant populations due to lower share of cycling.

Kanaleneiland – a neighbourhood in the southwest of Utrecht, on the other hand, shows high-high bivariate clusters of the CS_{10} and the percentage of people with an immigration background, percentage of people receiving welfare, and percentage of social housing. This indicates that Kanaleneiland is a better practice neighbourhood where people with lower income and immigration backgrounds also have access to the services of the 10 min city.

Fig. 9-e shows a strong relationship between the percentage of children and the CS_{10} at Vleuten-De Meern and the south of Houten (western and southeastern part of the study area) where CS_{10} is low while the percentage of children is high. The CS_{10} is remarkably high in the city centre but relatively few children live here. Fig. 9-f shows the correlation between the CS_{10} and the percentage of elderly. Similar to the children, the CS_{10} is high in the city centre but relatively few ageing people live here. CS_{10} is relatively low in parts of Bilthoven (northeast Utrecht), Maarssen (northwest Utrecht) and the south of Nieuwegein (south Utrecht), while the percentage of elderly is high in these neighbourhoods. Some notable high-high clusters are located in Zeist and Bunnik (west Utrecht), where the elderly live in a 10 min city.

5.2.1. *Spatial regression findings*

Two spatial models (Table 5), Model A and Model B were developed (see Section 4.4). A spatial statistics test (Lagrange Multiplier - LM) was conducted to identify the best-fitting spatial autoregressive model, showing that only spatial dependence for lag was found to be significant both in Model A and Model B. Thus, a spatial lag model (SAR) was constructed for both models using a “Rook” contiguity for spatial weights matrix (based on Moran’s I value of the residuals). The dependent variables are the CS_{10} scores excluding job accessibility.

The results in model A indicate that the higher the percentage of households living under social minimum the higher the CS_{10} score,

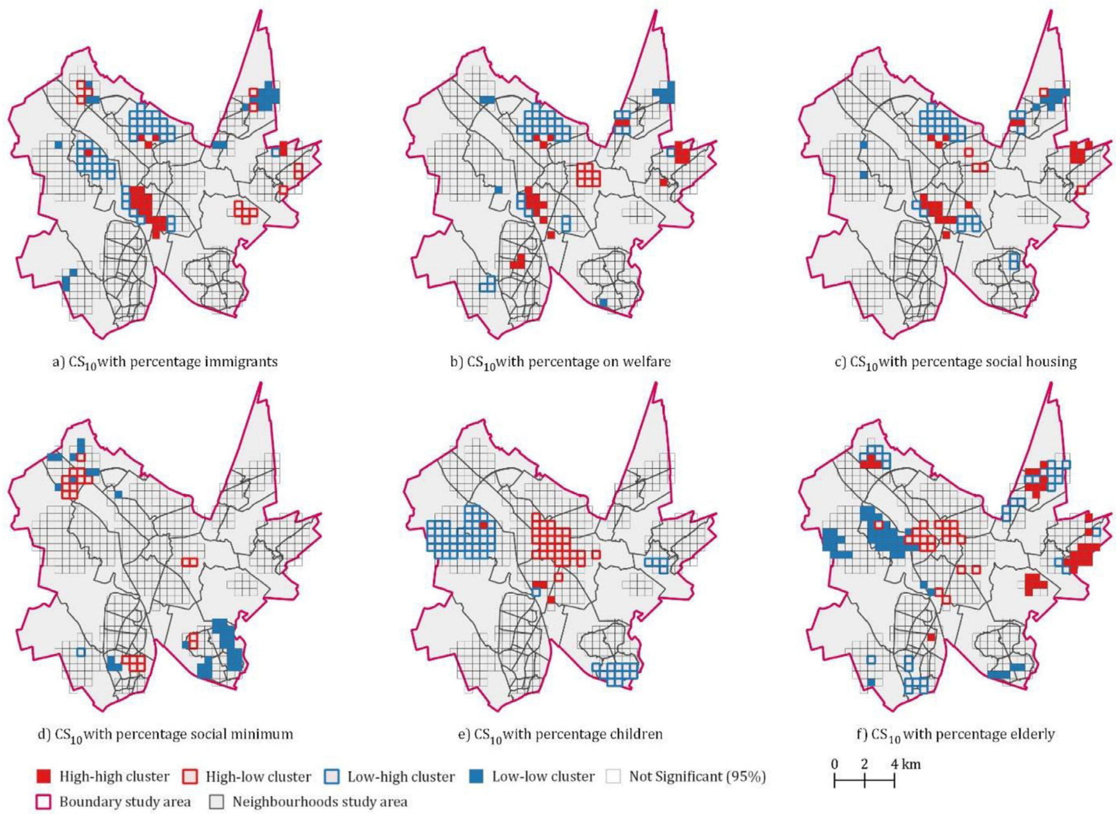

Fig. 9. Bivariate local Moran's I of CS10 and socio-demographic characteristics.

Table 5
Spatial regression results, dependent variable: CS_{10} without job accessibility.

	Model A			Model B		
Variables	β	St. Error	Sig.	β	St. Error	Sig.
Constant	0.201	0.041	***	0.096	0.046	*
% soc. minimum	0.014	0.004	***	0.005	0.005	
% welfare	0.394	0.148	**	0.302	0.151	*
% > 65 years	-0.034	0.097		0.045	0.099	
% < 15 years	-0.520	0.121	***	-0.369	0.140	**
% immigrants	-0.112	0.073		-0.157	0.075	*
D train station	-0.043	0.010	***	-0.028	0.010	**
% < 1945				0.010	0.003	***
% > 1994				0.006	0.003	*
% apartments				0.075	0.036	*
Income				0.005	0.073	
Pop. density				0.083	0.025	***
Rho (lag)	1.446	1.467	***	1.384	1.658	***
Spatial dependency residuals						
Global Moran's I z-value, p-value	1.323	0.186		1.201	0.230	
Model fit						
LL	113.90			135.69		
AIC	-211.79			-245.38		
R2	0.362			0.488		

*** = P < 0.001
** = P <0.01
* = P <0.05

which is a positive outcome for the equity and social fairness perspectives. Similarly, there is a significant positive relationship between the value of the CS_{10} and the percentage of people receiving welfare money. It is also an expected result that the larger the distance from the train stations, the lower the CS_{10} score, showing that train stations are generally the centre of urban activities and several services are close to the stations. An intriguing result is that there is a negative relationship between the CS_{10} score and the percentage of the population below 15 years old. The reason behind this outcome might be the preference of families with young children to live further away than urban centres, in suburban areas.

The Model B results are similar to Model A for the part of "transport poverty" indicators, except the percentage of households living under social minimum is not significant in Model B, whereas the percentage of people with an immigration background is significant. Results show that the percentage of people

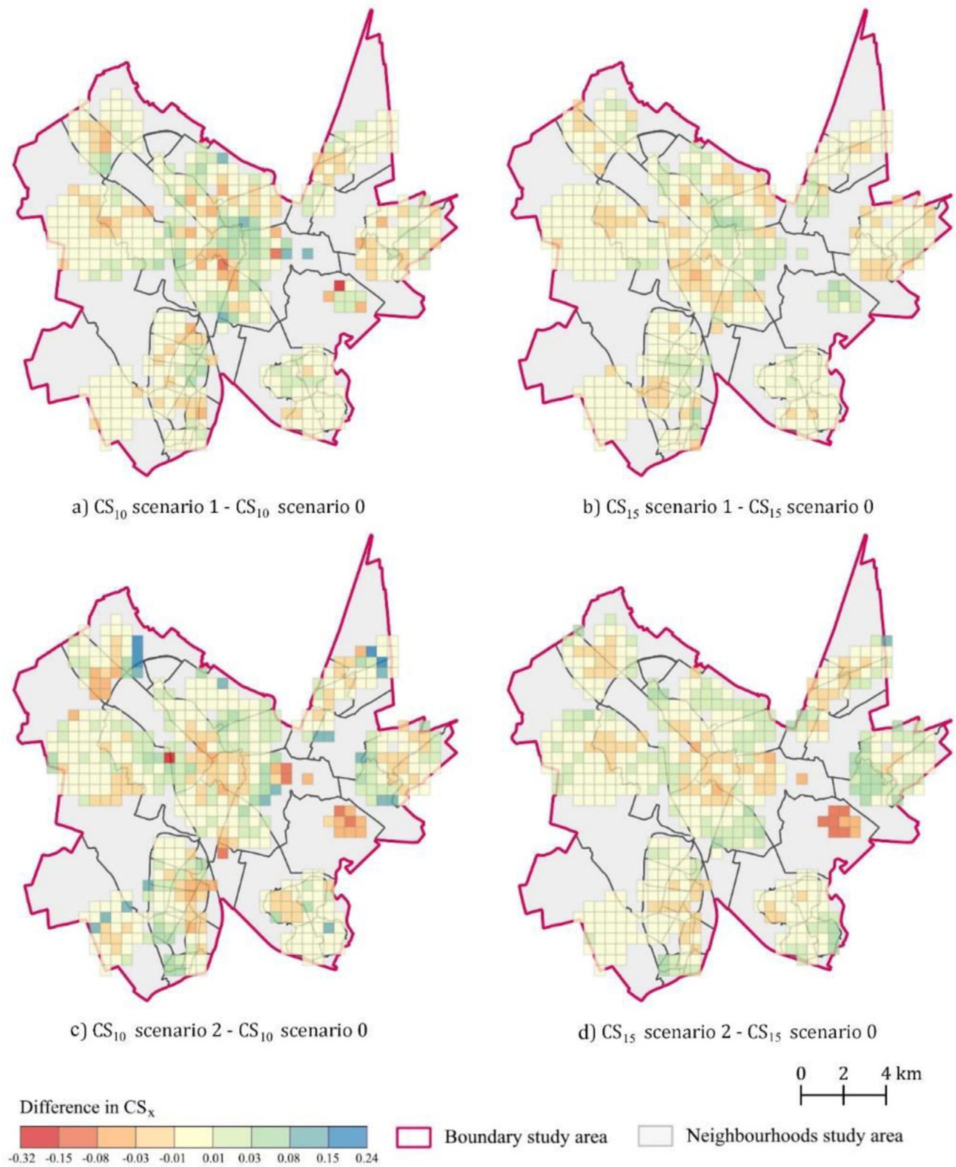

Fig. 10. Changes in CS10 and CS15 with scenario 1 and 2.

with an immigration background living in a grid cell has a negative relationship with the CS_{10} score.

Furthermore, the percentages of houses constructed after 1994 (i.e., VINEX neighbourhoods (Schepers, 2021)) and before 1945 have positive relationships with the metric. Similarly, the higher the percentage of apartments (i.e., the type of housing in the grid cell) and the population density, the better the CS_{10} score. Income level, on the other hand, has no statistically significant effect on the metric.

5.3. Scenario analysis

Two different scenarios were tested to identify the effect of future investments (i.e., new bridges and tunnels) and potential changes in the cycling speeds due to e-bike penetration. Fig. 10 shows the difference between tested scenarios and the base scenario (i.e., current situation). These changes, although generally perceived as positive for mobility and accessibility, may result in negative effects for some regions due to competition effects which increase the demand for services while supply stays the same. For example, when Scenario 1 is implemented, CS_{10} increases in the city centre compared to the base scenario, while the score reduces (or does not change) around the city centre and for most of the towns in the periphery. This difference is most notable in the CS_{10}, where the score decreases right around the city centre as a result of increased demand due to the new connections. The population density in this area is somewhat higher than in the city centre. In Scenario 1, the CS_{10} increases for 45.8% of the population, and decreases for 45.2% of the population. For CS_{15}, it increases by 45.6% and decreases for 50.6% of the population. However, note that the change in scores is very small (between -0.02 and +0.02) in 80% of grids.

Scenario 2, in which cycling speeds are increased for cycling highways and outside of the city centres, is possible to observe a contrary effect compared to Scenario 1. Fig. 10 shows that towns in the periphery and areas surrounding the city centre benefit from the increasing cycling speeds the most, while Utrecht city centre experiences a reduction in CS_x scores. The situation in Scenario 1 and Scenario 2 is due to the change in the supply-demand relationship. When new connections or modes (e.g., e-bikes) are established to improve accessibility, more services become reachable by more people from further away areas; therefore the demand is increasing while the supply for the local people remains the same. Because of this, the overall scores do not differ much between the base scenario and alternative scenarios (Scenario 1 and Scenario 2). Consequently, marginal improvement is observed in the CS_x scores, implying the ineffectiveness of detached infrastructure measures without taking the urban design and land use into account.

6. Discussion

6.1. Interpretation of results

The CS_{10} and CS_{15} in the study area show that while not every location is a 10 min city, almost every location is a 15 min city. However, this does not take the capacity of services into account, and some areas only minimally fulfil the requirements. Moreover, differences between the city centre of Utrecht and the surrounding periphery and towns are large, indicating an equity issue. It is also worth noting that an analysis focused on walking may reveal that Utrecht itself is also not a 10 min (walking) city. The results also show that people on welfare and people with low income generally do not have lower accessibility to services in the 15 min city in the study area, in contrast to the transport poverty literature (Jorritsma et al., 2018; Kampert et al., 2019). This finding reinforces the notion that cycling can be an effective solution to maintain transport equity in which the same opportunities are accessible to everyone.

From a social fairness perspective, people with immigration backgrounds (who were born outside of the Netherlands or whose parents were born outside of the Netherlands) tend to live more in neighbourhoods where the CS_{10} is lower. This may indicate a disadvantage for people with an immigration background. Moreover, people with immigration backgrounds generally have a lower cycling rate than other groups in the Netherlands (CBS, 2021). Therefore, the X-minute city score based on cycling might be even lower than the calculated levels when the preference for cycling as a mode is taken into account.

People with children (under 15 years) also tend to live in neighbourhoods where the CS_{10} is lower. Children are highly dependent on the bikeability and walkability of their place of residence to achieve independence at an early age, and they might benefit from having services such as schools, sports clubs, and recreation more accessible.

6.2. Practical implications

Improvements to the 10- or 15 min city scores can be achieved by economic and policy stimulation of more small stores, restaurants, and other leisure activities in neighbourhoods may alleviate pressure from the city centre as well as improve the score in these neighbourhoods. Recent city council elections in Utrecht showed that there is interest in such schemes amongst the political parties. The CS_x can help pinpoint areas to focus efforts on. Improvements in the surrounding towns may come from focusing not only on the cores but also the fringes, implementing new services in newly developed or developing neighbourhoods, and better cycling connections to the cores of the towns.

The proposed methodology is also effective to assess the impacts of new implementations such as network improvements or new housing developments on accessibility. For example, a scenario with improved cycling connections (i.e., bridges, tunnels, etc.) showed no significant changes in the score, aside from a small increase in the city centre. The metric can be used to evaluate scenarios like this and select the best options or prioritise projects that would be most beneficial for residents. The scenario analysis showed that not every new connection leads to an increase in the metric value in all grid cells, due to increased demand. New connections can be prioritised based on the net increase in CS_x they provide.

6.3. Limitations and future research

It should be noted that the accessibility analysis in this study does not consider the quality and safety of the cycling network, which may impact the experienced travel time. Also, the bike network was simplified by applying an average speed of 15 km/h on all roads. Thus, speed is only influenced by the wait time at the intersections included in the network and not by personal characteristics or (cycling) traffic intensities. Accessibility was only calculated for the shortest route, while the study shows that not everyone chooses the shortest route every time (Bernardi et al., 2018). Finally, including capacity and quality of services will provide more nuance and details in the results, but these factors were not available in the data used in this study. A possible future research direction can be including the capacity of services, diversity measures for restaurants and shops, and the quality of the network.

Another possible venue for future research would be to include level of traffic stress (LTS) classification by making a distinction between a low-stress cycling network and a complete cycling network to take the quality of cycling infrastructure into account. In this way, the X-minute metric can be even further deployed to assess results for different population groups such as children and elderly preferring low-stress bike routes, and it would provide insights into the safety of cyclists in the X-minute city. Furthermore, expanding the metric with walking accessibility scores may lead to more nuanced conclusions about a city, since some people that are unable to bike or use a similar mode of transport can walk. For walking, however, due to lower speed using 100-by-100 m grid cells or building-level analysis will be much more accurate than the 500-by-500 m grid cells used in this study. This significantly increases the data need and computational efforts for large network analysis.

In this study, a weighing scheme derived from the DMP recorded travel data was used, which only captures what people can do and currently do, but not what they want to do (preference). In the 15 min city, all six service categories as defined by Moreno are important to be present within the threshold. Personal preferences can be identified through surveys (Weng et al., 2019) and used as the weights of different services in the metric.

7. Conclusion

The main objective of this study was to develop a cycling accessibility metric for X-minute cities and apply this in a case study. An aggregated metric of gravity-based 2SFCA accessibility measures for nine different destination types was developed for this purpose. The results of the metric in the study area provide insights into the progress towards becoming an X-minute city and reveal problematic areas that may be prioritised to improve the score.

The number and type of services in the 15 min city are not universally agreed upon, with different studies using different definitions and destination types. In this study, nine destination types were defined. While bars and restaurants, entertainment venues, sports venues, and recreational areas are all grouped in the entertainment category in this original definition, this study defined them as separate destination types, thus capturing some of the diversity dimensions in the accessibility scores. The same is true for destination types of food and commercial (originally commerce). The 15 min city is different for every individual, depending on one's preferences and lifestyle, but should universally include food, job opportunities, entertainment and recreation, green spaces, commercial destinations, and healthcare. Other than that, the definition of the 15 min city can be modified to fit the culture of the location under study and its inhabitants. It is worth mentioning that a few destination types identified in the literature, namely hospitals, pharmacies, banks, religious facilities, and post offices, are not included in the developed metric. That is because these services are not very influential in the context of the study area. Nonetheless, there is still room for future research to identify the set of destination types for different contexts and user preferences. Therefore, the developed methodology allows for modification of the weights of the destination types, as well as the distance decay functions.

The results of the metrics show that the study area is a 15 min city for almost 100% of the population within the area, and a 10 min city for 94% of the population in the study area, with at least one service of each destination type accessible within 10 min cycling. Thus, it can be concluded that a very high percentage of the population in the study area lives in a 15- and even 10 min city. This is not surprising, as the city of Utrecht is well-known as a cycling city due to its cycling-friendly infrastructure. Furthermore, low-income groups do not have lower cycling accessibility to the services of the 15 min city in the study area, reinforcing the notion that the 15 min cycling city may reduce transport inequalities caused by not having access to a private car. However, some areas outside of the city centre and the town cores barely meet the definition of one service per destination type accessible within 10 or 15 min.

Scenario analyses show that improvement of the X-minute cycling city is not as straightforward with a net positive increase as a result of new connections or changes in travel speeds. While some areas benefit from new changes, in others the X-minute city metric decreases as a result of increased demand simultaneously with increased accessibility using the new connections. The methodology can be used to evaluate scenarios. Because both supply and demand are taken into account, the methodology is also suitable for measuring the effect of new neighbourhoods or developments on X-minute cities.

This research is the first study in which cycling accessibility measures are combined to quantify the X-minute city, and scrutinize a study area concerning the concept. A combination of walking and a mobility analysis in the area under study can provide further nuanced insights to assess the location as an X-minute city and pinpoint problematic aspects or areas where efforts of improvement should be focused.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Fig. A, Table A

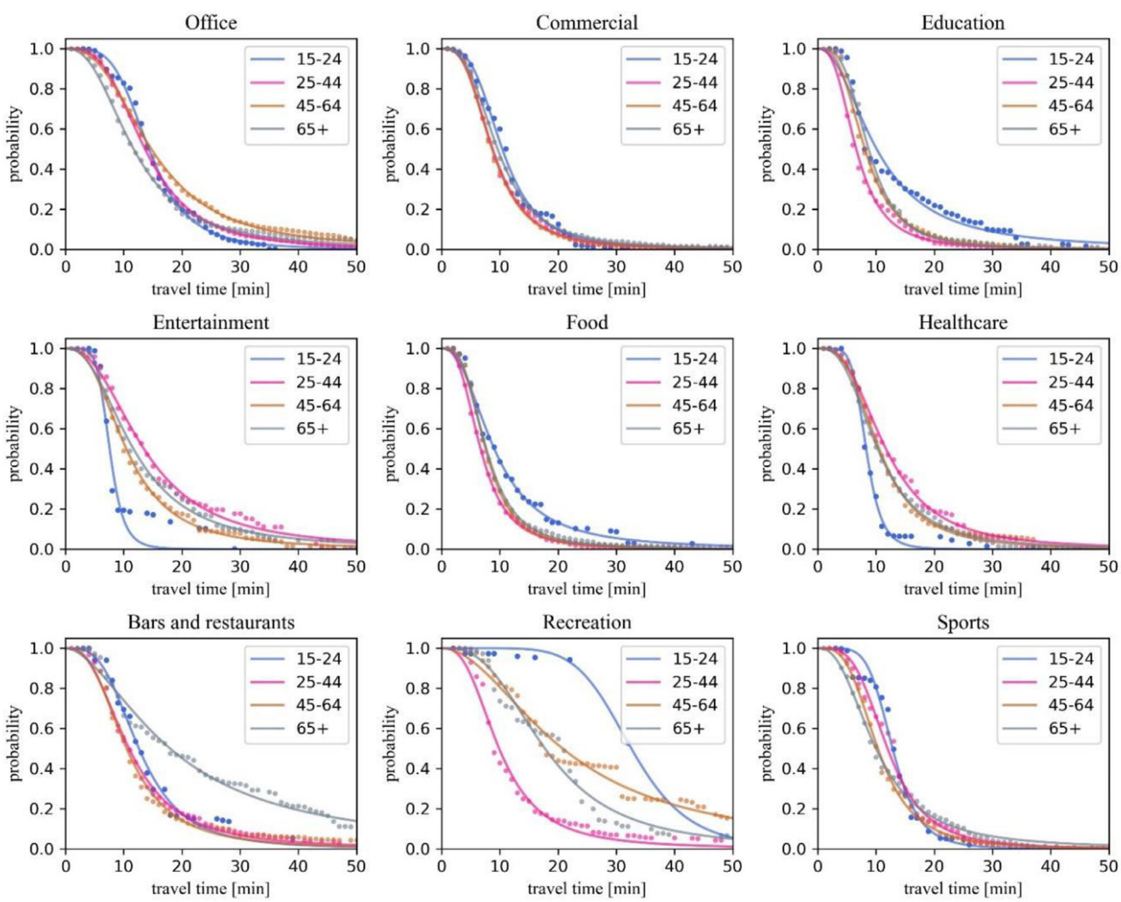

Fig. A. Distance decay functions by age group.

Table A
Descriptive statistics of travel times of recorded cycling trips

Destination	All	Jobs	Commercial	Food	Education	Sports	Healthcare	Restaurants, bars	Entertainment	Recreation
Trip duration (min)										
Mean	12.1	15.7	10.3	8.8	10.1	10.9	11.8	15.9	13.7	19.6
Std	10.4	11.5	8.9	7.9	7.9	8.3	8.4	16.4	11.6	22.4
Min	0.7	1.2	1.2	0.9	0.8	1.0	0.7	1.4	1.5	1.9
Max	215.8	215.8	173.1	197.1	136.5	146.8	95.2	193.6	116.5	196.2

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Assessing service characteristics of an automated transit on-demand service

Yves M. Räth[a], Milos Balac[a,*], Sebastian Hörl[b], Kay W. Axhausen[a]

[a] Institute for Transport Planning and Systems, ETH Zurich, Zurich, Switzerland
[b] Institut de Recherche Technologique SystemX, Palaiseau, France

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ABSTRACT

With the introduction of automated vehicles, new operating regimes for public transport services will become possible. A station-based Automated Transit on Demand service could be an attractive alternative to the current modes of transportation. In this paper, the impact of this kind of service on the modal share for the city of Zurich, Switzerland, and its surrounding area is modeled using an agent-based approach. Different scenarios regarding the operating area, pricing scheme, and a cordon charge are tested on their potential to make use of the benefits of the new service while preventing an overflow of automated vehicles in the urban core. Results show that if left unconstrained the proposed service can substantially impact the demand for public transport. A pricing scheme that bases the pricing of the new service relative to the accessibility of the current public transport service is a promising solution to increase the accessibility of the rural areas while maintaining a high modal share for public transport in the city center. Finally, using an optimization algorithm we show that the total car-fleet and public parking space can be reduced at the cost of a slight increase in vehicle kilometers traveled. Moreover, we find that the cost coverage of the proposed transit service is potentially much higher in comparison to current public transport services.

1. Introduction

Automated vehicles (AV) can potentially have a disruptive effect on transportation systems. Governments will need to carefully consider how AVs are introduced into their transportation networks. The trade-offs between private and shared AV ownership need to be evaluated to drive transport policy.

Three different types of AV usage can be distinguished. First, personally owned AVs (PAV) are likely the most attractive AV type for the passengers, given no regulation is in place, as the car will be available at any time and ensures the known level of privacy and comfort as it is provided by conventional vehicles today (Becker and Axhausen, 2017). Second, shared AV (SAV) systems could decrease the overall car fleet and ensure higher utilization of the vehicles during the day, as the cars pick up and drop off passengers like today's taxis (Bischoff and Maciejewski, 2016). Simultaneously, SAVs would increase the accessibility for people who do not have a driver's license or access to a car. Third, an Automated Transit on Demand (AToD) service, which is the focus of this paper, can be understood as a taxi-bus hybrid, as it is station-based, has a headway or predefined departure times, and allows connection from any station to any other station without making detours. At the same time, the passengers who have the same origin and destination stations at a particular time can share their ride. In summary, this service tries to bundle the traffic flows while giving the comfort of direct connections without any detours. The OD (origin-destination) pairs are only served whenever there is a demand to reduce empty mileage.

In this paper, the impact of an AToD service deployment is explored by using an agent-based transport simulation, MATSim (Horni et al., 2016), for the case-study of the city of Zurich. Furthermore, based on the analysis of the unconstrained AToD service and a literature review, several measures are tested with the aim to increase accessibility while at the same time ensuring an efficient use of the road- and parking capacities. Not only the modal share change is of interest, but also the implications thereof, e.g., how much additional infrastructure is necessary to ensure this service (i.e., parking capacity)? Furthermore, what are the mobility patterns, and how does the number of vehicle kilometers traveled change with the introduction of AToD? How can it be ensured that the new service does not challenge the existing, highly bundled transportation flows in the commuter rail and tram network to avoid increasing externalities as observed in other studies on shared automated services (see for example Hörl et al., 2021)? Is it possible to reduce the overall car fleet and can it be achieved with a high level of cost coverage?

To answer these questions, we create multiple scenarios, with combinations of various planning and policy measures, to quantify their overall impact. This paper's insights can be used as initial guidance for

* Corresponding author.
E-mail address: milos.balac@ivt.baug.ethz.ch (M. Balac).

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policymakers to allow a thought-through introduction of the new transportation mode into the existing transport system.

The remainder of this article is structured as follows. At first, an overview is provided of the related literature, followed by a description of the simulation method and the case studies. After presenting the results from the simulations, the discussion pinpoints the limitations and concludes with the gained insights.

2. Background

Current literature includes many studies related to AVs. Initially, most studies focused on SAVs and frequently relied on simplistic assumptions without explicitly modeling mode-choice decisions. Zhang et al. (2015) assign 2% of the population to SAVs, and in (Zhang and Guhathakurta, 2017), the authors assume 5% of the population would switch from their current car to the use of SAVs. Spieser et al. (2014) replace "all modes of personal transport" in Singapore with SAVs. Also, Javanshour et al. (2019) replace all car trips in the south-eastern part of Melbourne, Australia, with a single-rider SAV fleet. All of the studies that do not employ behavioral models find that the car fleet can be reduced at the expense of increasing VKT when a service is composed of single-occupancy SAVs. Using an agent-based simulation, Javanshour et al. (2019) find that the car fleet can be reduced by 79% but increases VKT by 61%. Pooling rides has been seen as a potential solution to counteract the increase in VKT generated by empty vehicle mileage. Heilig et al. (2017) model a region in Stuttgart, Germany and conclude that 85% of all vehicles can be replaced, and VKT can be decreased by 20% if trips can be pooled. Fagnant and Kockelman (2018) report that for a case study in Austin, Texas with increasing adoption of SAV service or willingness to deviate from trip-timing due to pooling can decrease the overall VKT. Ruch et al. (2021), however, find that the efficacy gains of ride-sharing are relatively small compared to the losses in the quality of service measures.

The AToD service tries to further increase the potential of ride-pooling to overcome some of the losses in the quality of service due to increases in travel time. Examples of modeling an AToD service can be found in Wang et al. (2018) and Balac et al. (2020). Wang et al. (2018) provide an algorithm to calculate the necessary AToD fleet size with DRS (Dynamic Ride Sharing) in MATSim. A number of 250 8-seater AVs are necessary during peak-hours to serve the demand of the 8,483 agents and only 30 during off-peak hours in Singapore. Therefore, many of the vehicles are used only during a short period of the day. To model the performance of AToD, Balac et al. (2020) replace all current car trips with AToD in the city of Zurich, Switzerland. Their results indicate that the current demand can be supplied with a fleet of only 3.7% of its current vehicle fleet. The VKT can also be reduced by as much as 9.1%. However, the authors point out that one of the limitations of their work is not modeling mode decisions, which is one of the gaps addressed in this paper.

Recently, several studies included a mode-choice component in their simulations of automated vehicles. Vosooghi et al. (2019b) and Vosooghi et al. (2019a) use an agent-based approach where they integrate mode-choice as one of the choice dimensions of agents. However, they rely on assumptions on the values of travel time associated with the automated vehicle mode. Oh et al. (2020) study the impacts of shared automated vehicles by integrating an estimated mode-choice model based on a stated-preference survey within an agent-based simulation SimMobility. Hörl et al. (2021) go even further, by obtaining the values of time for an AV service via a stated preference survey in the Canton Zurich and combining it with the agent-based simulation with a detailed model of costs for automated mobility (Bösch et al., 2018). Therefore, it is the first simulation study that takes into account mode-choice decisions, cost of service based on the fleet size and utilization of the service to forecast the demand for shared AVs.

To add to the body of literature on AToD we present an agent-based methodology that combines an estimated mode-choice model and fleet optimization algorithm to investigate potential impacts of this service on the mobility behavior under different scenarios. To the best of our knowledge, this is the first study that incorporates all these dimensions to investigate the potential impacts of an automated transit on-demand service with a mixed fleet.

3. Study and service design

This study analyzes the potential impact of Automated Transit on-Demand service on mobility behavior, using the city of Zurich as a case study. Additionally, the study area includes a perimeter of 5km around the municipal boundary of the city as shown in Fig. 1.

The AToD service is defined as an offer that connects predefined PUDO (pick-up and drop-off) stations in the city. They are located based on a hexagonal grid with a cell radius of 500 m, leading to a mean access/egress distance of 300 m. This is considered an attractive walking distance for this type of service (Weidmann, 2008). To travel from one PUDO to another, people would use an app or phone-based reservation system to notify the operator of their planned trip. Departures from any available PUDO are ensured to happen at fixed times of the day. A customer can therefore choose the origin PUDO, destination PUDO and a departure slot, for instance at 9:15, 9:30, and so on. Once the request is accepted, a seat will be reserved in a vehicle providing a direct ride between the PUDOs at the reserved time.

We set that departures happen in 15 minute slots, which resembles the headway of a high-frequency regional bus. As the aim of the service design is to encourage the use of the system over car use, but, at the same time, not reduce the use of more aggregated public transport services, this frequency is expected to attract the most relevant user groups.

The AToD system combines the flexibility of the private car with the convenience of not having to own a vehicle, which is similar to regular (automated) on-demand systems. However, through the spatial aggregation by PUDOs and scheduled departure times, traveler flows can be better aggregated on a small scale. Contrary to a dynamic ride sharing system, where an operator adapts the fleet movements to highly dynamic customer requests, here, customers adapt to the locations and times offered by the operator, resembling more a classic public transport service. By aggregating the demand and known times and locations AToD service can potentially provide higher pooling rates than a dynamic ride-sharing system.

The operator in the proposed scenarios utilizes electric and automated vehicles that can carry a maximum of either two, five or ten passengers. Vehicles are dispatched intelligently such that each booking on the PUDO relations can be served.

Bösch et al. (2018) provide a cost calculator for conventional, electric and automated mobility services in Switzerland. Based on their methodology, a cost per passenger kilometer can be estimated. While the actual cost of the service depends on a variety of inputs, such as the ratio between customer and empty distance, the vehicle size, the frequency of maintenance trips, and others, which would only be known after assessing the attraction of the service, assumptions have to be made a priori. We assume that the vehicles have on average a 50% occupancy (including empty mileage), and every 10th ride is a maintenance ride for cleaning and charging. The empty travel time, i.e., relocation time of the vehicles, is an output of the model and would, therefore, require multiple iterations to calculate the costs correctly. Instead, we assume, like Bösch et al. (2018), that the vehicles travel empty 15% of the time. This results in costs of 0.30 CHF per passenger kilometer. On top, the operator can choose to add a base fare.

To summarize, the service operates under the following conditions:

- Pick-up and drop-off locations (PUDOs) are placed on a 500 m hexagonal grid over the city with average access/egress walk distances of 300 m.
- Customer book rides between PUDOs at specific time slots in 15 minute intervals.

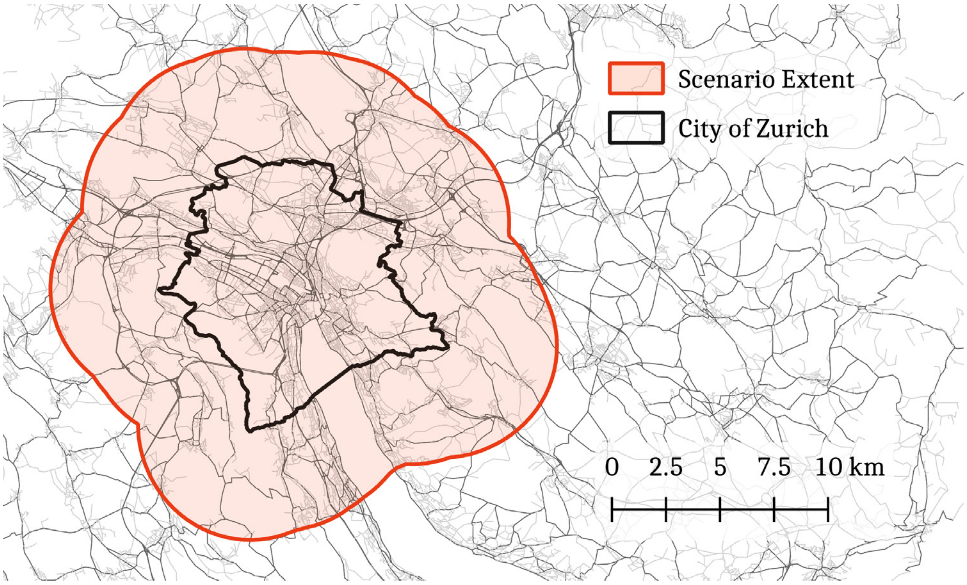

Fig. 1. City of Zurich and the analyzed study area.

- Each accepted ride is served without detour between the PUDOs.
- The price per ride is assumed as 0.30 CHF/km plus a scenario-dependent base fare (see below).

The following sections describe the methodology to analyze the effects of such service while trying to reinforce the benefits through several measures.

4. Methodology

To assess the efficiency and systemic effects of the AToD service in Zurich, as well as the influence of specific policy measures, we make use of two major methodological components. First, we use an agent-based transport simulation developed, calibrated and validated for the city of Zurich (Hörl et al., 2021) to which we add the AToD service. Agents are then allowed to make use of the service dependent on their choice preferences and prices and travel times on the relevant PUDO relations. Second, an optimal fleet sizing algorithm is run based on the AToD demand obtained from simulation. This way, a lower bound is established in terms of fleet size and service efficiency. The following sections describe both components in detail.

4.1. Agent-based simulation

We base the current work on an existing implementation of a transport simulation for Zurich that was presented by Hörl et al. (2021). The baseline case of the simulation includes four prevalent modes of transport in Zurich: private car, public transport, bicycle, and walking. The simulation consists of a detailed representation of households, persons and their daily activity chains that has been created using the *eqasim* pipeline (Hörl and Balac, 2021).

The simulation starts with MATSim's queue-based traffic simulation component which yields travel times on the road network. Those are subsequently used to inform a mode choice model that is applied to the agents' daily plans using the discrete mode choice extension for MATSim (Hörl et al., 2018; 2019). Hence, if high car travel times are predicted for a specific trip in an agent's plan, public transport may be chosen instead, or vice versa. By repeating iteratively the steps of traffic simulation and choice making, the system arrives in an equilibrium state in which the agent choices are in line with observed travel conditions.

The choice model used in (Hörl et al., 2021) has been estimated on a large-scale stated preference survey in the canton of Zurich and contains preferences for the default modes mentioned above and, additionally, an Automated Mobility on Demand (AMoD) service which resembles a normal taxi, but without a driver. As the AToD service can not be compared directly with the AMoD service, but resembles a combination of characteristics of AMoD and public transport, we describe the preference for the AToD service using a new utility function that is based on the two other modes.

For public transport and AMoD, Hörl et al. (2021) use the following utility functions in a multinomial logit model; all other modes are omitted here for brevity:

$$\begin{aligned} u_{pt} = \ & \beta_{\text{ASC,pt}} \\ & + \beta_{\text{inVehicleTime,train}} \cdot \xi_{\text{TD}} \cdot x_{\text{inVehicleTime,train}} \\ & + \beta_{\text{inVehicleTime,other}} \cdot \xi_{\text{TD}} \cdot x_{\text{inVehicleTime,other}} \\ & + \beta_{\text{inVehicleTime,feeder}} \cdot x_{\text{inVehicleTime,feeder}} \\ & + \beta_{\text{transferTime,pt}} \cdot x_{\text{transferTime,pt}} \\ & + \beta_{\text{accessEgressTime,pt}} \cdot x_{\text{accessEgressTime,pt}} \\ & + \beta_{\text{headway,pt}} \cdot x_{\text{headway,pt}} \\ & + \sum_{G} \beta_{\text{ptQuality,G}} \cdot x_{\text{ptQuality,G}} \\ & + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot \xi_{\text{CI}} \cdot x_{\text{cost,pt}} \end{aligned} \quad (1)$$

$$\begin{aligned} u_{AMoD} = \ & \beta_{ASC,AMoD} \\ & + \beta_{\text{inVehicleTime,AMoD}} \cdot \xi_{\text{TD}} \cdot x_{\text{inVehicleTime,AMoD}} \\ & + \beta_{\text{waitingTime,AMoD}} \cdot x_{\text{waitingTime,AMoD}} \\ & + \beta_{\text{highAge,AMoD}} \cdot [a_{\text{age}} \geq 60] \\ & + \beta_{\text{work,AMoD}} \cdot x_{\text{work,AMoD}} \\ & + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot \xi_{\text{CI}} \cdot x_{\text{cost,AMoD}} \end{aligned} \quad (2)$$

All β represent model parameters that were estimated from survey data while x represent per-trip variables and a represent per-agent variables. The utility function for public transport makes a difference between routes that include a train with $x_{\text{inVehicleTime,train}}$ quantifying the travel time in the main stage and $x_{\text{inVehicleTime,feeder}}$ quantifying the rest. Only if no train is included in the route, $x_{\text{inVehicleTime,other}}$ has a value while the other two are set to zero. The *pt quality* parameters and variables are based on a methodology of the Federal Office for Spatial Development quantifying the accessibility by public transport ARE, Federal Office for Spatial Development (2011). Furthermore, the model includes two interaction terms ξ which establish non-linear dependencies

Table 1
Choice model parameters relevant for the defintion of the AToD mode (Hörl et al., 2021).

	Parameter		
Public transport	$\beta_{\text{ASC,pt}}$	0.000	[u]
	$\beta_{\text{inVehicleTime,feeder}}$	-0.045	[u/min]
	$\beta_{\text{inVehicleTime,other}}$	-0.012	[u/min]
	$\beta_{\text{inVehicleTime,train}}$	-0.007	[u/min]
	$\beta_{\text{transferTime,pt}}$	-0.012	[u/min]
	$\beta_{\text{accessEgressTime,pt}}$	-0.014	[u/min]
AMoD	$\beta_{\text{ASC,AMoD}}$	-0.061	[u]
	$\beta_{\text{inVehicleTime,AMoD}}$	-0.015	[u/min]
	$\beta_{\text{waitingTime,AMoD}}$	-0.093	[u/min]
	$\beta_{\text{work,AMoD}}$	-1.9377	[u]

Table 2
Choice model parameters for the AToD mode.

	Parameter		
AToD	$\beta_{\text{ASC,AToD}}$	0.0	[u]
	$\beta_{\text{inVehicleTime,AToD}}$	-0.015	[u/min]
	$\beta_{\text{waitingTime,AToD}}$	-0.012	[u/min]
	$\beta_{\text{accessEgressTime,AToD}}$	-0.014	[u/min]
	$\beta_{\text{work,AToD}}$	-1.9377	[u]

of the utility of travel time and cost on distance, and of household income on the perception of cost. The estimated mode parameters relevant for the definition of the new AToD mode are documented in Table 1.

To account for the specific characteristics of the AToD service, we propose the following utility function:

$$\begin{aligned} u_{AToD} = \beta_{ASC,AToD} &+ \beta_{\text{inVehicleTime,AToD}} \cdot \xi_{\text{TD}} \cdot x_{\text{inVehicleTime,AToD}} \\ &+ \beta_{\text{waitingTime,AToD}} \cdot x_{\text{waitingTime,AToD}} \\ &+ \beta_{\text{accessEgressTime,AToD}} \cdot x_{\text{accessEgressTime,AToD}} \\ &+ \beta_{\text{work,AToD}} \cdot x_{\text{work,AToD}} \\ &+ \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot \xi_{\text{CI}} \cdot x_{\text{cost,AToD}} \end{aligned} \tag{3}$$

In comparison to AMoD, where a door-to-door service is considered, Eq. (3) adds a component to consider access and egress to and from the PUDOs. Otherwise, the structure is kept equal to AMoD.

The parameter values for AToD are based on the existing values for AMoD and public transport. As both alternative-specific constants (ASCs) for public transport and AMoD are very close to zero compared to the ASCs of the other modes, we also set $\beta_{\text{ASC,AToD}} = 0$. For the valuation of travel time we choose to set $\beta_{\text{inVehicleTime,AToD}} = \beta_{\text{inVehicleTime,AMoD}}$ as the small to medium size vehicles of the proposed AToD service are assumed to resemble more closely the comfort of the AMoD service in comparison to a bus. The perception of waiting time, on the contrary, is assumed to be closer to a bus service, because customers know exactly the departure time of their vehicle and, thus, can adapt accordingly. Hence, we set $\beta_{\text{waitingTime,AToD}} = \beta_{\text{transferTime,pt}}$. Based on the same argument, we assume the same valuation of access and egress time for AToD as for public transport. Finally, we choose to keep the value of $\beta_{\text{work,AToD}}$ which quantifies a reluctance of the population to use a dynamic service for their work commute. This is justified by the fact that, in reality, the AToD service still shows a certain degree of unreliability in terms of whether a request might be rejected. Table 2 summarizes the parameter values for the AToD mode.

To assess the demand for the AToD service we make use of the following simulation dynamics. For each trip, given the exact departure and arrival location by coordinate, we determine the closest origin and destination PUDO. This allows to calculate the necessary access and egress walk time for the trip. After, for each trip, we find the shortest path in the road network between the two PUDOs, taking into account the currently estimated car travel times in the system. The resulting value is taken as the in-vehicle travel time of the trip. Finally, the difference between the actual departure time of the trip in the agent plan and the next possible departure time from the PUDO (in 15 minute slots) is assumed for the waiting time, and it is determined whether the destination activity of the agent is a "work" activity. The AToD alternative with its utility is then added as the fifth alternative in the multinomial logit model instead of the AMoD mode, along with the default ones and the choice is sampled based on the characteristics of all modes.

In summary, this process allows to estimate the attractivity of the AToD service in Zurich as agents can freely choose the service or another mode, based on the prices, travel times and waiting times for each specific trip in their plan. Also, given that more agents switch to the AToD service, an effect on congestion may be noticeable as individual car traffic is reduced in the detailed traffic simulation phase.

4.2. Optimal fleet sizing

As a result of the iterative simulation process we arrive at a state in which choices and travel characteristics are in equilibrium. In that state we can track all performed AToD trips with information on their origin and destination PUDOs and their departure time slot. Using this information, we add a post-processing step in which we perform an optimal fleet sizing for a mixed AV fleet with 2-, 5-, and 10- passenger capacities, that yields the number of vehicles necessary to serve the demand. The applied algorithm was introduced by Balac et al. (2020) and is described briefly in the following. As the fleet sizing is done in the post-processing-step, the AToD vehicles do not affect the traffic simulation in MATSim.

The algorithm is based on a graph that considers all combinations of PUDO and time slot as nodes. Hence, each node in the graph represents a possible location of vehicles or customers in space time. Nodes are connected by edges which represent vehicle movements. For instance, given two PUDOs A and B, there may be an edge between the nodes (A, 9:00) and (B, 9:15) meaning that it is possible that a vehicle departs at 9:00 from PUDO A and arrives at PUDO B before the end of time slot 9:15. If the travel time between PUDO A and B (with the given departure time) is longer than 15 minutes, the edge does not exist, but there may be an edge between (A, 9:00) and (B, 9:30) if the vehicle can arrive on time.

Each edge has a weight representing the number of vehicles that need to be moved from the origin node to the destination node. Non-zero edges therefore describe the movements of vehicles in space and time. Some edges have a fixed weight as we know that a specific number of vehicles *must* move along the edge as there is customer demand and each customer must be accompanied by a vehicle.

In order to perform the fleet sizing, all edges which are not a priori defined by customer movements and are valid in terms of travel time *can* be traversed by a number of vehicles. To ensure that there are always enough of vehicles when customer demand is departing at a node the algorithm defines that the sum of vehicles coming in through the incoming edges equals the number of vehicles going out through the outgoing edges.

Additionally, the algorithm defines a virtual "depot" node at time zero in which the vehicles reside initially. The inflow to this node must be zero. However, the outflow is adjusted by the algorithm such that all node constraints are fulfilled, meaning that all customer flows between the nodes are served in the sense that the vehicle flow into these nodes is large enough. The outflow of vehicles from the "depot" thus represents the minimum fleet size needed.

To perform a fleet sizing, we first compute what part of the demand should be served by 10-, 5- and 2-seater vehicles. For that the demand is aggregated into "packages" of maximum ten requests for the 10-seater vehicles, for instance. This is done in a way that vehicles have an occupancy of at least 60%. Thus, if there are 13 requests going from A to B at the same time, one passenger flow package of 10 would be calculated for this relation, requiring one ten seater to serve the relation. In contrary, a flow of 16 request would lead to two 10-seaters being used

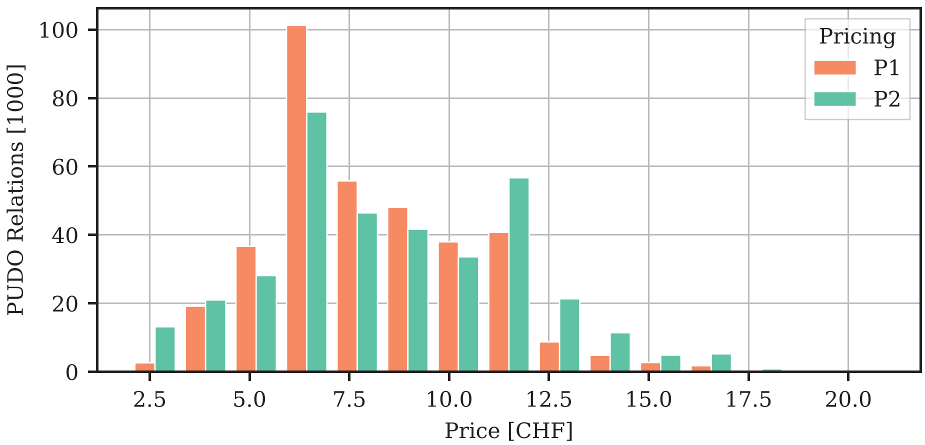

Fig. 2. Distribution of the AToD Fares in the unconstrained AToD scenario (P1) and with the alternative pricing strategy (P2).

for the relation. After, the algorithm finds the respective vehicle flows of 5-seaters based on the remaining requests on all relations, also with a minimum occupancy of 60% (i.e., 3 passengers). Finally, the remaining requests must be served by 2-seater vehicles.

For each vehicle demand sets (10-seaters, 5-seaters, 2-seaters) between the PUDOs and time slots, the problem, which can be rendered as a minimum cost flow problem (Balac et al., 2020), is solved to obtain the number of required vehicles. Once it is known how many vehicles move between the PUDOs at any time of the day, it is possible to derive additional information such as the total distance travelled by the fleet, or the distance that is covered without a customer for vehicle relocation.

For a detailed mathematical description of the fleet sizing algorithm we like to refer the interested reader to Balac et al. (2020).

5. Baseline AToD scenario

A baseline scenario (denoted as Scenario 1) represents the current state of the system, without an AToD service. It serves as a reference to evaluate the impacts of the AToD service. To measure the potential of an AToD service, we simulate an unconstrained service, denoted as Scenario 2. In this scenario, the AToD service operates in the whole study area and offers rides at a price composed of two components. First is the base fare of 3 CHF for all trips. The second is a distance-based variable fare of 0.30 CHF/km. The distance fare is based on the cost-based analysis of pooled automated vehicles for Zurich (Bösch et al., 2018).

Today, a one-way ticket for the city of Zurich costs 4.40 CHF and longer distance trips in the canton can cost as much as 17.20 CHF (for children and adolescents between 6–16 it is half the price) (ZVV, Zurich Transport Network, 2022). The pricing scheme of the AToD service is, therefore, within the range of a single public transport ticket.

The distribution of prices paid by the travellers in Scenario 2 can be seen in Fig. 2, which compares the unconstrained scenario with an alternative pricing scenario that will be introduced later. The base pricing scheme is denoted as $P1$.

Figure 3 shows the mode share in Zurich in the baseline case (Scenario 1) in comparison to the unconstrained scenario (Scenario 2) and other scenarios, which will be looked at in detail further below. Between the two first cases, one can see a substantial mode shift towards the AToD service in Scenario 2 with a modal share 19.6%. Except for walking (−1.01%), all modes lose about one third of trips to the AToD service. The most considerable shift can be observed from car trips to AToD, where 33.0% of all car trips are replaced. Public transport loses 31.2%, while cycling loses 30.7%.

Figure 4 a shows the daily OD flows of passengers for the AToD service. To increase the figures' legibility, only OD relations with a demand above 25 trips per day are displayed, and the values are presented in a logarithmic scale. The majority of trips are performed entirely within the city of Zurich. Having a closer look, one can see that the darkest lines, i.e. the OD pairs with highest demand, are rather short and in the city's core. These trips directly challenge the use of the tram and bus network in the city, as well as bike trips.

Furthermore, we perform an analysis of the parking demand in the high demand area in the city's core. In the current state of the system, the parking demand (number of parking locations) during the evening hours (16:15 to 18:00) can be seen in Fig. 5. In Fig. 6, the change in parking demand, after the introduction of the AToD service, includes the demand for both the PUDO stations and parking spaces for conventional vehicles. The demand for PUDO stations is calculated by the number of required simultaneous vehicle departures within the 15-minute headway. The individual peak value of each zone is displayed. Most zones experience an overall decrease in parking places demand. For the observed area, a total decrease of 1,352 parking places is possible. As can be seen, especially the area in the center of the city experiences a substantial decrease in parking demand. However, at the edges of the area, an increase in parking demand is noticeable. As these areas are mostly residential and the parking demand during the day is very low, additional AToD departures are causing an increase in the required number of parking spaces. A similar effect is reported in Hörl et al. (2021),

Table 3
Studied AToD service characteristics overview.

Base cost	P1	3.00 CHF
	P2	1.50 – 15.00 CHF (dependent on public transport accessibility)
Cordon charge	C1	2.00 – 10.00 CHF (dependent on entry rate)
Service Area	A1	Entire scenario area
	A2	Exclusion of high public transport accessibility area

Table 4
Overview of the applied measures per scenario.

Scenarios		1	2	3	4	5	6	7	8	9
With AToD			x	x	x	x	x	x	x	x
Area	*A1*		x	x	x	x				
	A2						x	x	x	x
Cordon Price	*C1*				x	x			x	x
Price	*P1*		x		x		x		x	
	P2			x		x		x		x

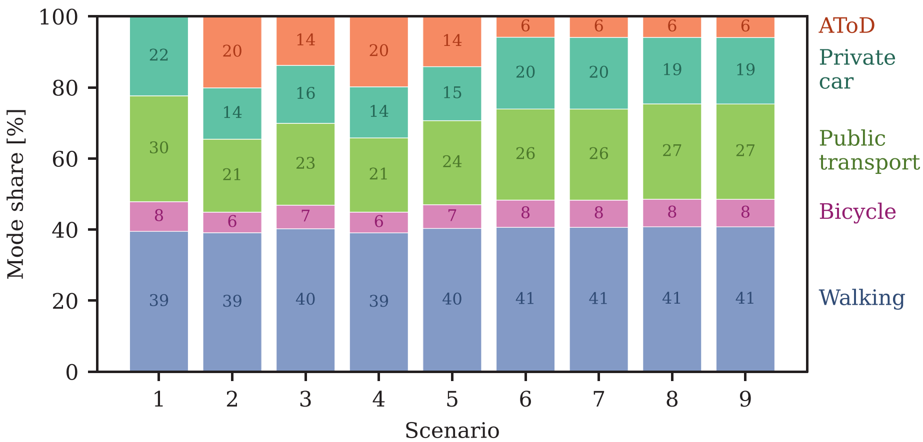

Fig. 3. Modal share by trips (definition of scenarios is available in Table 4).

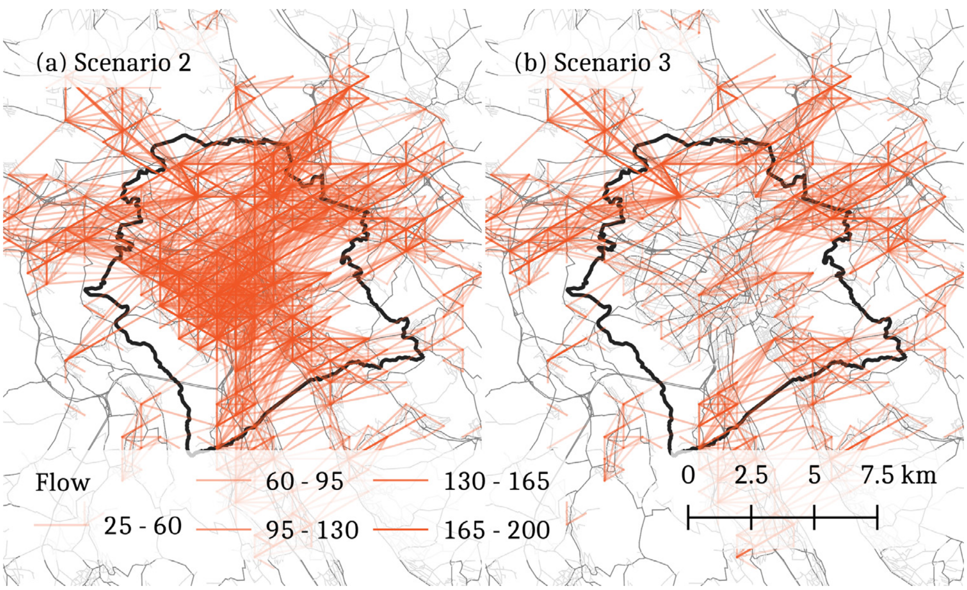

Fig. 4. High demand OD flows with more than 25 trips for (a) Scenario 2 and (b) Scenario 3.

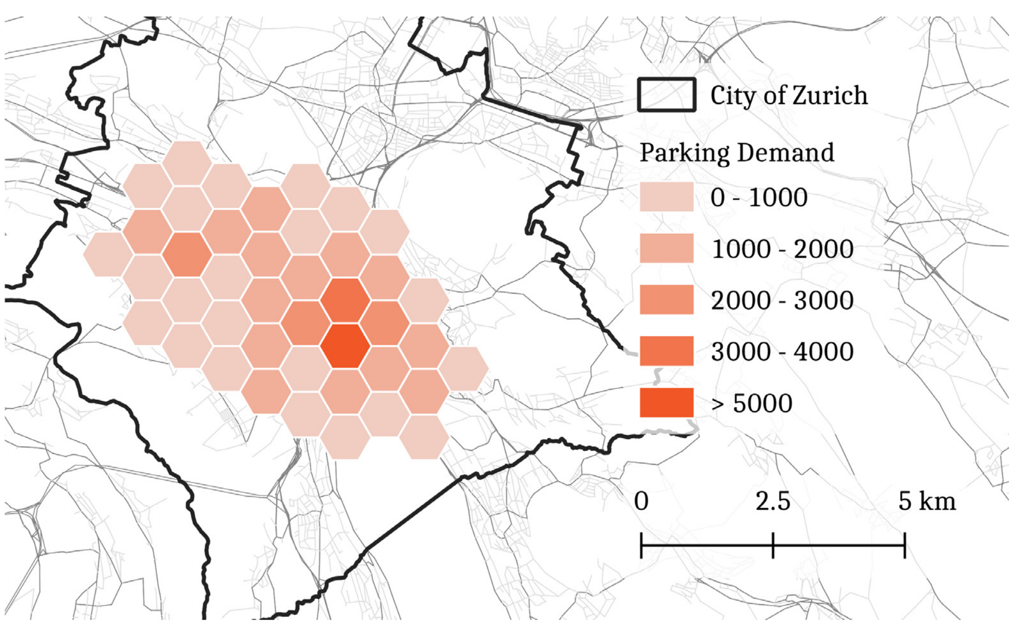

Fig. 5. Parking demand around the evening peak (S1).

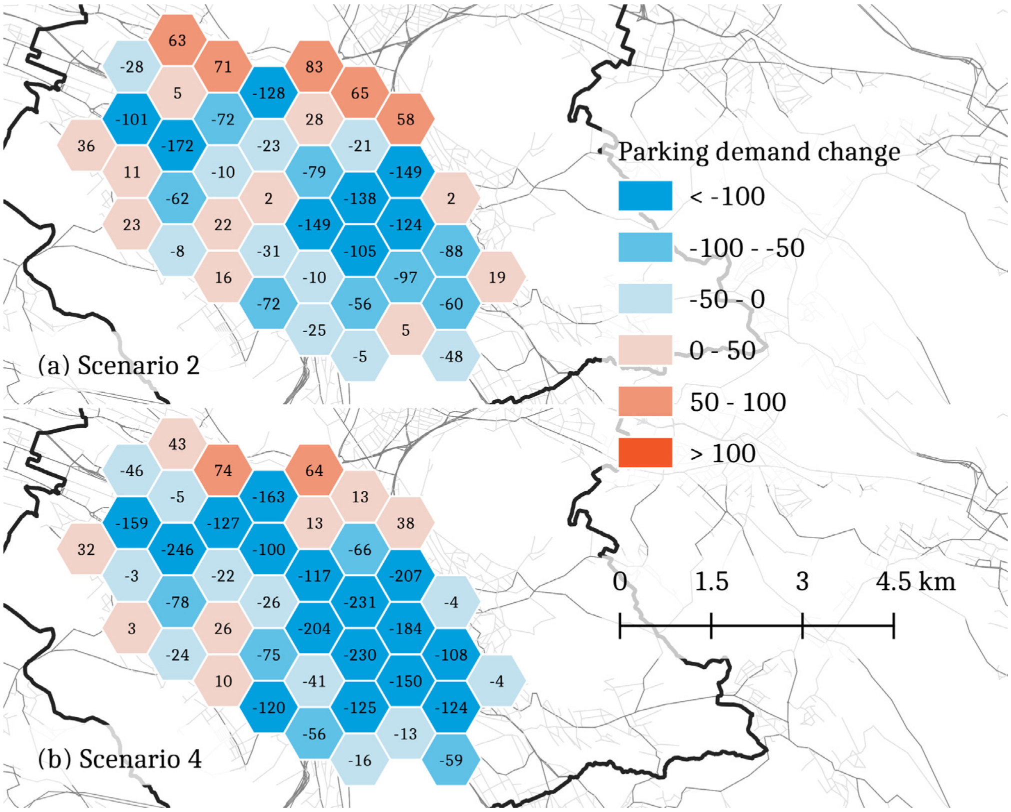

Fig. 6. Parking demand change for cars and AVs over the whole day: (a) Scenario 2 vs. baseline and (b) Scenario 4 vs. baseline).

where the authors report most of the shared on-demand AV departures occurring in residential areas.

6. Proposed measures

We evaluate different measures through several simulation studies to emphasize the benefits of the AToD service that does not compete with public transport or active modes. With expected impacts on mode share, user patterns, and spatial demand for parking and urban traffic, the developed measures focus on three vectors. First, with a different *pricing* scheme, the travel patterns can be influenced, while still allowing the connection of all OD pairs if the willingness to pay is high enough. Second, a *cordon charge* for conventional vehicles in the urban core can be imposed to potentially further reduce the parking demand and traffic congestion. Lastly, the *service area* design can allow an exclusion of high population density areas to protect them from too much traffic and parking demand.

6.1. Pricing scheme

The first measure is the pricing structure of the AToD service. An alternative pricing scheme (*P2* in Fig. 2) charges zones based on the current public transport accessibility of a zone. Origin and destination zones with high accessibility (≥ 5.7 in Fig. 9) add an extra surcharge of 6 CHF to the initial base fare (summing up to 15 CHF in total if both origin and destination are affected). For OD pairs where either origin or destination has a low accessibility (≤ 4.8) classification, a reduction of 1.5 CHF is offered. The goal of this pricing scheme is to discourage the usage of AToD in areas that are already well-connected while promoting the use of AToD instead of private cars where access to public transport is low.

The distribution of the price paid between all PUDOs, for pricing scheme, *P2* is shown in Fig. 2.

6.2. Cordon charge

The second measure concerns the usage of cars in the core of the city. To further strengthen public transportation, reduce VKT, and especially reduce the demand for parking in the urban core, a cordon charge is implemented (*C1*).

The cordon charge area is the high demand area, which can be seen in Fig. 7. Using the pricing schemes of London, Singapore, and Stockholm as references (Bhatt et al., 2008; TSTC, Tri-State Transportation Campaign, 2017), the price is set between CHF 2.00 and CHF 10.00 dependent on time of the day. In a previous study for Zurich a cordon price of around 4 CHF was calculated to potentially reduce the VKT inside of the cordon by 20% (Meyer de Freitas et al., 2017). The average price of our scheme is slightly above this value.

To define the price, all car trips which originate outside the cordon and end within the cordon, have been binned in hourly arrivals. The charge is scaled linearly to the demand between CHF 2.00 and CHF 10.00. While the charge in the early morning hours is set to CHF 2.00, the peak price of CHF 10.00 is charged at 08:00 am (see Fig. 8). Only those individuals entering the cordon with a private vehicle are charged.

6.3. Service area

The third proposed policy vector is the service area. We denote the baseline service area, which is shown as the shaded area in Fig. 9, as *A1*. Additionally, we introduce an alternative service area *A2*, in which PUDOs with high public transport accessibility during rush-hour (07:00 am departure time) are excluded from the AToD service. We calculate accessibility by the number of work places that an agent can reach within 30 minutes from its zone of residence, and Fig. 9 shows the obtained values on a logarithmic scale. For comparison, we show areas of high public service quality (Quality Class A) as defined by the Swiss Federal Office

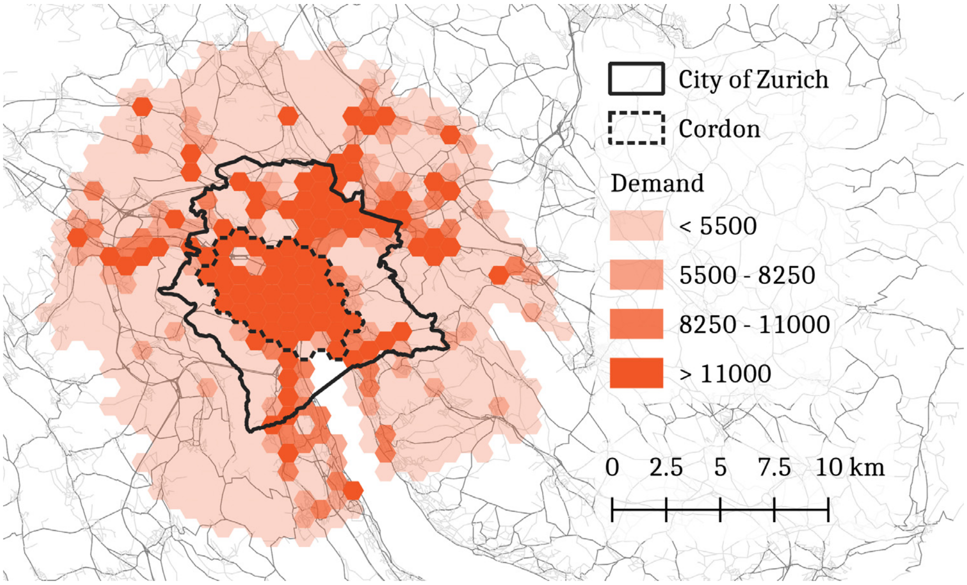

Fig. 7. Daily total travel demand in arrivals per day and cordon.

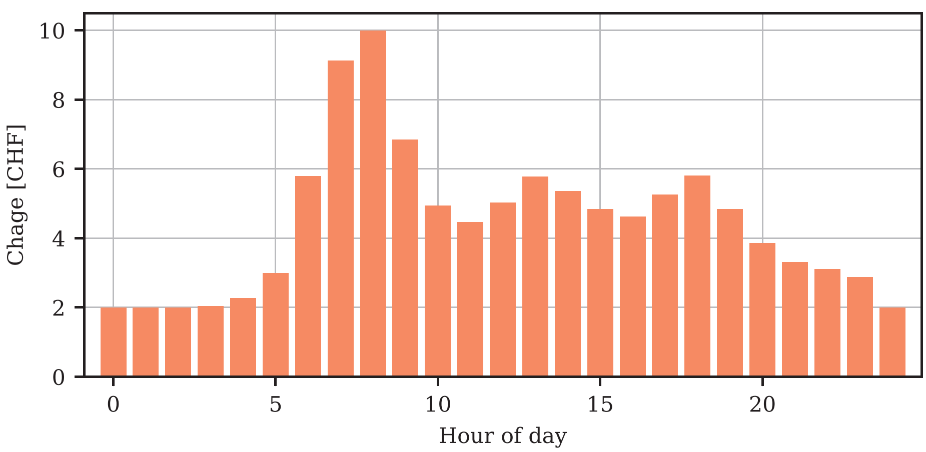

Fig. 8. Cordon charge.

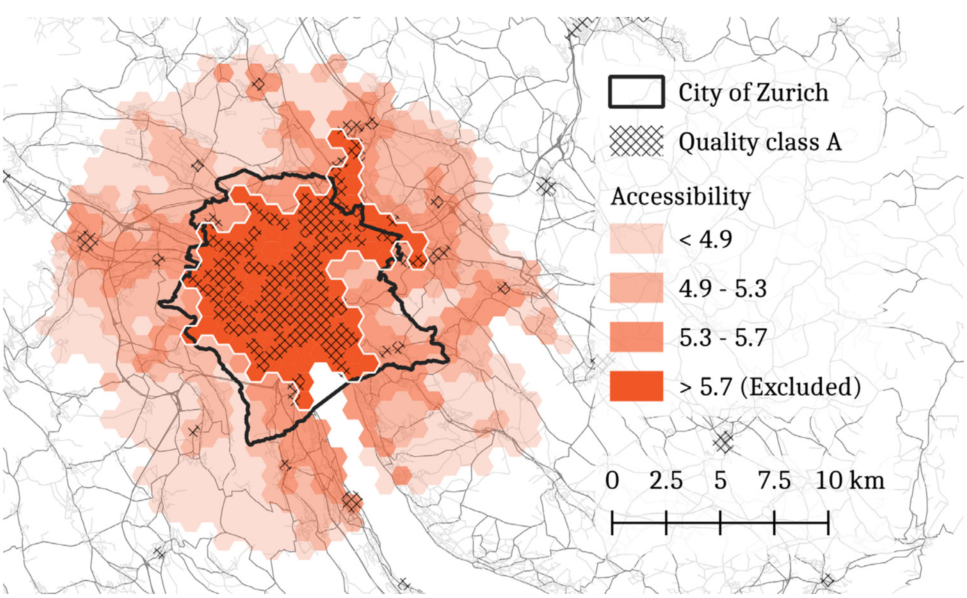

Fig. 9. Logarithmic public transport accessibility at 07:00 am. *Source:* ARE, Federal Office for Spatial Development (2020).

Table 5
Population characteristics of AToD users in percent.

	Scenario	2			3		
Attribute	AToD user	yes	no	Δ	yes	no	Δ
Gender	m	49.5	54.2	*+4.7*	49.0	54.0	*+5.0*
	f	50.5	45.8	*-4.7*	51.0	46.0	*-5.0*
Employed (age 15+)	yes	76.7	71.8	*-4.9*	76.4	72.2	*-4.2*
Car available (age 18+)	yes	82.8	83.2	*+0.4*	82.8	83.2	*+0.4*
Bike available	yes	78.6	75.8	*-2.8*	78.8	75.9	*+2.6*
PT	season ticket	27.5	30.4	*+2.9*	27.6	30.2	*+2.6*
	half-fare (age 16+)	36.5	37.6	*+1.1*	35.9	37.6	*+1.7*
Mobility-tools (age 18+)	3	13.6	14.5	*+0.9*	13.4	14.5	*+1.1*
	2	62.1	58.6	*-3.5*	62.5	58.8	*-3.7*
	1	21.7	23.2	*+1.5*	21.6	23.2	*+1.6*
	0	2.6	3.6	*+1.0*	2.5	3.5	*+1.0*

for Spatial Development (ARE, Federal Office for Spatial Development, 2020). Comparing these two indicators, we define a logarithmic accessibility of 5.7 as the threshold value above which to exclude PUDOs. Basing the selection on accessibility values allows us to automatically include several transit hubs of the commuter rail outside the city center, while a pure filtering by Quality Class would exclude them sparsely. Furthermore, this measure of accessibility can easily be applied to other use cases than Zurich.

6.4. Scenarios

The summary of the proposed measures above can be seen in Table 3. The three measures are further combined to generate 8 scenarios, which are summarized in Table 4. As explained, Scenario 1 is the *Base case*, i.e., the situation without any AToD. *Scenario 2* is an unconstrained scenario with the AToD service.

7. Results

The following sections present results obtained from the MATSim simulations with the proposed measures. First, the usage of the AToD service is analyzed in detail. After, results from solving the MILP fleet sizing problem are presented to estimate the required vehicle count and fleet composition.

The impact of the three measures differs in their strength to change the modal share and the resulting travel patterns. As can be seen in Fig. 3 the modal share changes substantially whenever the pricing scheme changes (scenario 2 vs. 3, or 4 vs. 5) and when the service area is reduced (2–5 vs. 6–9). Moreover, the combination of the measures brings little additional change. Therefore, we primarily focus on the analysis of the impacts of individual measures - pricing, cordon charge, and service area.

7.1. Pricing scheme

The proposed pricing scheme $P2$ has a substantial impact on mode choice (Scenario 3 in Fig. 3). The AToD service loses 29.6% of the trips compared to Scenario 2 (S2). Comparing scenario 3 with the base case, it is interesting to note that car trips decrease by 27.2%, while PT share decreases by 22.8%.

Figure 4 b shows the daily OD flows for scenario 3. One can immediately see the heavy impact on the demand. The trips within the high accessibility PT region disappear almost entirely, as the base price for these short-distance trips can be as high as CHF 15.00. On the other hand, some OD pairs experience a slight increase in trips in comparison to S2. The *low to low* accessibility relations receive an increase of trips in S3 in comparison to S2 (+10.56%). The *high to high* accessibility trips had a substantial decrease of −76.2%. The largest reduction in absolute terms is measured for *medium to/from high* accessibility trips (−64.512 trips, i.e., −37.4%), which occur from the suburbs to the city and vice versa.

Table 5 presents an overview of the AToD users. The population was divided into two groups, agents that use AToD during their daily plan and those who never make use of the service. To see the sensitivity on the pricing schemes, scenarios 2 and 3 are compared. For scenario 2, 28.5% of the population make at least one AToD trip, and in scenario 3 it is 16.3%.

The PT variable *season ticket* describes the percentage of people who own at least one PT season ticket, which can be a general abonnement (allows unlimited PT travel in Switzerland for one year for 3,860 CHF) (SBB, Swiss Federal Railways, 2020a), point-to-point travel card (allows unlimited PT travel between a specific OD pair) (SBB, Swiss Federal Railways, 2020c) and network pass (allows unlimited PT travel within Canton of Zurich for one year for 2,226 CHF) (ZVV, Zurich Transport Network, 2020). The variable *half-fare* describes the share of the population above 16 years of age, which owns a half-fare travel card (allows the purchase of single trip tickets in Switzerland for half the price for one year for 185 CHF) (SBB, Swiss Federal Railways, 2020b). Mobility-tools are vehicles or season tickets, which are available for the agent. Unlike Scott and Axhausen (2006), the mobility tools exclude *half-fare*, as it was deemed to over emphasize the status of the half-fare ticket. As adolescents can start an apprenticeship at age 15 (swissinfo.ch, 2019), only agents that are above 15 years of age are taken into consideration for the variable *Employed*. The legal age to drive a car in Switzerland is 18 years. For this reason, only agents that fulfill this constraint are compared for *Car available*.

Interestingly, a smaller share of the AToD users has a car or bike available, and fewer own a PT season ticket. When combining the mobility tools, the difference is less pronounced between the two groups. More pronounced is the lack of PT season tickets in S3 of the AToD users in comparison to Scenario 2. At the same time, the difference in car availability has decreased.

7.2. Cordon charge

The cordon charge measure, simulated in Scenario 4, produced a similar impact on the mode share as previously reported for a study in Zurich (Meyer de Freitas et al., 2017) with a reduction of around 1% in car trips (see also Fig. 3). The AToD share is largely unaffected, and the main benefit is for the public transport operator.

The impact of the cordon charge on the parking demand is shown in Fig. 6b. Even though, some of the zones still experience growth, compared to the as-is scenario, it is not as substantial as in the unconstrained AToD scenario. The urban core, benefits from further reduction of parking space. In total, the demand for parking places decreases by 2,817 for this scenario (PUDO and conventional parking combined), which is a parking space reduction of around $32,000 m^2$.

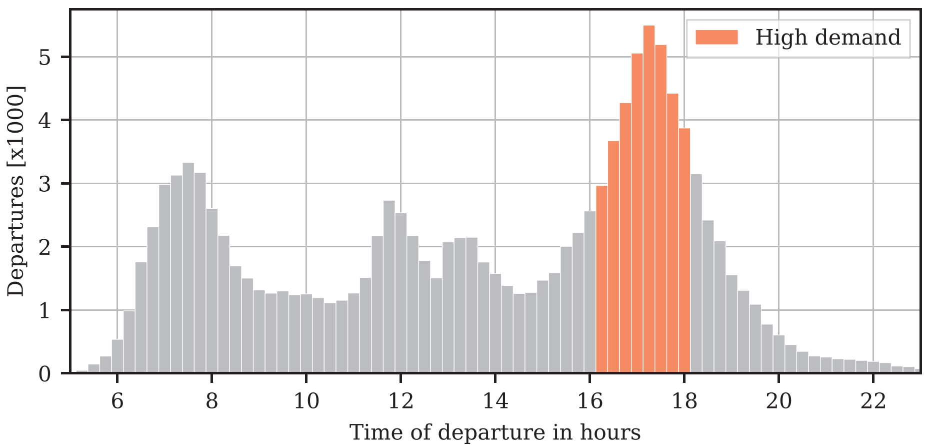

Fig. 10. AToD Passenger Departures per 15 Minute Headway (S2).

Table 6
AV cost parameters.

[*CHF*]	2 seater	5 seater	10 seater
per vehicle km	0.098	0.220	0.405
per customer trip	0.375	0.375	0.375
per vehicle and day	33.300	33.630	33.760

7.2.1. Service area

The service area, simulated as Scenario 6, has a substantial impact on the modal share. With the decreasing service area, the AToD trips decrease as well. In Scenario 6, the PT modal share is reduced to 25.6% in comparison to 29.8% in the base case. Therefore, the PT high accessibility zones' exclusion has the desired effect to protect the conventional, bundled PT flows. Cycling has almost the same modal share again as in the base scenario, indicating that the majority of cycling trips occur within the core of the city (7.67% vs. 8.35%).

7.3. AToD fleet size and performance

The number of AVs and their size and the VKT they produce are analyzed in the post-processing phase. The calculation of the performance indicators is based on the approach documented in Balac et al. (2020) and summarized in Section 4. As the optimization problem is computationally expensive given the number of zones in our scenarios, only the peak period is optimized. This ensures an adequate level of service during the highest demand period and consequently throughout the day. In Table 7, the summary of the optimization result for the evening peak (16:15-18:00) is presented. In Fig. 10, the observed period is marked on the histogram of the AToD passenger departures. The y-axis does not state how many cars are departing, but only the number of passengers.

Table 7 provides the optimization results. Input parameters are *S.* - Scenario; and *Reloc.* - Relocation zones considered. The algorithm then provides the number of AVs *N* needed for fleets of vehicle *Size* 2, 5, and 10. The table furthermore provides the vehicle distance traveled (*AVKT*) by the AToD service and the person distance traveled (*APKT*). *Occup.* is the mean occupancy of the vehicles while they are serving passengers. The empty mileage, which would lead to a minor decrease in this value, is not included. As the difference in the possible relocation zones does not impact the VKT with passengers, the occupancy is only reported for one of the two relocation operating schemes to increase the table's legibility. The same applies to AV PKT. *Reloc. km* indicates how many of the AV VKT are empty relocation kilometers in percent. Δ *VKT* indicates the percentage change of overall VKT on the road, including private cars. The base case scenario's conventional car VKT serves as a reference. Δ *Fleet* shows how the car fleet on the road changes with the applied measures, again including all private cars that are used throughout one simulated day. *VRR* describes the vehicle replacement rate, i.e. how many cars can be replaced with one AV. Eventually, *Cost. Cov.* indicates the cost coverage of the service. The cost for the service had been calculated on the basis of Bösch et al. (2018). The values used in this paper can be found in Table 6.

The evening peak duration covers eight departures with the 15 minute headway. For scenario 2, this results in 77,864 unique OD Flows, i.e., on average 9,735 OD pairs are served per headway (departure slot). Noteworthy is that only 20 observations have more than 11 passengers. These are the only flows where one vehicle is not sufficient to transport all passengers at once. Therefore, two vehicles will have to drive behind one another to supply the demand. Furthermore, these high demand OD pairs are on average only 1.98 kilometers apart, whereas the overall travel distance by AToD is 7.39 kilometers. In scenario 3, no OD pair has a demand of more than ten passengers per headway. The same is true for scenario 6.

The fleet configuration relies heavily on two-seater AVs. Also notable is the decrease of necessary ten-seater AVs, the less attractive travel in high PT accessibility area becomes. In scenario 8, only 12 ten-seater are necessary for a fleet of 5,674 vehicles. This indicates that, with the presented setup, only the urban core is suitable to pool more than five people per headway and OD. As ten-seaters are primarily serving the urban core, they replace PT and cycling trips in this area.

The average occupancy of the vehicles is rather low. Considering that most vehicles are two-seaters and the mean occupancy is only about 56% for all three scenarios, many passengers travel alone in two-seaters. Larger zones or a longer headway could improve this but would make the service less attractive.

The empty mileage of the AVs is around 10% in all scenarios. It can be seen though that the increased relocation range has an impact on the VKT by the AVs. A doubling of the relocation range results in a 40 to 44 percent growth of empty relocation kilometers. Due to this increased flexibility of the AVs, the fleet size can also be reduced, although only to a small extent.

Interesting to see is the change in overall VKT. Whereas Balac et al. (2020) report a decrease of VKT (up to 9% less compared with today), this paper's results predict an increase. Whereas Balac et al. (2020) replaces all car trips with AToD trips, the agents in the work at hand can adapt their modes of travel. Therefore, agents switch not only from car but also from PT to AToD (and bike, as well as we have seen).

In all three scenarios the combined vehicle fleet used decreases. In scenario 2, 8.39% fewer cars are on the road, potentially decreasing the overall demand for parking facilities. The measures also impact the vehicle replacement rate. Whereas in scenario 2 an AV replaces 3.35 cars, the replacement rate increases to 4.71 cars per AV in scenario 6.

Table 7
AV fleet and performance (evening peak).

S.	Reloc.	Size	N	AVKT	Occ. [%]	Reloc. km [%]	Δ VKT [%]	Δ Fleet [%]	VRR	Cost Cov. [%]
2	**6**	∑	17,828	646,867	57.7	9.52	+9.47	−8.39	3.35	74.8
		2	16,683	627,446	56.9					
		5	985	17,989	69.6					
		10	160	1,431	70.1					
	12	∑	15,914	675,826		13.39	+10.59	−8.77	3.76	82.0
		2	14,981	654,424						
		5	823	19,753						
		10	110	1,649						
3	**6**	∑	13,643	514,155	55.8	9.25	+6.99	−6.93	3.54	109.6
		2	13,078	506,407	55.4					
		5	513	7,489	67.7					
		10	52	259	66.4					
	12	∑	12,124	537,436		13.18	+7.89	−7.23	3.98	120.6
		2	11,663	528,749						
		5	418	8,391						
		10	43	295						
6	**6**	∑	4,648	191,910	56.6	9.73	+1.24	−3.02	4.24	79.3
		2	4,373	188,755	56.1					
		5	246	3,041	68.2					
		10	29	114	63.7					
	12	∑	4,192	201,629		14.08	+1.62	−3.11	4.71	86.0
		2	3,971	198,011						
		5	198	3,485						
		10	23	134						

The cost coverage is relatively high. Currently, the public transport services in Zurich have a cost coverage of 65% (Avenir-suisse.ch, 2020). In all scenarios the cost coverage is higher. Since the cost per vehicle and day has too much weight in this calculation, the cost coverage would likely be even higher, had the optimization been done for the entire day. Despite this, scenario 3 with an increased relocation range is able to operate even with a profit margin.

8. Discussion

The following sections provide a discussion of the obtained results and limitations to be addressed in future research.

8.1. Interpretation of the results

The results show that AToD has the potential to drastically influence the transportation system in Zurich. It can become a more dominant mode than conventional public transport or even car travel. Parking can become an issue in certain areas and demands thought-through strategies and policies as to how a city or municipality can balance, on the one hand, the increase of parking demand due to AToD and, on the other hand, a reduction of the parking demand for conventional vehicles.

By excluding the high accessibility PT area from the service area of the AToD, the mode share can be shifted, so that the number of PT trips in the urban core and cycling trips are hardly affected, but car trips become less frequent. This might lead to an improved level of service on the road, as the additional VKT is relatively low (in the peak period). In the long run, this shift might discourage a car purchase for a share of the population. The substantial reduction of the car fleet can then eventually lead to a reduction of urban space for parking. At the same time, the costs are almost entirely covered with this pricing scheme.

8.1.1. Modal share

The case studies presented in this paper show a definite impact of AToD on the mode choice and the agents' travel patterns. Since the AVs share the infrastructure with conventional cars, it is seen as desirable to primarily siphon off trips, which are currently done by car rather than by any other mode. Undesirable, and unfortunately observed, is the switch from public transport trips and even bike trips to AToD.

Therefore, a city has to consider if it is desirable to have AToD operating within its core, where the public transport service is sophisticated and operates efficiently. The only place where it might be desirable to replace public transport trips with AToD is on rural bus routes with low occupancy and long headways.

8.1.2. Spatial dimension

The setup of the AToD presented in this paper appears highly attractive for short-distance urban trips (shorter than 5 km). For possible operators like Uber or Grab, the urban core is likely the most attractive area. The utilization of the vehicles in this area is much higher. Not only the occupancy rate increases, but also the vehicle size can be larger. Relocation kilometers are less frequent as the travel patterns inside the urban core are less directional in comparison to the time-dependent direction of rural-to-urban trips. With the different pricing structures and, of course, excluding the high PT accessibility zones from the service, the travel pattern can be shifted to the rural areas.

For a city, it is questionable if AToD is a suitable addition to the existing modes. Especially for cities where car travel is increasingly discouraged by the government, as is the case for Zurich (NZZ, Neue Zürcher Zeitung, 2017), AToD does not seem a suitable alternative. Rather it is a service that can be attractive for rural municipalities where PT is offered at a low level of service and operates inefficiently, as regulated in Scenarios 3 and 6.

8.1.3. Cordon charge and AToD

The cordon charge studied in this paper had the desired and similar impact as reported in previous work for Zurich (Meyer de Freitas et al., 2017). As expected, the cordon charge can further reduce the parking demand in the urban core. However, the increase of parking space requirement in certain areas could not be completely compensated with this measure. What remains an open question is the overall welfare effects of the cordon charge in combination with the AToD service.

8.1.4. Fleet size and cost-coverage

The necessary fleet size for the AToD service with the setup presented here is rather large with a fleet of up to 17,828 vehicles. More importantly though, is the reduction of the overall fleet, as one AV can replace as many as 4.71 conventional cars (a much higher replacement rate was reported by Balac et al. (2020) as their approach only looked at serving previous car users). This results in a reduction of the entire fleet between 3.02 and 8.77%, which can be seen as substantial, but far from utopian values when no mode-choice is considered. This also results in an overall reduction of parking demand. In terms of cost coverage, all scenarios outperform the current public transport service in Zurich. Had the optimization been done for the entire day, the cost coverage would be even higher, as the cost per vehicle remains constant.

8.2. Potential methodological improvements

One of the limitations of the current methodology is the mentioned lack of simulation of the AVs in the mobility simulation. The roads are, therefore, less loaded in the simulation than they would be in real life. It would, therefore, be interesting to feed back the optimal number of vehicles obtained from the optimization to the simulation to quantify the congestion effects of this service in future work.

Another limitation is the lack of parking prices in the model for conventional cars. The model itself is calibrated to reflect the travel patterns observable in real life as close as possible. Nevertheless, the parking price is not included, and neither are travel patterns like parking search behavior. This would be difficult to overcome, as the available data on parking costs and trade-offs individuals make when parking is considered is limited.

Dynamic ride-sharing (i.e., detouring to pick up additional passengers) was purposely not considered in this work as we envisioned an express AToD service in order to compensate for access and egress walk trips. However, it would be interesting to compare these two types of services and to see where potential trade-offs can emerge.

Currently, pricing and cordon charge strategies are implemented heuristically. Pricing is based on the current pricing strategies for public transport and on-demand services in Zurich, and cordon charges on current experiences in London, Singapore and Stockholm and the previous work based in Zurich. Therefore, the results are specific to prices implemented in the study. Finding optimal pricing structures goes beyond the work presented here. However, the presented methodology can be extended to support implementation of pricing optimization similar to the work by Hörl et al. (2021).

9. Conclusion

This paper assess the possible impact of an AToD service on mobility behavior in and around the city of Zurich. The presented case studies for the AToD as a public transport express service, aim to increase accessibility in rural areas, and reduce car travel while maintaining a high level for PT modal share.

The analysis of the simulations show, that if left unconstrained, AToD has the potential to shift the modal share drastically. Especially for short-distance urban transport, the AToD appears highly attractive due to its low price, direct connections, and fast travel speeds. This results in a possibility to reduce the overall car fleet with a vehicle replacement rate of up to 4.71. With the reduced system level vehicle fleet, the public parking space can be reduced as well, especially in the city core. However, the parking effects are not homogeneous in space and some areas experience an increase in parking demand. At the same time the service is able to operate close to cost coverage, or even with a slight profit, which is an important insight for the public transport operators.

With benefits and drawbacks of the proposed service in mind, further measures can be designed and tested. The proposed AToD service simulation is easily combinable with other types of AV services (i.e., door-to-door service, DRS AV service), which opens the possibility to analyze more complex mobility systems that might arise in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Sensitivity analysis of the mode-choice model

AToD service presented here is hypothetical. It bears similarity to current public transport services, but also to a possible automated on-demand service. To investigate the potential mode-choices of the population we have made use of the stated preference survey that includes automated transport services and mode-choice model estimated based on the survey results. However, certain assumptions on the value of time and alternative specific constants have been made as described in Section 4. Therefore, we performed sensitivity analysis on these two parameters. Table A.1 presents the tested VOTs and ASCs, and resulting statistics on AToD. Figure A.1 presents the obtained mode shares.

We observe that doubling the VOT decreases the AToD demand from the baseline by 12%, while reducing the VOT by 50% increases the demand by approximately 6.3%. We set the ASC of the AToD service in the baseline scenario (S2) to the value of zero as estimated ASCs of public transport is 0.0 and of AMoD is at -0.061 very close to zero. The range of further evaluated ASCs are within the range of of ASCs of other modes (car at 0.224, cycling at 0.152 and walking at 0.590). We further test negative values of AToD ASC as views towards this mode might be more negative then for AMoD service due to safety or other concerns. Changing the ASC in steps of 0.112 changes the demand in approximately 5.6% steps.

While the demand for AToD changes with the changing VOT or ASC, this only changes the intensity of the flows, but not the patterns ob-

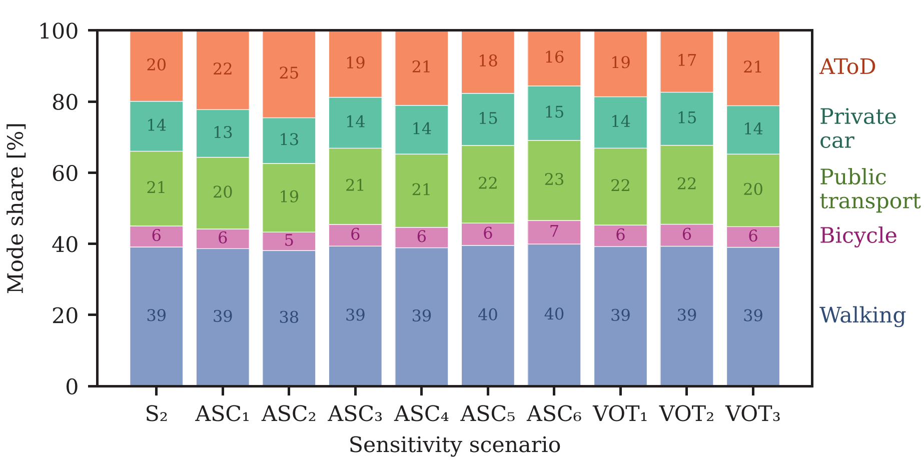

Fig. A.1. Modal share by trips.

Table A.1
Sensitivity analysis scenarios.

Scenario	$\beta_{ASC,AToD}$	$\beta_{inVehicleTime,AToD}$	AToD Demand	AToD Demand Change [%]
S_2	0	-0.015	483005	-
ASC_1	0.224	-0.015	540038	11.81
ASC_2	0.448	-0.015	595629	23.32
ASC_3	-0.112	-0.015	455570	-5.68
ASC_4	0.112	-0.015	510681	5.73
ASC_5	-0.224	-0.015	428733	-11.24
ASC_6	-0.448	-0.015	377668	-21.81
VOT_1	0	-0.0225	451925	-6.43
VOT_2	0	-0.03	420999	-12.84
VOT_3	0	-0.0075	513316	6.27

served. Therefore, the findings presented above would only change in absolute, but not in relative terms.

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Who is living a local lifestyle? Towards a better understanding of the 15-minute-city and 30-minute-city concepts from a behavioural perspective in Montréal, Canada

Carolyn Birkenfeld, Rodrigo Victoriano-Habit, Meredith Alousi-Jones, Aryana Soliz, Ahmed El-Geneidy*

McGill University, Canada

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ABSTRACT

Policy makers worldwide are increasingly embracing the idea of a "15-Minute City" or "30-Minute City" as part of their sustainable-development strategies. These planning concepts propose an urban environment where residents can meet their essential needs within a short trip from their home using active modes of travel. However, there is limited understanding about the replicability and usefulness of these concepts in influencing the travel behaviour of residents to meet the 15- or 30-minute-city reality. Drawing from a travel-behaviour survey and open-source geospatial data from Montréal, Canada, this article seeks to identify which groups of households are living a 15- or 30-minute city lifestyle to understand the compatibility of the x-minute city planning approach with the local North American context. Findings indicate that the 15- and 30-minute city paradigms provide goals that are hardly reachable in the context of a large North American city. Very few households are able to conduct all their daily travel within close proximity to their home, even if the built environment was substantially altered. These findings suggest that the x-minute city is not a one-size-fits-all model. The findings from this study can be of interest to transport professionals aiming to apply the x-minute city as it highlights the challenges associated to meeting such target in a North American context.

1. Introduction

Local and regional accessibility policies have been gaining momentum in the planning field in recent years, especially the concepts of "15-Minute City" and "30-Minute City." These concepts aim to enable urban residents to fulfil essential social functions (including living, working, commerce, healthcare, education, and entertainment) within 15 or 30 min from their homes by active travel (Moreno, Allam, Chabaud, Gall & Pratlong, 2021). The cited benefits of implementing this planning framework include reaching sustainable-mobility goals and improving the general wellbeing of urban populations (Allam, Nieuwenhuijsen, Chabaud & Moreno, 2022). The movement of the 15-minute city has emerged from historically older European regions, which were designed prior to the car-domination era (ibid). These regions have experienced population growth and expansions over the past decades with recent prioritization of car-oriented planning, which imposed large burdens on their population when it comes to travel time to reach desired destinations. As such, the 15-minute city has become a popular vision among some European decision makers, representing a reorientation toward local living. Reflected in various election campaigns, policymakers across the globe are discussing these initiatives, including the possibility of adopting it in North American contexts (Bruemmer, 2021; Gower & Grodach, 2022; TED Conferences, 2021). In regions where the automobile played a structural role in urban planning, the 30-minute city has emerged as an adaptation to the concept, yet these discussions remain largely limited to Australia and New Zealand (Levinson, 2019).

Given the rising interest in adopting the 15- and 30-minute cities in different contexts, what will these planning approaches look like on the ground in a range of urban environments? Is it possible for any city to apply these concepts and see results? While benefits of x-minute cities are widely shared, the concepts have also been challenged for their feasibility within existing built environment, affordability, and socio-cultural constraints (Dunning, Calafiore & Nurse, 2021; Guzman, Arellana, Oviedo & Aristizábal, 2021). Moreover, though extensive research has been conducted on what built-environment features could potentially encourage the 15- or 30-minute city (Capasso Da Silva, King & Lemar, 2019; Gaglione, Gargiulo, Zucaro & Cottrill, 2022; Moreno et al.,

* Corresponding author.
E-mail addresses: carolyn.birkenfeld@mail.mcgill.ca (C. Birkenfeld), rodrigo.victoriano@mail.mcgill.ca (R. Victoriano-Habit), meredith.alousi-jones@mail.mcgill.ca (M. Alousi-Jones), aryana.soliz@mcgill.ca (A. Soliz), ahmed.elgeneidy@mcgill.ca (A. El-Geneidy).

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2021), it remains unclear which groups of the population can achieve this lifestyle.

In this article, we test the practicality of the x-minute city goal in the Montréal metropolitan region (Canada). Our aim is to evaluate whether the 15-minute city planning approach championed by Carlos Moreno is an appropriate measure toward improving local accessibility within this context. The definition stipulates that all social functions, including work, food, health, education, culture, and leisure are conducted within a 15-minute travel time radius using walking and cycling modes (TED Conferences, 2021). In this study, we expand the definition to *include public transit* as an alternative mode given that it has been described as a 'quasi-active mode' (Ermagun & Levinson, 2017) and has proven important to promoting active living environments (Winters, Buehler & Götschi, 2017), especially in North American contexts (Crist et al., 2021; Daley et al., 2022). To accommodate the land use reality of the study area, we further expand Moreno's definition by testing a 30-minute threshold in addition to the 15-minute version, which has been promoted in newer cities.

Using existing travel behaviour data, we identify which groups of households are living a 15- or 30-minute city lifestyle and which built-environment and personal characteristics differentiate these groups from those maintaining longer travel distances. In line with the definition discussed previously, we conceptualize "15- and 30-Minute Households" as those whose trips do not surpass these respective travel-time thresholds and are all completed using active transport modes: walking, cycling, and/or public transit. Using disaggregate mobility data from a sample of 22,040 households from the 2018 Montréal Origin-Destination (O-D) survey, we estimate binary logistic models followed by a sensitivity analysis to assess the built-environment and household factors defining a 15- or 30-minute household using these active modes. Following these analyses, alternate definitions of x-minute city households are explored to test other ways of conceptualizing local accessibility metrics that are based on travel-time thresholds. First, trips to work and school destinations are excluded from the analysis to recognize the regional scale of employment and education. Second, households that conduct 65% or more of their trips with active modes in the travel time threshold are considered 15- and 30-minute households. This two steps analysis shows how far a North American city is from applying a modified 15 min and the 30 min city concepts, while the statistical models show the factors that can be used to achieve either of these concepts in practice through policy and planning tools.

2. Literature review

Sustainable urban mobility is increasingly being recognized as a high priority for policy makers and planners globally. While decades of car-centric policies have improved travel speeds, they have led to rising issues of urban sprawl, traffic congestion, greenhouse gas emissions, as well as air and noise pollution (Hickman & Banister, 2014; Meschik, 2012; Silva & Altieri, 2022). Rather than being the simple result of consumer preferences, research has demonstrated how car dependency has been fuelled through complex structural, political, economic, and socio-cultural dynamics (Doughty & Murray, 2016; Furness, 2010; Gopakumar, 2020; Sheller & Urry, 2000). Thus, efforts to phase-out carbon-intensive transport systems require both broad-based critical thinking as well as careful attention to the particularities of diverse urban, neighbourhood, and household dynamics (Soliz, 2021).

As a part of the movement for sustainable-urban transitions, the notion of the 15-minute city has been gaining traction as a means of creating higher-density, mixed-use neighbourhoods that help to enhance local resiliency and social wellbeing (Caselli, Carra, Rossetti & Zazzi, 2022; Moreno et al., 2021; Pozoukidou & Chatziyiannaki, 2021). From this perspective, each neighbourhood unit should provide efficient access to quality-of-life amenities and fulfil essential social functions, including living, working, commerce, healthcare, education, and entertainment within a 15 min travel time threshold by active modes of transport (Hosford, Beairsto & Winters, 2022; Moreno et al., 2021). By prioritizing active modes—especially cycling and walking—this concept is seen as fostering a paradigm shift in contemporary urban planning, supporting healthier travel patterns and social interactions (Allam et al., 2022). In this sense, the 15-minute city is often regarded as the contemporary manifestation of the classic "human scale," prioritizing neighbourhood liveability along with people's time and collective wellbeing (Abdelfattah, Deponte & Fossa, 2022; Weng et al., 2019). Although similar paradigms (such as the neighbourhood-unit concept) have been used since the 1920s (Kissfazekas, 2022), the notion of the 15-minute city has gained popularity among policy makers in recent years, with added attention to enhancing positive social, environmental, and public-health outcomes (Allam et al., 2022).

Notwithstanding the promise of planning for the 15-minute city, the concept has recently been subject to critical questioning by various researchers. By prioritizing neighbourhood efficiency, does this model neglect the mobility needs of people with disabilities and those who cannot afford to stay in dense urban areas (Zivarts, 2021)? Is the concept simply a utopian buzzword, or does it have the potential to generate substantive changes to improve urban environments and social wellbeing (Gower & Grodach, 2022; Herbert, 2021)? What are the risks that this movement will spark neighbourhood transformations that lead to gentrification and social displacement, thus exacerbating urban inequalities (Dunning et al., 2021)? Furthermore, given that the concept was adapted primarily from older European cities, to what extent can 15-minute cities be replicated in different global contexts (Guzman et al., 2021)? While examples of 5, 15, 20, and 30-minute cities abound (Di Marino, Tomaz, Henriques & Chavoshi, 2022; Gaglione et al., 2022; Hosford et al., 2022; Levinson, 2019; Peters, 2019), what thresholds should be used to guide new planning interventions, and how might these targets need to be modified across diverse urban realities? Furthermore, with several urban-mobility scholars calling for an expanded understanding of active travel to include 'quasi-active modes,' notably public transit and other intermodal options (Agyeman & Cheng, 2020; Ermagun & Levinson, 2017; Sagaris & Arora, 2016; Sagaris, Tiznado-Aitken & Steiniger, 2017), how can x-minute-city research help to integrate these insights into urban-planning frameworks?

Indeed, there is compelling evidence that the concept of the 15–30-minute city requires greater attention to residents' actual needs, lived experiences, neighbourhood characteristics, and socio-economic conditions (Calafiore, Dunning, Nurse & Singleton, 2022; Guzman et al., 2021; Logan et al., 2022; Olsen et al., 2022). As Richard Dunning and colleagues propose, working towards x-minute cities will require "planning for the possible in the context of the existing" (2021, p. 157). This process should not preclude the goals of creating more sustainable, mixed-use, and higher-density cities, but rather requires moving beyond tokenistic discourse about x-minute cities, towards greater engagement with unique urban and neighbourhood contexts (ibid.).

While critical and socially engaged thinking on x-minute cities is on the rise, surprisingly little attention has been given to actual household dynamics and travel behaviour in these discussions. Thus, this paper builds on the literature attending to the relationship between household characteristics and transport planning (Chidambaram & Scheiner, 2020; Habib, 2014; Hawkins, Weiss & Habib, 2021) to better nuance analyses and planning interventions aimed at fostering the x-minute city. Studies on travel behaviour have long commented on the need to account for the unique social, economic, and demographic trends that result in changing household dynamics and travel patterns (Clark, Huang & Withers, 2003; Surprenant-Legault, Patterson & El-Geneidy, 2013; White, 1988). For example, research on walkability measures and their relationship to actual observed travel patterns has found that walkability indexes do not have the same correlation with travel behaviour for all individuals and households (Manaugh & El-Geneidy, 2011). By bringing together this literature on the relationship between household characteristics and transport planning with recent theorizing on 15–30-minute cities, we hope to help move the conversation beyond utopian thinking about urban sustainability, towards more contextualized strategies grounded in people's actual travel experiences, neighbourhood characteristics, and household realities.

3. Data and methods

In this paper we define households who are living the 15- or 30-minute city lifestyle as those households who are conducting all their travel to their desired daily destinations within a 15- or 30-minute travel-time radius from their home and are using active modes of transport (walking, cycling, and/or public transport) to reach them. To do so, we use the 2018 Montréal Origin-Destination (O-D) survey. The O-D survey is administered every 5 years by the regional public transport planning authority in the Montréal metropolitan region, collecting a travel diary record from a 5% random sample of Montréal-area households covering the most recent weekday. Each observation in the O-D survey represents a trip made by an individual on the survey day from a specific household. All trips made by the entire household on the same day are recorded and coded to enable aggregation to the person or household level.

3.1. Data cleaning

We restricted our analysis to households whose trips consisted of O-D pairs within Montréal's metropolitan area boundary. Trips with missing O-D information or those that reported modes other than walking, cycling, public transit, and/or car (driving or passenger) were removed since accurate travel times could not be estimated except for these modes. Travel times for each trip were measured between the respondent's home location and the trip destination, based on the mode used to reach the destination. This approach helps correct for potential trip chaining, wherein the trip origin and destination are far from the home location, to capture a true travel time radius of all destinations from the home location.

Network routing for each home-destination pair were calculated using the r5r package in R, supported by OpenStreetMap (OSM) utilizing its sidewalk, cycling, and roadway networks. A speed of 4.5 km/h was used to estimate walking travel time and 16 km/h for cycling (Bastos Silva, Cunha & Silva, 2014; El-Geneidy, Krizek & Iacono, 2007). We assembled General Transit Feed Specification (GTFS) data for all public transport agencies providing service in the study area, with feeds downloaded from OpenMobilityData we calculated travel times by public transport trips using the r5r routing tool (Pereira, Saraiva, Herszenhut, Braga & Conway, 2021). Since the public transport routing procedure relies on schedules from the GTFS, r5r was programmed to measure travel time based on the departure time reported for each trip. The OSM network and GTFS files were downloaded from 2019 and public transport trips were simulated on a typical weekday schedule of April 23rd, 2019. To our knowledge no significant road network changes or public transport service adjustments occurred between the time of the survey and the date the travel time routing data was sourced. It is important to note that congested car travel time was not calculated for this analysis since the goal of the study is to identify households living the 15- or 30-minute lifestyle while exclusively using active modes of transport. For this reason, households with car users were not considered to be living the 15- or 30-minute lifestyle.

With relevant travel times calculated, all trips in the sample (n = 147,274) were then aggregated to the household level for further analysis (n = 50,904). The maximum travel time recorded for each household and the modes used for all trips were utilized to determine whether the household classifies as a 15-minute household or a 30-minute household. To capture daily travel behaviour consisting of a range of trip types, a household was excluded from the sample if it had less than two trips recorded in the survey, and/or if school and work were the only destinations visited by all members of the household. Households were also removed from the sample if their survey results were missing key demographic information such as income that are needed for the analysis. The final cleaned sample consisted of 87,328 trips reported by 22,040 households.

3.2. Statistical models and variables

As a central aim of our research is to learn the personal and neighbourhood factors contributing to a household living the 15- or 30-minute city lifestyle based on all of their trips, we used a binary logistic regression to unravel the characteristics that differentiate these households from those with longer travel times. A multilevel binary logistic model was also tested with census tracts as the higher level of analysis. However, when comparing the multilevel model to the binary logistic model, the LR test (p = 0.31) indicated that it is not needed. For the purposes of this analysis, a 15- or 30-minute household is defined as one whose daily trips (a) do not surpass the respective travel-time threshold and (b) are completed using only active modes (walking, cycling, and/or public transit).

Two groups of explanatory variables, household characteristics and built-environment factors, were included in the models. For the former, sociodemographic information by household was pulled from the O-D survey. Variables included per capita annual income, a binary indicator of household vehicle access, and household size by age and occupation status. For the purposes of modelling, the household composition is indicated by seven variables that count mutually exclusive categories of individuals which comprise households: children (age <5), students (age 5–12), students (age 13–18), students (age 19+), full-time workers, retirees, and other. This disaggregated representation of household size allowed us to pinpoint the influence that household members in varying life stages may have on the ability to meet daily needs within 15- and 30-minute travel-time thresholds.

The built-environment factors included two measures of local and regional accessibility, the ease of reaching destinations, around each household (Handy, 2020; Manaugh & El-Geneidy, 2012). The first is WalkScore, a popular measure of local accessibility by active modes that has been proven reliable in predicting walking behaviour in the Montréal context (Manaugh & El-Geneidy, 2011). This measure reflects neighbourhood-level walkability as an index produced through a gravity-based assessment of amenities within 1-mile of each location. In our analysis, household home locations were spatially joined to postal code-level WalkScore values. To capture the varying impact of WalkScore, four dummy variables were generated in line with the official WalkScore groupings: car dependent (score 0–49), somewhat walkable (score 50–69), very walkable (score 70–89), and walker's paradise (90–100) (Walk Score, 2022).

A public transport gravity-based accessibility measure is the second built-environment metric, defined as the quantity of jobs reachable within the region's from a location and weighted by a gaussian-fit decay function derived from the Census 2016 commuting flows (Palacios & El-geneidy, 2022). Travel time calculations for job accessibility by public transport were produced using the r5r package in R for every minute between 8:00 am and 9:00 am then averaged to account for variation in scheduling and waiting time (Pereira et al., 2021). Job location data was obtained from Statistics Canada (Statistics Canada, 2018). To highlight the policy relevance of this study, a sensitivity analysis was developed after discussing the statistical models showing the odds of different household structures in achieving the 15- or 30-minutes city lifestyle while varying the local accessibility levels.

3.3. Samples for alternate 15- and 30-minute city definitions

Two additional samples were prepared to reclassify the same households based on definitions of 15- and 30-minute cities that are less rigid compared to the expectation that all household travel is conducted within the travel time radius. The first sample excludes all work and

Table 1
Descriptive statistics of independent variables grouped by 15- and 30-minute households.

Variable		Variable Description	Mean (Std. Dev.)			
			15-min *households*	*Non-15*-min *households*	*30*-min *households*	*Non-30*-min *households*
Household Characteristics						
Income (per capita)	*[$10,000/year]*	Respondent's annual household income, divided by household size	3.38 (2.52)	3.78 (2.62)	3.56 (2.68)	3.78 (2.62)
Household vehicle access	*[1 = yes]*	Access to a household vehicle	0.4 (0.49)	0.91 (0.29)	0.37 (0.48)	0.93 (0.25)
Household Composition						
Children (age <5)	*[count]*	Number of children under the age of 5	0.06 (0.25)	0.15 (0.44)	0.09 (0.35)	0.15 (0.44)
Students (age 5–12)	*[count]*	Number of students between the ages of 6 and 12, inclusive	0.16 (0.52)	0.34 (0.71)	0.18 (0.54)	0.34 (0.71)
Students (age 13–18)	*[count]*	Number of students between the ages of 13 and 18, inclusive	0.04 (0.25)	0.19 (0.51)	0.06 (0.29)	0.2 (0.52)
Students (19+)	*[count]*	Number of students ages 19 or older	0.08 (0.32)	0.15 (0.42)	0.12 (0.39)	0.15 (0.42)
Full-time workers	*[count]*	Number of full-time workers	0.4 (0.63)	1.08 (0.88)	0.61 (0.74)	1.09 (0.88)
Retirees	*[count]*	Number of retired individuals	0.69 (0.74)	0.52 (0.76)	0.55 (0.72)	0.52 (0.77)
Other household members	*[count]*	Number of other household members	0.3 (0.58)	0.26 (0.51)	0.28 (0.53)	0.26 (0.5)
Built Environment						
WalkScore	*[1–100]*	WalkScore of home location	84.9 (18.5)	59.6 (27.3)	87.2 (15)	58.3 (27)
Transit accessibility to jobs	*[1 = 10,000 jobs]*	Gravity-based accessibility to jobs	42.5 (18.7)	21 (19.4)	45.4 (16.4)	19.9 (18.8)
Percent of Sample			1.8%	98.2%	6.0%	94.0%

school trips to evaluate x-minute household status based on each household's non-education and employment destinations. It is understood that work and school destinations tend to assume a more regional scale relative to home locations as individuals seek opportunities that best align with their needs. Moreover, travel for work and school purposes is often more inflexible than other purposes, as their destinations cannot easily be changed (Schwanen & Dijst, 2003). As such, these destinations often span beyond the neighbourhood vicinity and may conflict with our evaluation of local accessibility to other destinations such as leisure, shopping, health, etc. For this sample, work and school trips were filtered out based on the trip type variable included in the Montreal O-D survey. The resulting sample included 55,642 non-work and non-school trips reported among 22,040 households.

The second alternative sample defines 15- or 30-minute city households as such if 65% or more of the household's trips are completed using active modes within the travel time threshold. Under the assumption that household members may choose to travel to longer-distance destinations despite closer options being available, it may be an unreasonable expectation to measure local accessibility based on an exclusive travel time radius. The 65% benchmark was selected because it reflects a household's trip majority for those that have as few as three total trips recorded. This sample includes the same number of households (n = 22,040) and trips (n = 87,328) as the original sample.

4. Results

4.1. Descriptive statistics

Our preliminary analysis shows that a minority of households in Montréal are living the 15- and 30-minute city lifestyles (Table 1). Among the 22,040 Montréal households analysed, 1.8% conduct all their daily activities within 15 min from their home using active transport (walking, cycling, and/or public transport), and 6% within 30 min. Households living a 15- and 30-minute city lifestyle tend to have fewer people than those who are not. This distinction is slightly more pronounced when comparing households within and outside of the 15-minute travel-time threshold to the 30-minute one.

For the built-environment variables, WalkScore and public transport accessibility to jobs are higher for 15- and 30-min households (Fig. 1), with a bigger change in WalkScore observed between households within and outside of the 30-minute city compared to the 15-minute ones. These preliminary findings suggest that the 15-minute city lifestyle is more related to household composition, whereas the 30-minute city lifestyle is more closely linked to the built environment.

4.2. Model results

Our binary logistic model results allow us to assess the impact of household and built environment characteristics on the probability that all household's trips will fall within a 15-minute or a 30-minute travel-time threshold and using active modes of transport (cycling, walking, and/or public transport). The odds ratios presented in Table 2 for both models reflect the relative importance of each variable on this probability. First, in terms of income, the models indicate that an increase of $10,000 in a household's per capita income results in an 8% decrease in the probability of being a 15-minute household, and a 6% decrease in the probability of being a 30-minute household, while keeping all other variables constant at their mean value. Thus, while the effect of income is significant, and lower income households are more likely to belong to these local accessibility groups, the effect is also relatively small. On the other hand, vehicle ownership has a considerably higher effect. A household that owns one or more vehicles is 78% less likely to be a 15-minute household, and 87% less likely to be a 30-minute household, while keeping all other variables constant at their mean.

Both models also attempt to explain the impact of household composition on the probability of staying within the 15- and 30-minute travel-time thresholds while only using active modes of transport. To simplify the interpretation of individual characteristics in the model, Fig. 2 presents the varying effects of the number of individuals with certain characteristics on the probability of a household being characterized as a 15- or 30-minute household. Each additional household member which has a statistically significant effect, negatively affects the probability of being a 15- or 30-minute household. This effect varies based on the age and status of this additional household member. Thus, larger households are less likely to stay within the assessed thresholds regardless of their specific composition, especially for 15-minute households, if all other variables are kept constant.

Retirees have the smallest effect on the probability of being a 15-minute household, meaning that a household comprised of only one retiree would be the most likely to have a 15-minute travel radius while only using active modes of transport. This is followed by the "other household member" category (non-employed and non-students) and students of 13 to 18 years of age. Finally, students over 18 years old and full-time workers have the largest effect, meaning that they are the least likely to stay within a 15-minute threshold. For the probability of being

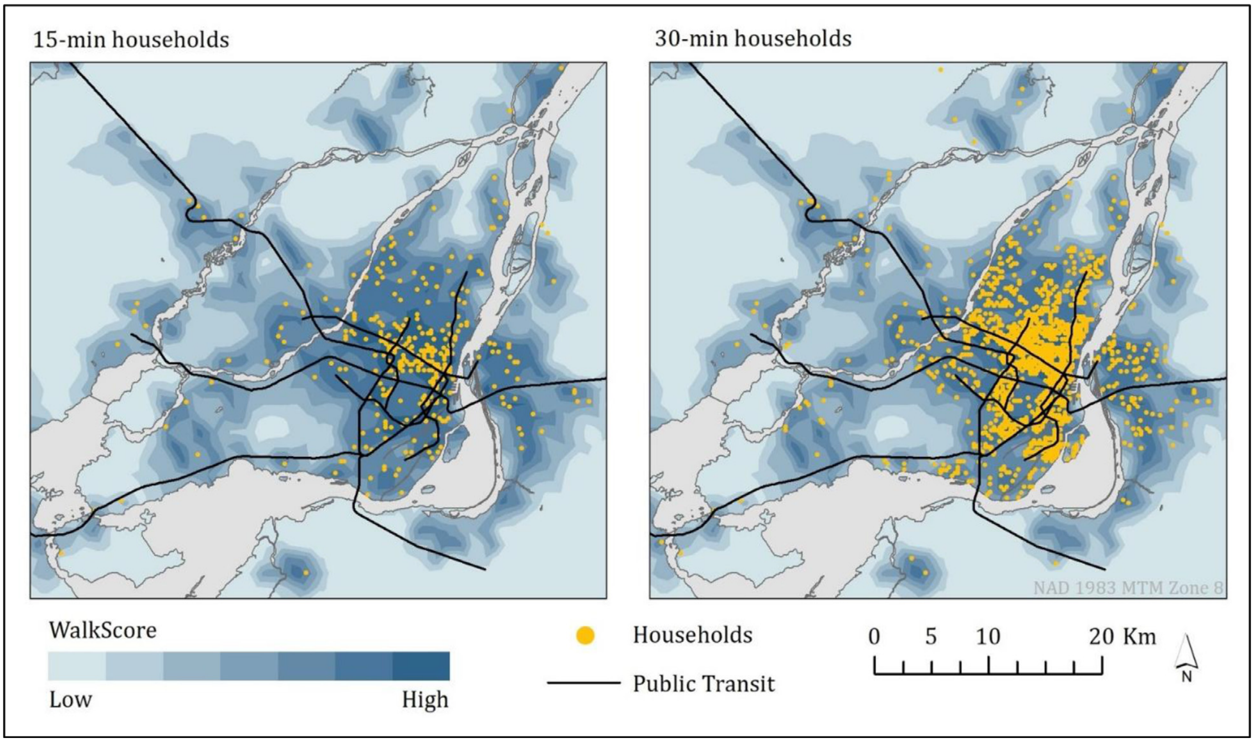

Fig. 1. 15- and 30-min household home locations and neighbourhood WalkScore.

Table 2
Model results for 15-minute and 30-minute households.

Predictors	15-min households		30-min households	
	Odds Ratio	*CI*	*Odds Ratio*	*CI*
Intercept	0.05 ***	0.03 – 0.09	0.08 ***	0.06 – 0.13
Household Characteristics				
Income (per capita)	0.92 **	0.88 – 0.97	0.94 ***	0.91 – 0.96
Household vehicle access	0.22 ***	0.17 – 0.29	0.13 ***	0.11 – 0.15
Household Composition				
Children (age <5)	0.71	0.46 – 1.03	0.92	0.76 – 1.11
Students (age 5–12)	1.14	0.91 – 1.40	1.05	0.92 – 1.19
Students (age 13–18)	0.52 **	0.32 – 0.77	0.60 ***	0.48 – 0.75
Students (19+)	0.39 ***	0.26 – 0.56	0.59 ***	0.49 – 0.71
Full-time workers	0.34 ***	0.26 – 0.42	0.54 ***	0.47 – 0.61
Retirees	0.78 *	0.62 – 0.98	0.90	0.78 – 1.04
Other household members	0.74 *	0.57 – 0.96	0.80 **	0.68 – 0.94
Built Environment				
WalkScore (50–69)	1.77 *	1.02 – 3.16	1.71 **	1.17 – 2.54
WalkScore (70–89)	2.38 **	1.40 – 4.19	2.34 ***	1.63 – 3.44
WalkScore (90–100)	4.33 ***	2.34 – 8.26	4.24 ***	2.81 – 6.50
Transit accessibility to jobs	1.02 ***	1.01 – 1.03	1.04 ***	1.03 – 1.04
Observations	22,040		22,040	
R^2 (McFadden)	0.25		0.36	
AIC:	3050.73		6442.21	
BIC:	3162.74		6554.22	

* $p<0.05$ ** $p<0.01$ *** $p<0.001$.

a 30-minute household, "other household members" have a relatively small effect, followed by students over the age of 13. Similar to the 15-minute households, full-time workers have the largest effect, suggesting that work-related responsibilities interfere with the ability to live within a 30-minute travel-time threshold while only using active modes of transport.

Children under 5 years of age and students from 5 to 12 years of age have no statistically significant effect on the probability of a household having a 15-minute or 30-minute travel-time threshold. This means that a household belonging to one of these two travel-time categories is more related to the presence of adults and students over 13 years of age in the household, as younger children show no additional effect.

The models also shed light on the relevance of the built environment on the likelihood that a household will belong to one of the 15- or 30-minute household categories. In this context, the household location's WalkScore has a strong and statistically significant effect on the odds of a household being a 15- or 30-minute one. Compared to households located in areas with the lowest WalkScore values, of 0 to 49, households located in areas with a WalkScore of 50 to 69 are 1.77 times more likely to be a 15-minute household and 1.71 times more likely to be a

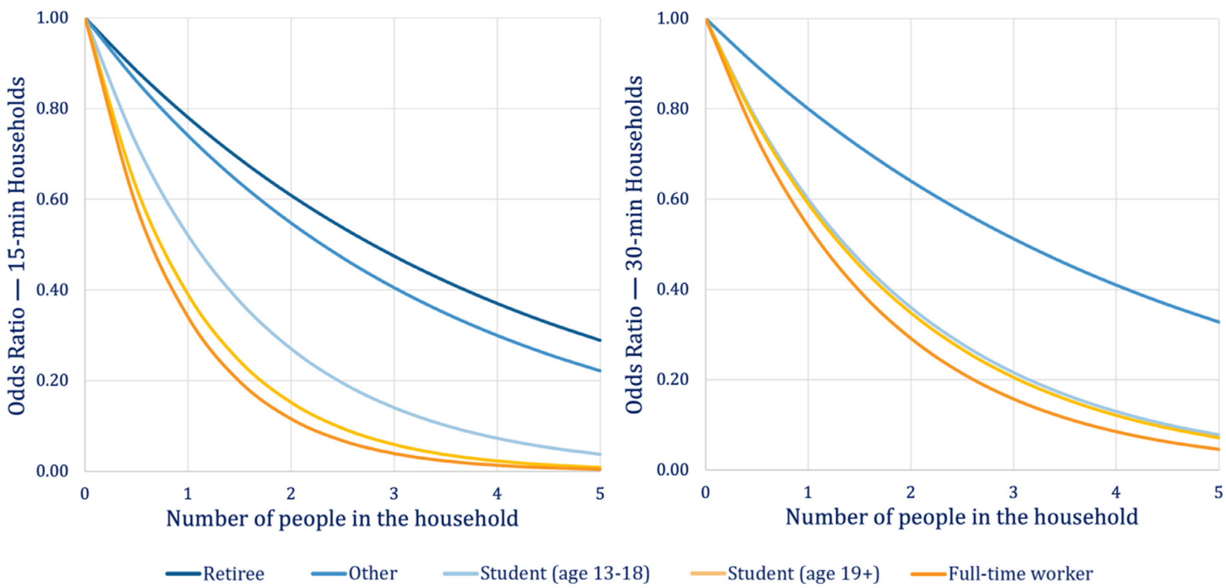

Fig. 2. Odds ratios for 15-minute and 30-minute households by number of household members.

30-minute household while keeping all other variables constant at their mean. Households living in neighbourhoods with a WalkScore between 70 and 89 are 2.38 times more likely to be a 15-minute household and 2.34 times more likely to be a 30-minute household when compared to households residing in neighbourhoods with the lowest WalkScore. Finally, households living in areas with the highest WalkScore, with scores of 90 to 100, are 4.33 times more likely to be a 15-minute household and 4.24 times more likely to be a 30-minute household compared to those households residing within the lowest values, while keeping all other values constant at their means.

The probability of being a 15-minute household increases by 2% for every additional 10,000 jobs (weighted based on the gravity decay function) that can be reached by public transit in the region's mean commute time from the household location, while keeping all other variables constant at their mean. On the other hand, the probability of being a 30-minute household increases by 3% for every additional 10,000 jobs that can be reached. These results show that not only local accessibility is relevant for households to live a 15- or 30-minute city lifestyle, but public transit accessibility as well.

4.3. Sensitivity analysis

To better understand the implications of the all-trips model results, we propose a sensitivity analysis based on 8 household profiles:

- 1 adult ("other household member": non-employed and non-student), with no car
- 1 student, with no car
- 1 worker and 1 student (13–18), with no car
- 2 adults, with a car
- 1 worker, with a car
- 1 worker, 1 student (19+), 1 student (13–18), with a car
- 1 worker and 1 student (13–18), with a car
- 2 workers and 1 student (13–18), with a car

These 8 household profiles with varying compositions and car ownership only include household members that showed statistically significant effects on both models presented in Table 2. For the sensitivity analysis, we predict the probability that each of these household profiles will be a 15- or a 30-minute household for varying WalkScore levels, while fixing per capita income and public transport accessibility levels at their respective mean values. This analysis allows for evaluation of which household structures are more likely to lead to 15- and 30-minute households, as well as to assess the relevance of varying local accessibility levels for these profiles, a strategy that is being heavily promoted in the 15-minute city literature (Allam et al., 2022; Moreno et al., 2021). Further, we calculate this likelihood for all Montréal households in the sample while varying WalkScore levels. Fig. 3 presents the results of the sensitivity analyses. The percentages for each household profile can be interpreted either as the probability that each profile would be a 15- or 30-minute household, or as the share of each household profile that only makes trips within the assessed travel-time thresholds using active modes of transport.

The household structure with the highest share of 15-minute households is composed of 1 non-employed, non-student adult with no private vehicle. For this household structure, the share of 15-minute households would be 15% when located in a neighbourhood with a WalkScore of 90 or above. However, all other profiles have shares of under 10% meeting the 15-minute household status, and all profiles with more than one person in the household have shares of under 5%. These results illustrate how having to perform work activities and having larger households strongly restricts the possibility of staying within a 15-minute threshold. Improving the local accessibility levels for all areas in the Greater Montréal Metropolitan region to the highest WalkScore levels (90 to 100) would lead to only 2.7% of all households attaining a 15-minute travel-time radius that relies on active modes of transport only. This represents an increase of only 0.9% in the number of households relative to the existing 1.8% 15-minute households currently experiencing this lifestyle.

Compared to 15-minute households, the share of households that would stay within the 30-minute travel-time threshold is higher for all profiles. In this case, the profile with the highest probability is also 1 non-employed, non-student adult with no car, for which the share would be 33.2% when located in a neighbourhood with a WalkScore of 90 or more. This is followed by other profiles without a private vehicle, all of which have a share of over 10% when located in the highest WalkScore level. On the other hand, all profiles with at least one car have shares of less than 7% of 30-minute households. Finally, for the current Montréal population, 8.0% of households would be categorized as a 30-minute household if local accessibility was improved to WalkScore levels of 90 or more. This represents an increase in 2.0% of households compared to the existing 6.0% 30-minute households in the Greater Montréal Area.

These sensitivity analysis results provide insights into the feasibility of the 15-minute and 30-minute city planning approaches in the North American context, as well as into the potential planning measures that

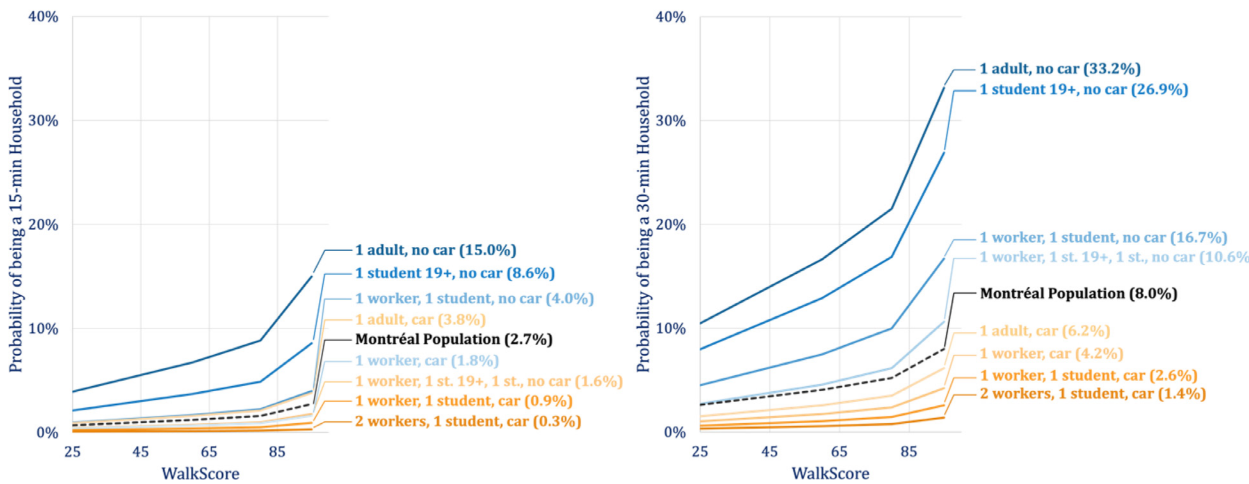

Fig. 3. Sensitivity analysis results.

Table 3
Percent of households that meet different versions of x-minute city concepts.

	Percent of Montréal households			
Trips that conform to the x-minute city definition	15-min households	Non-15-min households	30-min households	Non-30-min households
100% of trips	1.8%	98.2%	6.0%	94.0%
Non-work and non-school trips	5.9%	94.1%	11.1%	88.9%
65% of trips	4.3%	95.7%	10.4%	89.6%

can be taken to move toward these goals. First, we can conclude that the expectation that households will be able to perform all their trips in 15 min or less while only using active modes of transport is unrealistic for most existing household structures, even if local accessibility was considerably increased. More specifically, households with employed members are much more likely to perform trips with a duration of more than 15 min, which shows the current incompatibility of the 15-minute city paradigm with the distribution of working activities. Additionally, households with more than one person are also highly unlikely to remain within the 15-minute threshold, meaning that more complex household structures tend to be less compatible with a 15-minute-city lifestyle. The 15-minute city planning approach, as defined by maintaining all trips within 15 min of the home, does not only provide a difficult goal to reach for North American cities, but it is more related to household-structure characteristics, which are not within the scope of planning and policy interventions and less with the built environment.

On the other hand, while the 30-minute city lifestyle is also strongly related to household structure, the probability of being a 30-minute household is higher for a variety of household profiles. This includes households with workers and a larger number of members, meaning that the expectation that all of a household's trips could be performed in 30 min or less by active modes is not contradicting the necessity of commuting for work or the needs of more complex household structures as much as the 15-minute travel time threshold. Our findings also show that the goal of encouraging the 30-minute city lifestyle can be achieved through planning policy interventions, such as increasing local and regional accessibility around households. While this is in line with previous studies (Boisjoly, Wasfi & El-Geneidy, 2018; Manaugh & El-Geneidy, 2015), we have also found that households that own one or more cars are considerably less likely to live the 30-minute-city lifestyle. This means that to aim for the 30-minute-city and encourage more local and active lifestyles, built-environment interventions should be accompanied by travel-demand management policies aiming to reduce car ownership.

4.4. Alternate 15- and 30-minute city definitions

Both the 15- and 30-minute city lifestyles in which all trips are conducted using active modes within the given travel time threshold are not achievable by most people in Montréal. With only a 0.9% increase in the number of households meeting the 15-minute standard when WalkScore is increased to the highest levels across the Greater Montréal area, and a 2% increase for the 30-minute standard, the metric used to determine x-minute city eligibility is far too strict. Furthermore, this definition of local accessibility does not account for natural variations in travel behaviour that include trips to destinations in different neighbourhoods of a city. Conducting all travel within a certain travel time may not be realistic or desirable and may instead reflect a constrained mobility experience.

These results point to a need for more contextually appropriate parameters for the x-minute city that can lead to benefits for a greater proportion of people. In this study, Moreno's 15-mincute city definition was already expanded from its original conceptualization to include public transit as an acceptable mode and allow for a larger travel time radius of 30 min, even with such expansion the number of households living these lifestyles were limited and the planning interventions that can be applied on the ground are also limited to a large extent. Two further expansions are explored below.

In the first of the two alternative definitions, 15- and 30-minute households were reclassified using only non-work and non-school trips. This analysis provides another perspective into travel-time trends while recognizing the regional nature of employment and education opportunities. For the second alternative definition, households meet the 15- and 30-minute city status as long as a minimum of 65% of their trips were conducted within the travel time and using active modes. Table 3 shows that when these modifications are applied, a higher proportion of households meet the standard. Excluding trips to work and school destinations leads to 11.1% of households conducting their trips using active modes within a 30-minute travel time radius of their home.

Table 4
Model results for 15-minute and 30-minute households for non-work and school trips.

Predictors	15-min households		30-min households	
	Odds Ratio	*CI*	*Odds Ratio*	*CI*
Intercept	0.04 ***	0.03 – 0.06	0.13 ***	0.10 – 0.16
Household Characteristics				
Income (per capita)	0.95 ***	0.92 – 0.97	0.94 ***	0.92 – 0.96
Household vehicle access	0.31 ***	0.27 – 0.36	0.15 ***	0.13 – 0.17
Household Composition				
Children (age <5)	1.02	0.88 – 1.17	0.92	0.82 – 1.04
Students (age 5–12)	1.18 ***	1.08 – 1.29	1.07	0.99 – 1.16
Students (age 13–18)	0.82 **	0.70 – 0.95	0.84 **	0.75 – 0.95
Students (age 19+)	0.86	0.74 – 1.00	0.94	0.83 – 1.06
Full-time workers	1.04	0.93 – 1.15	1.01	0.92 – 1.10
Retirees	0.74 ***	0.64 – 0.85	0.81 ***	0.72 – 0.90
Other household members	0.90	0.78 – 1.04	0.97	0.87 – 1.09
Built Environment				
WalkScore (50–69)	1.66 ***	1.24 – 2.24	1.79 ***	1.41 – 2.27
WalkScore (70–89)	2.92 ***	2.20 – 3.90	2.66 ***	2.11 – 3.37
WalkScore (90–100)	5.18 ***	3.70 – 7.29	4.61 ***	3.51 – 6.09
Transit accessibility to jobs	1.02 ***	1.02 – 1.03	1.03 ***	1.03 – 1.04
Observations	22,040		22,040	
R^2 (McFadden)	0.19		0.30	
AIC:	8036.86		10,812.88	
BIC:	8148.87		10,924.89	

* $p<0.05$ ** $p<0.01$ *** $p<0.001$.

Table 5
Model results for households with 65% or more trips meeting the 15-minute and 30-minute definition.

Predictors	65% 15-min households		65% 30-min households	
	Odds Ratio	*CI*	*Odds Ratio*	*CI*
Intercept	0.03 ***	0.02 – 0.06	0.08 ***	0.06 – 0.10
Household Characteristics				
Income (per capita)	0.93 ***	0.90 – 0.96	0.96 ***	0.94 – 0.98
Household vehicle access	0.28 ***	0.24 – 0.33	0.13 ***	0.12 – 0.15
Household Composition				
Children (age <5)	1.38 ***	1.19 – 1.60	1.18 **	1.04 – 1.33
Students (age 5–12)	1.80 ***	1.64 – 1.98	1.50 ***	1.39 – 1.62
Students (age 13–18)	0.69 ***	0.56 – 0.84	1.02	0.90 – 1.15
Students (19+)	0.60 ***	0.49 – 0.74	0.87	0.76 – 1.00
Full-time workers	0.65 ***	0.57 – 0.74	0.80 ***	0.73 – 0.88
Retirees	0.95	0.81 – 1.11	1.00	0.89 – 1.12
Other household members	1.00	0.85 – 1.18	1.01	0.90 – 1.15
Built Environment				
WalkScore (50–69)	1.54 *	1.07 – 2.24	1.83 ***	1.39 – 2.41
WalkScore (70–89)	3.03 ***	2.16 – 4.30	2.84 ***	2.19 – 3.71
WalkScore (90–100)	5.49 ***	3.67 – 8.28	5.30 ***	3.92 – 7.23
Transit accessibility to jobs	1.02 ***	1.02 – 1.03	1.04 ***	1.03 – 1.04
Observations	22,040		22,040	
R^2 (McFadden)	0.22		0.34	
AIC:	6159.69		9779.13	
BIC:	6271.69		9891.14	

* $p<0.05$ ** $p<0.01$ *** $p<0.001$.

Around 10.4% of households meet the 30-minute city status when only 65% of trips need to occur within the 30 min of the home. These alternate definitions provide examples of some methods for creating x-minute city parameters that reflect more local travel behaviour.

4.5. Modelling alternative definitions of x-minute city

For the first alternative definition the 15- and 30-minute households were reclassified and modeled using only non-work and non-school trips among the same 22,518 households (Table 4). This analysis provides another perspective into travel-time trends while recognizing the regional nature of employment and education opportunities. Findings from this analysis reflect similar results compared to the model that included all trips, with a few distinctions.

Firstly, the number of full-time workers became non-significant and weak toward influencing households' travel-time thresholds when trips to work were excluded. This is a notable difference compared to the models accounting for all trips, yet it has a consistent implication that trips to employment destinations generally take longer than 15 and 30 min. The impact of other household members remained relatively consistent, with the exception of students 5–12 years of age positively impacting 15-minute households, and students over the age of 19 positively impacting 30-minute households. This supports our earlier inclination that university students are likely to live in households that maintain a travel-time radius between 15- and 30-minutes.

In terms of built environment factors, the effect of WalkScore follows the same pattern between both sets of models with a higher magnitude influence when work and school trips are excluded. Transit accessibility to jobs remains significant and positive toward predicting 30-minute households, while for the 15-minute threshold this variable becomes slightly less significant. This definition provide transport professionals with more evidence that achieving the 15-minute and 30-minute city is more reachable if you exclude work and that changes in the built environment will have a stronger effect.

The second alternative is to set a threshold of the number of trips to be under 15 min and 30 min, the current alternative definition sets it at 65% of all trips. This alternative was modeled using the same sample of 22,518 households (Table 5). The model is generally consistent with the previous models, except for the highest WalkScore showing a much stronger impact of the built environment compared to previous models. In other words, providing an alternative definition that expands the 15 min or 30 min constraints to partially include the majority of trips, 65% and above in this case, provides professionals with more tools to reach these goals compared to the original 15-minute or 30-minute definitions.

5. Conclusion

As political interest in adopting 15–30-minute city concepts gains momentum, policy makers must confront questions of how and for whom will this goal come to fruition. This research responds to this need by evaluating the current reality of local accessibility in Montréal to test the practicality of setting targets based on Carlos Moreno's popular concept of the 15-minute city. This study has shown that even when the 15-minute city planning paradigm is expanded to include public transit and to be defined by a larger travel time radius, the concept provides goals that are hardly reachable in the context of a large North American city. The main reason for this is that maintaining 100% of travel within a 15- or 30-minute travel time radius is not compatible with a wide variety of household structures. In this sense, increasing the number of households that are living the 15- or 30-minute city lifestyle is less related to planning or policymaking and more with varying household structures and their specific needs, which are not possible to modify through transport policy interventions. Therefore, striving for a city in which everyone conducts the entirety of their travel within 15 or 30 min from their home is not a useful target. This goal does not accommodate the actual variability of real travel behaviour and is more constricting than it is opportunistic. Cities interested in implementing an x-minute city planning approach must think critically about designing a framework that is both feasible and desirable in the local context.

This study has demonstrated the importance of accounting for household dynamics and travel behaviour in assessing the feasibility of policies aimed at fostering local lifestyles. However, due to the use of O-D survey data, there are some limitations in our analysis. For instance, the identification of 15- and 30-minute households was limited to using a one-day travel diary per household member, which doesn't allow to account for variability in travel between days. Additionally, the analysis was limited to using modelled travel time instead of observed travel time, which may introduce bias into the results. Finally, we could not account for the effect of residential self-selection on households' resulting travel patterns. For these reasons, future research on this topic would need to be conducted by using multiple-day activity-travel data which may be obtained, for instance, through GPS data. While this study used actual travel from an O-D survey, future studies can incorporate data from other sources to account for un-met transport needs to have a more nuanced understanding of the 15-minute or 30-minute city. Additional research can incorporate different measures of accessibility such as accessibility to healthcare by public transit and to retail jobs. Our preliminary analysis has shown these to be highly correlated with accessibility to all jobs by public transit.

Further research is also needed to assess these dynamics across other urban environments to examine the extent to which planning interventions aimed at fostering 15–30-minute cities are within reach, and how to tailor these approaches to best meet the needs of the target populations. Qualitative research is also needed to better understand residents' experiences and perceptions of their local neighbourhoods, including considerations of the comfort and adequacy of facilities for walking, cycling, and public transport, as well as the extent to which local amenities meet residents' needs and wants. Greater research and public engagement are also needed to explore the intersections of x-minute-city frameworks and issues of urban (in)justice, including potential changes to housing prices and affordability as well as the need to better integrate the perspectives of people with disabilities and other underserved groups in urban-policy discussions. By taking local particularities seriously, we hope to help move beyond one-size-fits-all approaches to the x-minute city, towards more contextualized strategies grounded in people's actual needs, lived experiences, and household realities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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