Article

Accessibility of Transit Stops with Multiple Feeder Modes: Walking and Private-Bike Cycling

Mingzhu Song ^{1,2}, Yi Zhang ^{1,3,4}, Meng Li ⁵ and Yi Zhang ^{1,2,*}

¹ Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, Shenzhen 518055, China; smz15@mails.tsinghua.edu.cn (M.S.); zhyi@mail.tsinghua.edu.cn (Y.Z.)

² Future Human Habitat Division, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China

³ Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, SiPaiLou #2, Nanjing 210096, China

⁴ Department of Automation, Tsinghua University, Beijing 100084, China

⁵ Department of Civil Engineering, Tsinghua University, Beijing 100084, China; mengli@mail.tsinghua.edu.cn

* Correspondence: zy1214@sz.tsinghua.edu.cn

Abstract: The accessibility of transit stops (ATS) is a critical index for the evaluation of transit service, focusing on the first/last mile portions of transit trips. It is significantly affected by feeder modes, such as walking and cycling. Comparison of the application of different modes has been addressed in previous research, thus there is mostly only one feeder mode considered in this case study. This study has proposed a model for ATS with multiple feeder modes (ATSMFM), capable of integrating multiple feeder modes and considering the heterogeneity of travellers from the perspective of city managers. It is a bi-level model, combining cumulative and utility-based approaches. The final form of ATSMFM is developed referring to the cumulative approach, while the determination of the catchment area is utility-based. A numerical experiment has been conducted to demonstrate the necessity and applicability of ATSMFM. The results show that the ATS with a single feeder mode, such as cycling or walking, underestimates the catchment area of nearly one-third or two-thirds of travellers. As for ATSMFM, this proposed approach can automatically select the feeder mode from alternatives according to traveller attributes, thus removing the limitation of a single feeder mode, and is suitable for calculating ATS in the complex environment with multiple feeder modes. Besides, the ATSMFM model can support city managers with different emphases in transit planning via flexibly setting the threshold.

Keywords: accessibility of transit stops; multiple feeder mode; catchment area

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1. Introduction

Accessibility of transit stops (ATS) indicates the number of opportunities within the catchment area of transit services, focusing on the first/last mile portion of transit trips [1]. ATS is a critical index for the evaluation of transit service because the access/egress to/from the transit stop is a significant component of the transit trip [2,3]. It has been proved that high-quality ATS helps increase public transit usage [4–10]. Three aspects will affect the quality of ATS: the transit side (the deployment of transit stops), the feeder mode side, and the traveller side [11–13].

On the feeder mode side, the most commonly used feeder modes for bus transit are walking and cycling [12,14,15], as shown in Figure 1. Compared with walking, cycling can significantly enlarge the catchment area and increase the ATS, because cycling has a speed advantage over walking [12,16–18]. However, measurements of ATS with walking and cycling are usually studied separately, and there are few studies integrating walking, cycling, and other feeder modes in the evaluation of ATS.

Figure 1. Multiple feeder modes in accessing and egressing to/from the transit stop.

On the traveller side, studies have found that traveller attributes affect ATS. The catchment area of a transit stop is the spatial manifestation of ATS, within which people can access public transit service [13,19]. The size of the catchment area is found to vary with travellers of different socioeconomic attributes [12]. Besides, traveller attributes relate to the utility that travellers gain from public transit [13]. However, most studies ignore or use the average values of traveller attributes in calculating ATS [20–23]. There are a limited number of studies capturing the heterogeneity of traveller attributes when evaluating ATS [24–26].

There are three popular approaches for measuring accessibility: cumulative, gravity-based, and utility-based approaches. They have different strengths and focuses. Cumulative and gravity-based accessibility measures the number of opportunities within the accessible area, and they are from the perspective of planners or city managers [20]. The two approaches consider multiple travel modes by weighting travel modes based on a survey of travel mode split [27–31]. They are easy to understand in practice but neglect the relationship between travellers and accessibility [32]. On the other hand, utility-based accessibility measures the utility people can obtain from accessible activities or opportunities, and it is from the perspective of travellers by adopting the theory of traveller behaviour, which can consider various factors such as travel time, travel distance, travel cost, travel modes, and traveller attributes [24]. This approach considers multiple travel modes by integrating a travel mode choice model [33]. Utility-based accessibility measures the total surplus from the use of reachable opportunities, and it is difficult to understand without relatively complex theoretical knowledge of traveller behaviour [20,34,35].

This paper proposes a model for the ATS with multiple feeder modes by combining the cumulative and utility-based accessibility approaches. It is capable of integrating multiple feeder modes and considering traveller attributes in evaluating ATS, and is applicable for supporting city managers. A numerical experiment then is conducted to illustrate the necessity and applicability of multiple feeder modes included in ATS.

The remainder of this paper is organised as follows. Section 2 presents a literature review of the accessibility with multiple travel modes and accessibility to transit. Section 3 introduces the details of the ATSMFM model. Section 4 introduces the numerical experiment. Section 5 shows the results, and Section 6 presents the discussion. Section 6 gives a summary and identifies directions for future research. The symbols and abbreviations used in this paper are listed in Table A1 (Appendix A).

2. Literature Review

2.1. Accessibility of Transit Stops Approaches

There are three popular approaches for measuring the accessibility of transit stops: cumulative, gravity-based, and utility-based approaches.

The cumulative accessibility measures the number of opportunities within the catchment area of a transit stop [1,20,36,37]. Most studies define the catchment area as within 400 m from a bus stop and 800 m from a subway station [19,22,38–41]. Some studies have used 300 m or 800 m as the radius of a bus stop catchment area [13,42]. There is no standard distance threshold for the catchment area of the transit stop, generally ranging from 300 m to 1000 m. Moreover, the catchment radius is different for walking and cycling. For example, the 75th percentile travel distance from subway stations was 613 m with walking and 1579 m with cycling in Beijing [22]. The cumulative ATS usually only considers one travel mode in determining the catchment area [2,23]. Although some studies have compared the cumulative ATS with different feeder modes [43], in essence, they are still with a single feeder mode in each case and do not integrate multiple feeder modes in the calculation of ATS.

The gravity-based accessibility also counts the number of opportunities, but unlike the cumulative accessibility, it does not have a clear catchment concept. It discounts the number of opportunities located far from the origin using a decay function, so the gravity-based accessibility does not require a threshold to define the catchment area of a transit stop [21]. Cumulative and gravity-based approaches are from the perspective of planners and city managers, neglecting the relationship between travellers and accessibility [32].

Different from the cumulative and gravity-based accessibility, the utility-based accessibility measures the traveller's ease in accessing/egressing to/from the transit stop [26]. It is a decision utility and includes a choice model in the calculation [44]. The built-in choice model in transit accessibility usually deals with the problem of choosing the trip destination and transit stop [24–26,45]. The utility-based accessibility has an advantage in a better understanding of traveller behaviour than the other two accessibility measures [25]. Most studies measure utility-based accessibility of transit from the perspective of the transit network and use walking as the only feeder mode [24,45]. Few studies have used the utility-based approach or integrating multiple feeder mode in measuring the ATS.

Table 1 summarizes these three approaches. By integrating the advantages of cumulative and utility-based approaches, a new approach for measuring ATS is explored in this paper, which is from the perspective of city managers and considers the heterogeneity of travellers in ATS.

2.2. Methods of Considering Multiple Travel Modes in Accessibility

Studies have found that the travel mode can significantly affect the value of accessibility by comparisons of accessibilities with different travel modes [46,47]. An increasing number of studies have focused on accessibility with multiple travel modes [33,48], as shown in Table 1. There are two ways to consider multiple travel modes.

Table 1. Accessibility approaches and methods of considering multiple travel modes.

Approach	Cumulative	Gravity-Based	Utility-Based
Measurement	Cumulative number of reachable opportunities [1,20,36,37]	Weighted opportunities [21,32]	Surplus in using opportunities [20,34,35]
Directly relationship between travellers and accessibility [32]	No	No	Yes
Catchment area in the accessibility of transit stops (ATS)	No standard (400 m around the bus stop [19,22,38–41]; 300 m or 800 m around the bus stop [13,42])	No (with a decay function [21])	No
Method of considering multiple travel modes	Simple rules or pre-defined travel-mode splits (according to motor vehicle ownership [27]; travel distance segment [29]; travel time segment [30,31])		Mode choice model (mostly used: logit model [33,48–51])

Firstly, researchers develop simple rules for choosing travel mode or use pre-defined travel-mode splits in the approaches of cumulative and gravity-based accessibility. The basic models are proposed by Shen [27] and Luo and Wang [28], considering the resource competition of travellers with different travel modes. The rules of choosing travel mode vary across studies. For example, Shen [27] let travellers choose travel modes according to motor vehicle ownership; Mao and Nekorchuk [29] divided travellers into travel-mode groups according to their travel distance; Xing et al. [30] and Lin et al. [31] assigned travel modes to travellers based on travel time by setting travel-time thresholds for different travel modes.

Secondly, researchers adopt the mode choice theory by using the utility-based accessibility approach from the perspective of travellers. The most frequently used mode choice model is the logit model with a strong assumption of irrelevance between alternative travel modes, but the result is of a closed form that is convenient for practical application [33,48–51].

These studies of accessibility with multiple travel modes show that considering multiple travel modes can make accessibility comprehensive. However, there are few studies considering multiple feeder modes in the calculation of ATS. This paper explores the ATS considering multiple feeder modes.

2.3. Influencing Factors to Accessibility of Transit Stops

The factors considered in calculating the accessibility with walking or cycling usually include travel mode, infrastructure, quality of paths, amenities, environmental factors, etc. [14,43,52–56]. Sometimes disability and the age of travellers are also considered in ATS [57]. Traveller attributes such as income have been proven to affect the size of a transit stop catchment area and the extent to which travellers rely on the transit service [13]. Finance is one crucial aspect of accessibility when considering traveller attributes, especially for low-income travellers [13,58–60]. One popular method to consider both travel cost and other factors in calculating accessibility is to convert other factors into generalised costs, such as monetising travel time by multiplying the travel time by the value of travel time. The value of travel time is usually specified to be the minimum hourly wage or estimated based on mode choice theory [36,37].

The way to consider these factors varies with accessibility approaches. For example, when considering the travel mode, cumulative and gravity-based accessibility only considers one travel mode or considers multiple travel modes by pre-setting the ratio of travel modes according to travel distance [27,29]. However, the utility-based approach can incorporate many more factors in the choice of travel modes, such as travel time, travel

cost, and traveller income. Factors considered in the utility-based approach depend on its incorporated choice model. For example, the utility-based accessibility of transit network with choosing transit stops is not sensitive to transit fare, because the transit fare has no significant effect on the choice of transit stops for transit riders; thus, the model calibration weakens the influence of transit fare to travel utility [24].

Factors considered in the proposed model combines the factors in cumulative and utility-based approaches: travel time, travel distance, feeder mode, travel cost, and socio-economic attributes.

3. Accessibility of Transit Stops with Multiple Feeder Modes

This section describes the proposed ATS model with multiple feeder modes (named the ATSMFM model). The ATSMFM model combines the cumulative approach and the utility-based approach into a bi-level model. The inputs, parameters, and outputs of this model are displayed in Table 2, and the model structure is depicted in Figure 2. This model can be used for both individuals and groups. The upper level of the ATSMFM model adopts the cumulative approach, which counts the number of opportunities within the catchment area. Different from the traditional cumulative approach, the catchment area herein is for an individual or a group, and it varies with traveller attributes. The lower level of the ATSMFM model supports the upper level with the catchment area defined by the utility-based approach.

Table 2. The inputs, outputs and parameters of the proposed model of ATS with multiple feeder modes (ATSMFM).

Terms	Explanation	ATSMFM Model		
		Lower Level	Upper Level	
			for Individual	for Group
<i>Input</i>				
Feeder mode environment	Alternative feeder modes and their availability.	✓		
Attributes of a traveller	For example, the travel frequency, value of travel time, income, etc.	✓		
Distribution of traveller attributions	The distribution of traveller attributes for the considered traveller group.			✓
Distribution of opportunities	The spatial and temporal distribution of opportunities.		✓	✓
Deployment of transit stops	The spatial and temporal distribution of transit stops.	✓		
Road network	Road network with information such as geometry, slope, material, supporting facilities.	✓		
<i>Parameter</i>				
Utility-based threshold	The utility-based threshold is to define the boundary of the catchment area for a traveller. This threshold can vary with travellers.	✓		
Property threshold	This property threshold is to define the boundary of the catchment area for a group of travellers.			✓
<i>Output</i>				
ATS_s^n	The accessibility of transit stop s for traveller n .		✓	
ATS_s	The accessibility of transit stop s for the considered traveller group.			✓

3.1. Upper Level: Accessibility of Transit Stops for Individuals

The upper level adopted the approach of cumulative accessibility [20,36]. The ATS for individuals considers the heterogeneity of travellers, assuming that the catchment area varies with travellers with different attributes. In other words, whether an opportunity will be counted in the ATS depends on whether this opportunity is located in the specific catchment area of the traveller (individual catchment area, which is calculated by the lower level of the ATSMFM model). This part refines the ATS to each traveller, makes the ATS informative, and facilitates city managers to grasp the quality of public transit service for each type of travellers. The formula is as follows.

$$ATS_s^n = \sum_{j \in J} Op_j \cdot B_{s,j}^n, \quad (1)$$

$$B_{s,j}^n = \begin{cases} 0, & \text{if } d_{s,j} > RC_s^n \\ 1, & \text{if } d_{s,j} \leq RC_s^n \end{cases} \quad (2)$$

where ATS_s^n is the value of ATS for the individual n at the transit stop s . Op_j is the number of opportunities (jobs or activities) in location j , and J is the set of locations near the transit stop s . $B_{s,j}^n$ is a dummy variable regarding the comparison between $d_{s,j}$ and RC_s^n , where $d_{s,j}$ is the travel distance between transit stop s and location j , and RC_s^n (determined by the lower level) is the catchment radius at stop s for individual n .

3.2. Upper Level: Accessibility of Transit Stops for Groups

In addition to the ATSMFM for individuals, this upper level provides another perspective: for groups. A specific transit stop services a group of travellers whose origins or destinations are near the transit stop. The attributes of the traveller group may vary with transit stops in different cities and even within different districts of a city. Therefore, the ATSMFM model adds this group perspective to help city managers evaluate ATS based on the group of travellers served.

The ATS of a group (denoted by ATS_s) is defined as the number of opportunities within the catchment area of stop s for the group. This catchment area for a group (group catchment area) is the largest area where the overlap rate of individual catchment areas is at least P_c , as shown in Equation (6). This definition guarantees there are at least P_c of individuals in the group believing that this group catchment area is reachable (or does not exceed their individual catchment area), as shown in Figure 3.

$$ATS_s = \sum_{j \in J} Op_j \cdot B_{s,j} \quad (3)$$

Figure 2. Structure of the ATSMFM model.

s.t.

$$B_{s,j} = \begin{cases} 0, & \text{if } d_{s,j} > RC_s \\ 1, & \text{if } d_{s,j} \leq RC_s \end{cases} \quad (4)$$

$$RC_s = \max(RC) \quad (5)$$

$$P(RC_s^n \geq RC) \geq P_c \quad (6)$$

$$n \in N \quad (7)$$

where $B_{s,j}$ is a dummy variable regarding the comparison between $d_{s,j}$ and RC_s . RC_s denotes the radius of the group catchment area (group catchment radius), and RC is a variable of catchment radius. Here, the average value of RC_s^n is not used to determine the group catchment area, because the average value cannot reflect the variation of individual catchment areas. When the variation is large, the average value of RC_s^n cannot accurately represent the individual catchment areas of the group. N is the set of traveller group.

Figure 3. Group catchment radius.

3.3. Lower Level: Determination of Catchment Area

As described in the upper level (Sections 3.1 and 3.2), the individual catchment radius RC_s^n is the basis of the ATS calculation both for individuals and groups. The lower level of the ATSMFM model calculates RC_s^n to support the upper level. Previous studies usually used a certain travel time or distance as a threshold to determine the radius of the catchment area. In contrast, this paper uses a certain travel impedance (disutility) as a threshold to define the catchment area and allows each traveller to choose the feeder mode by incorporating a discrete choice model (Equation (9)). Specifically, RC_s^n is the maximal travel distance that the traveller can access/egress to/from the transit stop with the trip disutility less than the threshold IM_c^n , as expressed in Equations (8)–(12).

The individual catchment radius is the travel distance of the maximum travel impedance under certain conditions (Equation (8)). The conditions include the definition of travel impedance under the set of travel modes (Equation (9)), the definition of travel impedance with a particular travel mode (Equation (10)), and the condition of travel impedance threshold (Equation (11)). Equation (9) shows that the alternative with the lowest travel impedance is chosen, and the travel impedance under the set of travel modes is the ex-

pected minimum travel impedance associated with available travel modes; which is the definition of utility-based accessibility defined by Ben-Akiva and Lerman [61].

$$RC_s^n = \arg \max_{d_{s,j}} (IM_{s,j}^n) \quad (8)$$

s.t.

$$IM_{s,j}^n = E \left(\min_m (IM_{s,j}^{n,m}) \right) \quad (9)$$

$$IM_{s,j}^{n,m} = V_{s,j}^{n,m} + \varepsilon_{n,m} \quad (10)$$

$$IM_{s,j}^n \leq IM_c^n \quad (11)$$

$$m \in M, j \in J \quad (12)$$

where m is the indicator of a feeder mode, and M is the set of alternative feeder modes for transit. $IM_{s,j}^n$ is the minimum travel impedance considering all alternative modes from s to j . $IM_{s,j}^{n,m}$ is the travel impedance between location j and stop s for individual n with travel mode m , and it takes the form which consists of a deterministic part ($V_{s,j}^{n,m}$) and a random part ($\varepsilon_{n,m}$). $V_{s,j}^{n,m}$ is the observable component, and $\varepsilon_{n,m}$ captures the uncertainty. IM_c^n is a utility-based threshold of the catchment area of traveller n , enabling the ATSMFM model to achieve the following three goals. Firstly, different from the traditional catchment area with a single travel mode, the utility-based threshold herein provides a unified threshold for various travel modes, allowing the model to adjust the travel mode in determining the catchment boundary based on the attributes of the traveller. Secondly, the threshold is utility-based, making it possible to comprehensively consider multiple factors and traveller attributes, while the traditional catchment boundary is only based on travel distance or time, and does not consider the heterogeneity of travellers. In this way, it can make the ATS comprehensive and informative to support city managers. Thirdly, the threshold can emphasise various aspects of accessibility and can be designed according to the goal of city managers, which makes the ATSMFM model flexible and adaptable for different objectives. The utility-based threshold can be set to a constant for all travellers. In this way, the boundary of the catchment area varies with travellers, but these boundaries have the same travel impedance. Another way is to set the utility-based threshold to vary with travellers; for example, it can be set as the travel impedance of walking a constant distance for each traveller. In this way, the catchment area boundary varies with travellers, but the boundary has the same walking effort.

When city managers only want to know the representative accessibility of each type of travellers, the travel impedance (Equation (10)) can be defined to be deterministic, ignoring the random term. According to this objective, there is no need to know the exact ATS of each traveller, and the representative term can satisfy the requirement. Besides, the representative disutility has an advantage in computation and can make the proposed model more applicable. A detail explanation of using representative disutility is presented in Appendix B.

4. Numerical Experiment

Numerical experiments were conducted to illustrate the applicability of the ATSMFM model. There were three scenarios of alternative feeder modes: Scenario 1, with only walking; Scenario 2, with only private bikes; and Scenario 3, with both walking and private bikes.

The considered area was the region within the 5th Ring Road of Beijing, China. Firstly, the model was specified to accommodate the scenarios of feeder modes. Secondly, traveller attributes were obtained from the datasets of resident income and transit smart card records.

4.1. Model Specification

This section specifies the lower level of the ATSMFM model and presents an analysis of the roles of vital variables.

4.1.1. Model Structure

The deterministic term of $IM_{s,j}^{n,m}$ in Equation (10) is set to involve travel time and travel cost as Equation (13).

$$V_{s,j}^{n,m} = \alpha_n \cdot TT_{s,j}^{n,m} + TC_{s,j}^{n,m} \quad (13)$$

where α_n is the value of travel time (VOT) of individual n , $TT_{s,j}^{n,m}$ is the travel time between stop s and location j with mode m , and $TC_{s,j}^{n,m}$ is the travel cost between stop s and location j by mode m .

The travel cost of walking is set to be zero. The travel cost of private-bike cycling adopts the calculation approach used by Song et al. [62]: $TC_{s,j}^{n,pb}$ is the cost of using an available private bike for one trip, evenly allocating the cost of owning a private bike to all its trips. $TC_{s,j}^{n,pb} = C_{pb}^{day} / f_n$, where f_n is the number of trips by private-bike cycling per day, and C_{pb}^{day} is the cost of owning a private bike for one day considering the purchase cost, maintenance cost, and lifespan of a bike. Then, the travel impedances with walking and private-bike cycling are expressed as follows.

$$IM_{s,j}^{n,w} = \alpha_n \cdot \frac{d_{s,j}}{v_w} + \varepsilon_{n,w} \quad (14)$$

$$IM_{s,j}^{n,pb} = \alpha_n \cdot \frac{d_{s,j}}{v_{pb}} + \frac{C_{pb}^{day}}{f_n} + \varepsilon_{n,w} \quad (15)$$

where v_w is the velocity of walking, v_{pb} is the velocity of private-bike cycling, and $d_{s,j}$ is the travel distance between bus stop s and location j . $\varepsilon_{n,m}$ is assumed to have a Gumbel distribution, identically and independently across travellers and travel modes. In this case, $IM_{s,j}^n$ is known as the “logsum” [61]: $IM_{s,j}^n = \frac{1}{\mu} \cdot \ln \sum_{m \in M} \exp(-\mu \cdot V_{n,m})$, where μ is a scale parameter of the distribution of $\varepsilon_{n,m}$, and because $V_{n,m}$ is disutility, therefore it is $(-\mu \cdot V_{n,m})$ instead of $(\mu \cdot V_{n,m})$. The variation of this distribution is $\pi^2 / 6\mu^2$, and $\lim_{\mu \rightarrow +\infty} var(\varepsilon_{n,m}) = 0$ equals the situation without the random term.

According to Equations (8), (14), and (15), the mapping relationship between RC_s^n and IM_c^n is derived. In Scenarios 1 and 2, there is only one alternative in the choice set, resulting in the term $E\left(\min_m \left(IM_{s,j}^{n,m}\right)\right)$ being equal to the deterministic part of travel impedance $V_{s,j}^{n,m}$, so the corresponding catchment radius has nothing to do with the random term. However, in Scenario 3, there is more than one alternative, the corresponding catchment area related to the distribution of the random term, as shown in Equations (18) and (19). When considering the random term (Equation (18)), the catchment radius is a differentiable and monotonically increasing function of the utility-based threshold. However, when ignoring the random term (Equation (19)), the catchment radius is a piecewise linear function of the utility-based threshold, and it is continuous but not differentiable at the dividing point.

In Scenario 1:

$$RC_s^n = \frac{IM_c^n \cdot v_w}{\alpha_n}. \quad (16)$$

In Scenario 2:

$$RC_s^n = \begin{cases} 0, & \text{if } IM_c^n \leq \frac{C_{pb}^{day}}{f_n} \\ \frac{\left(IM_c^n - \frac{C_{pb}^{day}}{f_n} \right) \cdot v_{pb}}{\alpha_n}, & \text{if } IM_c^n > \frac{C_{pb}^{day}}{f_n} \end{cases} \quad (17)$$

In Scenario 3:

$$RC_s^n = \arg_{d_{s,j}} \left(\frac{1}{\mu} \cdot \ln \left(\exp(-\mu \cdot V_{n,w}) + \exp(-\mu \cdot V_{n,pb}) \right) \right) = -IM_c^n \quad (18)$$

$$\lim_{\mu \rightarrow +\infty} RC_s^n = \begin{cases} \frac{IM_c^n \cdot v_w}{\alpha_n}, & \text{if } IM_c^n \leq \frac{C_{pb}^{day} \cdot v_{pb}}{f_n \cdot (v_{pb} - v_w)} \\ \frac{\left(IM_c^n - \frac{C_{pb}^{day}}{f_n} \right) \cdot v_{pb}}{\alpha_n}, & \text{if } IM_c^n > \frac{C_{pb}^{day} \cdot v_{pb}}{f_n \cdot (v_{pb} - v_w)} \end{cases} \quad (19)$$

4.1.2. Role of Value of Travel Time

The express role of α_n is to convert travel time to an economic measure in the disutility function. According to the mapping relationship between the catchment radius RC_s^n and the travel impedance IM_c^n (Equations (16)–(18)), the role of the value of travel time is to reduce the marginal effect of catchment radius that increases with the threshold IM_c^n . The traveller with a large value of travel time has a small marginal catchment radius, and vice versa. As shown in Figure 4, the catchment radius curves with different values of travel time are of different gradients in all scenarios.

Figure 4. Cont.

Figure 4. Effect of the value of travel time on catchment radius. Scenario 1 (a), scenario 2 (b) and scenario 3 (c).

Figure 4c shows that as μ increases, the catchment radius curve becomes closer and closer to the curve of ignoring the random term. Under the utility-based threshold in the range of $[0, 5]$, there is a significant gap between the catchment radius with $\mu = 1$ and that ignoring the random term. The gap between the catchment radius with $\mu = 10$ and that of ignoring the random term is quite small, and it only exists near the dividing point.

4.1.3. Role of Bike Usage Frequency

The role of f_n is to allocate the purchase cost and maintenance cost of a private bike to all trips of this bike. According to Equations (17) and (19), f_n determines the dividing point of IM_c^n of the piecewise functions. A large f_n corresponds to a dividing position with a small IM_c^n value in Scenarios 2 and 3, and vice versa. Figure 5 illustrates that RM_c^n curves have different dividing locations of IM_c^n , but they have the same gradient because f_n is unrelated to the marginal RC_s^n . In Figure 5c, the effect of μ is the same as that in the analysis of Section 4.1.2.

4.2. Dataset

The considered traveller attributes include bike usage frequency and VOT. This section specifies the attribute distributions within the considered area in 2015. The smart card data were used to specify the distribution of transit-trip frequency for each traveller, and the income data released by Beijing Municipal Bureau Statistic were used to estimate the distribution of VOT.

Figure 5. Effect of bike usage frequency on catchment radius. Scenario 1 (a), scenario 2 (b) and scenario 3 (c).

4.2.1. Bike Usage Frequency

It was assumed that a private bike used to feed transit was used by only one person, the feeding trips accounted for 80% of all its trips, and a feeder bike can only serve a group of transit stops within a certain distance (set to be 0.5 km). Private-bike usage frequency of the traveller n at their stop-group g (denoted as $f_{n,g}$) equalled $1.25 \cdot f'_{n,g}$, where $f'_{n,g}$ denotes the bus trip frequency of traveller n at the stop-group g (referred to as “bus trip frequency” for short). Besides, there were no bike racks on transit vehicles in Beijing.

The $f'_{n,g}$ was calculated according to the smart card data of bus transit collected in October 2015 from Beijing Public Transit (the operator of all buses in Beijing). Passengers

tap the smart card when boarding and alighting the bus. The smart card system recorded the card ID, boarding time, boarding stop, alighting time, alighting stop, and bus line of each trip. The collected data included 5,379,827 cardholders, whose origin or destination stops were within the considered area. There were 22,056,515 valid trips within five workdays. The $f'_{n,g}$ was calculated with the procedure as shown in Figure 6, and Figure 7b plots its distribution. Due to the possibility of fare evasion and using the farebox instead of tapping a smart card, using the smart card records may underestimate the bus trip frequency to a certain degree [63].

Figure 6. Procedure of calculating bus trip frequency.

Figure 7. Distribution of bus trip frequency within the 5th Ring Road of Beijing in 2015: considered area and bus stops (a) and distribution of bus trip frequency (b).

4.2.2. Value of Travel Time

VOT is a key indicator of willingness to pay for travel time, which considers the implicit trade-off between time and money, and it can be obtained from revealed preference data and stated preference data [64–67]. VOT varies with traveller income, travel mode, and travel purpose [68–70]. There is no standard method to determine the VOT, which is generally 20–200% of the income [66,67,71]. This paper set the VOT equal to traveller income.

The distribution of resident income was estimated using data released by Beijing Municipal Bureau Statistic. The released detailed-distribution data closest to 2015 were of 2017, therefore the distribution of income in 2015 was estimated by using the distribution data of 2017 (Figure 8a) and the income increase rate from 2015 to 2017 (Table 3). The estimation assumed that people with the same income level had the same income increase rate. The average income of urban residents in Beijing in 2015 was 25.3 RMB/h, and the estimated distribution in 2015 is shown in Figure 8b. The income distribution was skewed, and the percentage of people with income below the average was 67.7%.

Figure 8. Distribution of per capita disposable income of urban residents in Beijing: (a) 2017 and (b) 2015 (data source for 2017 (a): [73]).

Table 3. Per capita disposable income of residents of Beijing (by income level) [72].

Group	Annual (RMB)		Hourly (RMB)		Increase Rate
	2015	2017	2015	2017	
Low income (20%)	18,343	22,170	8.78	10.62	0.2086
Medium-low income (20%)	32,968	38,452	15.79	18.42	0.1663
Medium income (20%)	45,239	53,023	21.67	25.39	0.1721
Medium-high income (20%)	60,627	71,451	29.04	34.22	0.1785
High income (20%)	99,621	116,018	47.71	55.56	0.1646
Average	48,458	57,230	23.21	27.41	—

Assuming that the bus trip frequency and the value of travel time are independent, the joint distribution of these two attributions $(\alpha_n, f'_{n,g})$ is illustrated in Figure 9.

Figure 9. Distributions of travellers (a) and bus trips (b) in Beijing.

4.3. Parameter Setup

However, in reality, travel time is affected by the quality of roads, the road slope, the age of the traveller, and many other factors [74,75]; due to the lack of data about these factors, the average walking speed (4 km/h) [76] and the average cycling speed (9 km/h) [77] were used as velocities of walking and cycling in the case study. According to the detailed structure of the cost of owning a private bike (Table 4), the parameter $C_{pb}^{day} = 0.712$ RMB/day.

Table 4. Cost structure of owning a private bike (adapted from Song et al. [62]).

Length of Use (5 Years)	Cost of Ownership	
	Maintenance Cost (RMB)	Purchase Cost (RMB)
1st year	60	600
2nd year	120	
3rd year	145	
4th year	175	
5th year	200	
Sum (RMB)	1300	

The setting of a utility-based threshold is flexible. In the numerical experiment, two types of thresholds were set: IM_{c1}^n (threshold I) and IM_{c2}^n (threshold II). IM_{c1}^n is the travel impedance of walking 400 m for traveller n : $IM_{c1}^n = 0.1 \cdot \alpha_n$. It was selected as a type of threshold because the catchment area of 400 m from the transit stop is the most widely recognised value in studies. Under threshold I, the boundary of catchment areas varies with travellers, but these boundaries have the same walking effort for all travellers. On the other hand, IM_{c2}^n is set to be a constant threshold, 2.5 RMB for all travellers. The value of 2.5 RMB was chosen because it is the average travel impedance of walking 400 m for travellers within the considered area where the average income is 25.3 RMB/h. The boundary of the catchment area varies with travellers, but these boundaries have the same travel impedance, 2.5 RMB.

The scale parameter μ of $\varepsilon_{n,m}$ was set to be 2, and the corresponding standard deviation was 0.6413, which is equal to the expected travel impedance of 85 m walking for a traveller with a value of travel time of 30 RMB/h. Besides, the situation where the random term is ignored ($\mu \rightarrow +\infty$) was also considered.

As discussed in Section 3.2 P_c is used to determine the catchment area of a traveller group at a transit stop. The experiment set nine P_c values ranging from 10% to 90% to study the influence of P_c on the results.

5. Results

This section presents the results of the numerical experiment in four parts. Sections 5.1 and 5.2 show the individual catchment radius under two thresholds (determined by the lower level of the ATSMFM model). Section 5.3 introduces how the threshold impacts results. Section 5.4 shows the results of the group catchment radius and ATS under two thresholds (determined by the upper level of the ATSMFM model).

5.1. Individual Catchment Radius with Threshold I

Table 5 shows the results of the individual catchment radius. The individual catchment radius with threshold I was the same (400 m) for all travellers in Scenario 1, which is the same as the commonly used catchment radius in existing studies. Therefore, the result of Scenario 1 with the threshold I works as the benchmark. As shown in Figure 10a, the individual catchment radius in Scenario 2 increased along with the value of travel time and the bus trip frequency. There were 48.27% of travellers with the individual catchment radius being zero, because for these travellers, the cost of owning a private bike alone made the travel impedance exceed threshold I.

Table 5. Results of the individual catchment radius.

Scenario	Threshold I			Threshold II		
	RC_s^n	Traveller Ratio	Bus Trip Ratio	RC_s^n	Traveller Ratio	Bus Trip Ratio
1	400 m	100%	100%	>0	100%	100%
2	$\leq RC_s^{n,w}$	73.87%	50.67%	$\leq RC_s^{n,w}$	73.99%	45.19%
	$> RC_s^{n,w}$	26.13%	49.33%	$> RC_s^{n,w}$	26.01%	54.81%
3	$\mu \rightarrow +\infty$	$= RC_s^{n,w}$	73.87%	$= RC_s^{n,w}$	73.99%	45.19%
		$= RC_s^{n,pb}$	26.13%	$= RC_s^{n,pb}$	26.01%	54.81%
	$\mu = 2$	$= RC_s^{n,w}$	66.10%	$= RC_s^{n,w}$	67.01%	41.29%
		$= RC_s^{n,pb}$	33.90%	$= RC_s^{n,pb}$	32.99%	58.71%

Note: $RC_s^{n,w}$ is the individual catchment radius at transit stop s with walking. $RC_s^{n,pb}$ is the individual catchment radius at transit stop s with private-bike cycling.

Figure 10b,c compare the results of Scenarios 1 and 2. Figure 10b shows that for travellers above the solid black line, the individual catchment radius with walking was 0 to 400 m lower than that with cycling. On the other hand, Figure 10c shows that for travellers below the solid black line, the individual catchment radius with private-bike cycling was 0 to 400 m lower than that with walking. Given the distribution of traveller attributes, 26.13% of travellers in Scenario 1 had a smaller catchment radius than in Scenario 2 (Figure 10d), and the bus trips of these travellers accounted for 49.33% of the total bus trips (Figure 10e). On the other hand, there were 73.87% of travellers in Scenario 2 having an underestimated catchment area (Figure 10d), and their bus trips accounted for 50.67% of the total bus trips (Figure 10e).

Scenario 3 considers both walking and private-bike cycling, as shown in Figure 10f,g. When ignoring the random term in travel impedance ($\mu \rightarrow +\infty$), the individual catchment radius was 400 m for travellers below the solid black line, the same as that of walking. On the other hand, the individual catchment radius was bigger than 400 m for travellers above the solid black line, the same as the individual catchment radius of private-bike cycling. This solid black line is the dividing line between the feeder modes used to calculate the catchment radius. The ATSMFM model can automatically adjust the feeder mode according to the traveller attributes. As shown in Figure 10g, when considering the random term in travel impedance ($\mu = 2$), there was not a dividing line for mode choice, and the catchment

radius is bigger than that with $\mu \rightarrow +\infty$. As the variation of the random term decreases (the value of μ increases), the catchment radius is closer to that with $\mu \rightarrow +\infty$.

(a)

(b)

(c)

(d)

(e)

Figure 10. Cont.

Figure 10. Individual catchment radius with threshold I: (a) individual catchment radius in Scenario 2, (b) underestimation in Scenario 1, (c) underestimation in Scenario 2, (d) travellers with underestimated catchment radius, (e) trips corresponding to (d), (f) individual catchment radius in Scenario 3 with $\mu \rightarrow +\infty$, (g) individual catchment radius in Scenario 3 with $\mu = 2$.

5.2. Individual Catchment Radius with Threshold II

The individual catchment radius with threshold II varied with travellers in all three scenarios, as shown in Figure 11. In Scenario 1 (Figure 11a), the individual catchment radius decreased as the value of travel time increased, and had nothing to do with the bus trip frequency. This is because the travel impedance with walking had nothing to do with the bus trip frequency. In Scenario 2 (Figure 11b), for travellers with a bus trip frequency less than 0.23 trips per day, the individual catchment radius was equal to zero, because threshold II was less than the cost of owning a private bike for these travellers. For travellers whose bus trips frequency were greater than 0.23 trips per day, the individual catchment radius varied with traveller attributes. Figure 11c,d show the catchment radius in Scenario 3. When $\mu \rightarrow +\infty$, the catchment area of multiple feeder modes is a simple integration of the catchment radius of a single feeder mode. However, as shown in Figure 11d, when μ is finite, the integration becomes complicated, and the catchment radius may be different from that of both Scenarios 1 and 2.

Figure 12a,b compare the results of Scenario 1 and 2. Figure 12a shows that for travellers with bus trip frequency higher than 0.41, the individual catchment radius with walking was 0 to more than 1000 m lower than that with private-bike cycling. On the other hand, Figure 12b shows that for travellers with bus trip frequency less than 0.41, the individual catchment radius with private-bike cycling was 0 to more than 1000 m lower than that with walking. Given the distribution of traveller attributes, 26.01% of travellers in Scenario 1 had a smaller individual catchment radius than in Scenario 2 (Figure 12c), and the bus trips of these travellers accounted for 54.81% of the total bus trips (Figure 12d). On the other hand, there were 73.99% of travellers in Scenario 2 having smaller individual catchment radiuses than in Scenario 1 (Figure 12c), and their bus trips accounted for 45.19% of the total bus trips (Figure 12d).

Figure 11. Individual catchment radius with threshold II: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, $\mu \rightarrow +\infty$, (d) Scenario 3, $\mu = 2$.

Figure 12. Comparison of catchment radiuses with the threshold II: (a) underestimation in Scenario 1, (b) underestimation in Scenario 2, (c) travellers with underestimated catchment radius, (d) trips corresponding to (c).

Scenario 3 integrates Scenarios 1 and 2, as shown in Figure 10b. For travellers with a bus trip frequency less than 0.41 trips per day, the individual catchment radius was calculated based on walking, while for travellers with bus trip frequency greater than 0.41 trips per day, the individual catchment radius was calculated based on private-bike cycling.

5.3. Comparison of Individual Results under Two Thresholds

The results in Sections 5.1 and 5.2 show that with both thresholds I and II, the individual catchment radius was significantly affected by the type of feeder mode. In the scenarios with only a single feeder mode, the catchment radius of some travellers was underestimated compared with other feeder modes, so ATS with a single feeder mode cannot well reflect the ATS with multiple feeder modes.

However, under the two thresholds, the correlations between the individual catchment radius and traveller attributes are different, as shown in Table 6. The two threshold settings make the changing trends of individual catchment radius different from or opposite to each other, which leads to different changing trends of ATSMFM under the two thresholds. When applying this ATSMFM model, the threshold should be designed according to specific objectives, and the setting method is not limited to the two methods used in this paper.

Table 6. Relationship between the individual catchment radius and the traveller attributes.

Traveller Attributes	Scenario 1		Scenario 2		Scenario 3	
	Threshold I	Threshold II	Threshold I	Threshold II	Threshold I	Threshold II
Value of travel time	0	—	0+	—	0+	—
Bus trip frequency	0	0	0+	0+	0+	0+

Note: 0 indicates irrelevant; + indicates positively correlated; — indicates negatively correlated; 0+ indicates that it is irrelevant when the attribute value is small, and they are positively related when this attribute value is big.

5.4. Group Catchment Radius and ATS under Two Thresholds

Due to a lack of opportunity distribution data, this numerical experiment assumes that opportunities are distributed evenly in the considered area. In this way, the ATS_s is proportional to the size of the catchment area. Therefore, this experiment uses the size of the catchment area to represent the value of ATS_s (Table 7).

Table 7. ATS_s with different parameter settings.

P_c (%)	With Threshold I: IM_{c1}^n								With Threshold II: IM_{c2}^n							
	Scenario 1		Scenario 2		Scenario 3 $\mu \rightarrow +\infty$		Scenario 3 $\mu = 2$		Scenario 1		Scenario 2		Scenario 3 $\mu \rightarrow +\infty$		Scenario 3 $\mu = 2$	
	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s	$RC_s(m)(km^2)$	ATS_s
10	400	0.503	636	1.271	636	1.271	652	1.336	980	3.017	808	2.051	>1000	>3	>1000	>3
20	400	0.503	498	0.779	498	0.779	539	0.913	729	1.700	515	0.833	819	2.107	852	2.280
30	400	0.503	345	0.374	400	0.503	467	0.685	591	1.097	336	0.355	662	1.377	689	1.491
40	400	0.503	198	0.123	400	0.503	432	0.586	507	0.808	195	0.119	558	0.978	581	1.060
50	400	0.503	33	0.003	400	0.503	414	0.538	442	0.614	88	0.024	483	0.733	502	0.792
60	400	0.503	0	0	400	0.503	408	0.523	387	0.471	0	0	420	0.554	437	0.600
70	400	0.503	0	0	400	0.503	403	0.510	337	0.357	0	0	362	0.412	376	0.444
80	400	0.503	0	0	400	0.503	401	0.505	290	0.264	0	0	309	0.300	320	0.322
90	400	0.503	0	0	400	0.503	400	0.503	229	0.165	0	0	243	0.186	252	0.200

As shown in Table 7, with threshold I, the group catchment radius in Scenario 1 is 400 m under all the nine P_c values, because threshold I is defined as the travel impedance of walking 400 m, so all travellers have the same catchment radius herein.

The group catchment radius in Scenario 2 is zero for $P_c = 60 \sim 90\%$. This is because 48.27% of travellers with threshold I (travellers in the dark area in Figure 10a) and 41.44% of travellers with threshold II (in the dark area in Figure 11b) have a catchment radius equal to zero, so the group catchment radius remains equal to zero when $P_c > 51.73\%$ with threshold I and $P_c > 58.56\%$ with threshold II.

With $\mu \rightarrow +\infty$ and threshold I, the group catchment radius of Scenario 3 remains 400 m when $P_c > 26.13\%$. This is because 73.87% of travellers (travellers below the solid black line in Figure 10f) have a catchment radius equal to 400 m. The ATS_s of Scenario 3 equals the corresponding ATS_s in Scenario 1 when $P_c > 26.18\%$, and equals the corresponding ATS_s in Scenario 2 when $P_c < 26.18\%$.

However, with threshold II, the ATS_s in Scenario 3 is always bigger than the ATS_s in Scenario 1 and the ATS_s in Scenario 2. The ATS with multiple feeder modes is not just a simple splicing combination of ATS with different feeder modes, but an integration: the ATS with multiple feeder modes may be different from all the ATS with a single feeder mode.

The comparison of ATS_s under the two thresholds in Scenario 3 is meaningless because their threshold settings emphasise different aspects. Threshold I emphasises the coverage of walking effort, and threshold II emphasises the coverage of economic cost.

6. Discussion

The results of the numerical experiment (Section 5) illustrate that this model can consider the heterogeneity of travellers and feeder modes in ATS, and its utility-based threshold can be adapted to support city managers with different goals. Besides, the ATSMFM model can calculate the ATS both for the individual and the group, making ATS more informative and directly related to the specific population served by the transit stop. There are three main limitations of this proposed model.

Firstly, this model is generalised. This paper does not provide a detailed description of how to construct all possible feeder modes in this model, because this paper focuses on the methodology. Possible feeder modes may include car driving, bus riding, electric-bike cycling, private-regular-bike cycling, shared-bike cycling, walking, etc. It is necessary to design the set of alternative feeder modes according to the actual situation and ensure that the model can distinguish these modes. The numerical experiment herein only regards private-bike cycling and walking. Future research could consider the modelling of other possible feeder modes, such as incorporating shared-bike cycling into the set of alternative feeder modes.

Secondly, the numerical experiment proposes two threshold settings. Future studies can explore other threshold settings to suit more scenarios and purposes.

Thirdly, though the ATSMFM model can provide a more comprehensive ATS, the calculation of ATS with this model is based on certain data, and the calculation process is more complicated than that of ATS with fixed travel time or distance of catchment radius (for example, 400 m). In the future, the calculation process can be modularised to unify input and output, making the model easier to apply.

7. Conclusions

ATS is a critical index for the evaluation of transit service, focusing on the first/last mile portion of transit trips. Studies have proven that the ATS is significantly affected by feeder modes and traveller attributes, but there are few studies integrating walking and cycling and considering traveller attributes in the evaluation of ATS. This study proposed a model of ATS with multiple feeder modes (ATSMFM), capable of integrating multiple feeder modes and considering the heterogeneity of travellers. The ATSMFM model can support city managers to formulate relative plans according to a complex feeder-mode environment and traveller attributes, which is consistent with people-oriented transportation planning.

A numerical study in Beijing was conducted to demonstrate the applicability of this ATSMFM model and clarified the process of the model in automatically adjusting the feeder

mode according to the traveller attributes. Three scenarios of alternative feeder modes were set: Scenario 1, only walking; Scenario 2, only a private bike; and Scenario 3, both walking and a private bike. There are three main conclusions. Firstly, the results of Scenarios 1 and 2 showed the heterogeneity of catchment radiuses of travellers. The comparison between Scenarios 1 and 2 showed that the individual catchment radius varied significantly with different feeder modes. For some travellers, the difference of the individual catchment radius in Scenario 1 and 2 could reach more than 400 m, which is a great distance in the concept of the bus stop catchment area. Secondly, in the scenarios with only a single feeder mode, the catchment radius of some travellers was underestimated and cannot reflect the value in the real situation with multiple feeder modes. About 26% of travellers in Scenario 1 and about 74% of travellers in Scenario 2 had an underestimated individual catchment radius. Thirdly, the ATS with multiple feeder modes was not just a simple splicing combination of ATSs with different feeder modes, but an integration: the ATS with multiple feeder modes may be different from all the ATSs with a single feeder mode. For example, under threshold II, ATS_s with two feeder modes $> ATS_s$ with walking $> ATS_s$ with private-bike cycling.

The threshold had a great influence on the results of the ATSMFM model. The two tested thresholds (IM_{c1}^n and IM_{c2}^n) not only led to different ATS values, but also changed trends of the ATS, or even made the values opposite to each other. When applying this ATSMFM model, the threshold should be designed according to specific objectives, and the setting method is not limited to the two methods used in this paper.

The proposed model is generalised, and it is necessary to design the set of alternative feeder modes according to the actual situation (the city's traffic environment and the traveller attributes) and ensure that the model can distinguish these modes. Due to a lack of opportunity distribution data, this paper did not show the spatial distribution of ATS_s in Beijing. In addition, to clearly discuss the mechanism of this model, the numerical study only considered private-bike cycling and walking, and did not include shared-bike cycling. Including bike-sharing into the set of alternative feeder modes would require additional considerations, such as the availability of shared bicycles. Future studies can expand the set of alternative feeder modes to include shared-bike cycling.

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Appendix A

Table A1. Description of symbols and abbreviations.

Symbols	Explanation
ATS	Accessibility of transit stops
$ATSMFM$	Accessibility of transit stops with multiple feeder modes
ATS_s	Number of opportunities within the catchment area of stop s for the group
ATS_s^n	Value of ATS for the individual n at the transit stop s
α_n	Value of travel time (VOT) of individual n
$B_{s,j}$	A dummy variable regarding the comparison between $d_{s,j}$ and RC_s
$B_{s,j}^n$	A dummy variable regarding the comparison between $d_{s,j}$ and RC_s^n
β_n	Corresponding vector of coefficients for $X_{s,j}^m$
C_{pb}^{day}	Cost of owning a private bike for one day considering the purchase cost, maintenance cost, and lifespan of a bike
$d_{s,j}$	Travel distance between transit stop s and location j
f_n	Number of trips by private-bike cycling per day
$f_{n,g}$	Private-bike usage frequency of the traveller n at their stop-group g
$f_{n,g}$	Bus trip frequency of traveller n at the stop-group g (“bus trip frequency” for short)
IM_c^n	Utility-based threshold of the catchment area of traveller n
IM_{c1}^n	Utility-based threshold I: the travel impedance of walking 400 m for traveller n
IM_{c2}^n	Utility-based threshold II: a constant threshold, 2.5 RMB for all travellers
$IM_{s,j}^n$	Minimum travel impedance considering all alternative modes from s to j
$IM_{s,j}^{n,m}$	Travel impedance between zone j and stop s for individual n with travel mode m
$IM_{s,j}^{n,pb}$	Travel impedance between zone j and stop s for individual n by private-bike cycling
$IM_{s,j}^{n,w}$	Travel impedance between zone j and stop s for individual n by walking
j	Indicator of a location
J	Set of locations near the transit stop s
m	Indicator of a feeder mode
M	Set of alternative feeder modes for transit
n	Indicator of a traveller
N	Set of traveller group
Op_j	Number of opportunities (jobs or activities) in zone j
pb	Feeder mode: private-bike cycling
P_c	Property threshold to define the boundary of the group catchment area
RC	A variable of catchment radius
RC_s	Group catchment radius
RC_s^n	Individual catchment radius at stop s for individual n
$TC_{s,j}^{n,m}$	Travel cost between stop s and location j for traveller n with mode m
$TC_{s,j}^{n,pb}$	Travel cost of using an available private bike for one trip for traveller n
$TT_{s,j}^{n,m}$	Travel time between stop s and location j for traveller n with mode m
VOT	Value of travel time
v_w	Velocity of walking
v_{pb}	Velocity of private-bike cycling
w	Feeder mode: walking
$X_{s,j}^{n,m}$	A vector of variables (such as travel time, travel distance, travel cost, comfort, etc.) affecting travel impedance of the trip between s and j with mode m

Appendix B

The travel impedance is considered to be the disutility obtained by the traveller, and it can be defined as a representative disutility: for certain objectives, Equation (10) can ignore the random term.

In the theory of random utility maximisation [78], the usual form of random disutility is the sum of a representative term (a non-random term reflecting the representative disutility) and a random term (reflecting the idiosyncratic effect of unobserved variables during each choice occasion) [79,80]. The random utility is mostly used in the choice theory to analyse or predict the choice behaviour of consumers or travellers [79]. Compared with

the result based on utility with only the representative term, the result based on the theory of random utility maximisation can better fit the choice of consumers or travellers.

However, different from the analysis of choice behaviour, the ATS is used for city managers, not needing to know the exact ATS of a single traveller. The objective of ATS is to support city managers to know the ATS for each kind of travellers with similar attributes and a group of travellers with different attributes, so they can make decisions according to the specific attributes of travellers within the considered area. We think that the purpose of ATS is to know what level of service people can access, not whether they ultimately choose this service. When there are several alternatives in calculating the level of service, the alternative that maximises the interested utility will be chosen to calculate the level of service. Therefore, the representative term can satisfy the requirement.

Secondly, representative disutility has an advantage in computation. The disutility with a random term will make the computation complex. Computation of the choice based on the representative disutility follows the principle of disutility minimisation to make a representative choice for each type of travellers, and it is easier than that with a random term. Although the logit-based logsum has been derived with a form which is easy to use, it is under the IIA (Independence of Irrelevant Alternatives) limitation [61]. When some alternatives are related, for example, when considering both private bicycles and shared bicycles, the logsum based on the nested logit model should be used.

Thirdly, only considering the representative term makes the proposed model more applicable. With a random term included in the disutility, detailed survey data are needed to estimate the parameters of the choice model, and the disutility is a relative value [24], making the physical meaning ambiguous. In contrast, only considering the representative term in the disutility has two advantages: (i) the disutility has a clear physical meaning, and city managers can set the physical meaning according to their objectives, for example, the disutility can be set to be the generalised cost; and (ii) the input data on traveller attributes can be coarse-grained or fine-grained. However, there is a disadvantage: the coefficient vector β_n should be defined by experts.

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