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Measuring Reliable Accessibility to High-Speed Railway Stations by Integrating the Utility-Based Model and Multimodal Space–Time Prism under Travel Time Uncertainty

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Abstract: Measuring the accessibility of each traffic zone to high-speed railway stations can evaluate the ease of the transportation hub in the transportation system. The utility-based model, which captures individual travel behavior and subjective perception, is often used to quantify the travel impedance on accessibility for a given origin–destination pair. However, existing studies neglect the impacts of travel time uncertainty on utility and possible choice set when measuring accessibility, especially in high-timeliness travel (e.g., railway stations or airports). This study proposes a novel integration of the utility-based model and multimodal space–time prism under travel time uncertainty to measure reliable accessibility to high-speed railway stations. First, the reliable multimodal space–time prism is developed to generate a reliable travel mode choice set constrained by travel time budgets. Then, the reliable choice set is integrated into the utility-based model with the utility function derived from a proposed mean–standard deviation logit-based mode choice model. Finally, this study contributes to measuring reliable accessibility within areas from Beijing’s 5th Ring Road to the Beijing South Railway Station. Based on the results, policymakers can effectively evaluate the distribution of transportation resources and urban planning.

Keywords: urban transportation; reliable accessibility; utility-based model; multimodal space–time prism; travel time uncertainty



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1. Introduction

Accessibility is usually defined as the ease among travelers of achieving their travel needs through transportation systems [1–4], such as food, health, employment, education, and so on [5,6]. Measuring accessibility could not only assist in evaluating urban services but also in analyzing some of the issues (e.g., travel equity, reliability, and justice) presented in current urban planning [6–12]. Moreover, an accessible transportation network would significantly improve the livability and welfare of people [13–17].

With the development of high-speed railways and increasing intercity travel demand, high-speed railways have become one of the most popular ways of long-distance travel. The essence of accessibility to high-speed railway stations is based on measuring the ease of travel for a given origin–destination (OD) pair. The accessibility from each traffic zone to a high-speed railway station is not only related to the location of the high-speed railway station but also to the structure of the road network and the distribution of traffic zones. For example, the accessibility of a traffic zone that is closer in physical distance to a high-speed railway station but has no suitable routes may be lower than that of a zone farther from the high-speed rail station. Due to the fixed train departure times and many cities only having one high-speed railway station, travel to the high-speed railway station has a high level of timeliness. However, the dynamic traffic condition causes uncertainty in travel time, which highlights the necessity of measuring reliable accessibility to high-speed railway stations.

Travel time in the road network fluctuates across different hours of the day, and individual travel activity is significantly affected by travel time uncertainty [18,19]. During peak hours, travel times are longer due to road congestion compared to off-peak hours. Moreover, special events or incidents can lead to heavy congestion, resulting in a significantly increased travel time and decreased accessibility. In addition, travel time uncertainty varies across different travel modes. For instance, metro systems operate with relatively stable travel times throughout the day as they are not constrained by road conditions. Travel time uncertainty can also impact the individual perception of the travel experience which is related to accessibility. Studies have found that travel time uncertainty is the principal factor for individuals' travel scheduling [20] and a 1-minute change in the standard deviation of travel times is equivalent to a 2-minute change in mean travel times [21]. Therefore, travel time uncertainty highly impacts accessibility and it is crucial to measure reliable accessibility considering travel time uncertainty.

With travel time uncertainty, individuals tend to avoid being late [18,22] and reserve extra safety time to arrive on time [23]. For this situation, Chen et al. [24] developed a reliable space–time prism (STP) to consider travel time uncertainty in measuring accessibility. However, this method failed to reflect the impact of actual travel behaviors on accessibility. Considering the impact of individual travel behavior on accessibility, researchers built the utility-based accessibility model [25]. The utility-based accessibility model can better capture individual travel behavior and their perception of space–time constraints in the transportation network [26]. However, most of the utility-based measures ignore both the impact of spatiotemporal constraints and travel time uncertainty on utility, resulting in some degree of error. Given the importance of timeliness in high-speed railway stations, an approach that considers travel time uncertainty is needed. This study takes Beijing South Railway Station as a case study and proposes an integrated method to measure reliable accessibility.

This study aims to contribute to the existing studies by exploring the following specific aspects:

- (1) A reliable accessibility measure is proposed by integrating a mean–standard deviation utility-based model and multimodal reliable space–time prism under travel time uncertainty, where mode choices are constrained by space and uncertain travel time.
- (2) A multimodal reliable space–time prism is proposed by considering the differences in travel time reliability among travel modes, where the impacts of individual risk attitude on travel time budgets are considered to build a possible mode choice set.
- (3) The proposed reliable accessibility measuring model is specified in Beijing to evaluate the reliable accessibility of each sub-district to Beijing South Railway Station under travel time uncertainty in a multimodal network.

The next section of this article provides a literature review of the existing accessibility measures. Section 3 introduces the methodology adopted in this study. Section 4 introduces the data and model specification as well as policy implications. Section 5 summarizes this study and puts forward prospects for future research.

2. Literature Review

Unlike the previous location-based accessibility model, this study focuses on exploring the travel impedance for a given OD pair to measure accessibility. In previous studies, travel time was recognized as one of the key factors in calculating travel impedance [7,27,28]. Due to the lack of detailed travel information, these studies calculated travel impedance based on the average road speed, which causes bias in measuring reliable accessibility [29,30]. Moreover, they made simple assumptions about transfer waiting time and ignored the correlation between different travel modes [30–32]. The uncertainty of spatiotemporal constraints, which significantly affects travel time and travel cost for OD pairs in road networks, has made the measurement of reliable accessibility more challenging.

The big data era makes it possible to accurately collect detailed and intricate travel information from multiple sources to calculate travel impedance. Travel impedance refers to

the resistance to travel in the traffic network, including travel time, route length, congestion level, and so on [33,34]. These data can record the whole process of travel, which includes travel time and waiting time with different routes and travel modes. Based on these data, a large number of studies adopt the schedule-based shortest path algorithm to calculate travel impedance for a given OD pair under various spatial–temporal constraints [35–39]. For example, Liao and van Wee [40] developed a family of accessibility models to evaluate the robustness of traffic networks by calculating the overlap of travel routes in a given OD pair under spatial–temporal constraints. Although their study provides a method to accurately calculate the travel impedance in an OD pair, they ignore the traveler’s behavior and subjective perception of the travel. The assumption that total travel time can represent travel impedance is limited in capturing individual perception. In reality, travel behavior and travel time budgets are not uniform among different travelers, which affects route choice and significantly impacts the perception of accessibility in OD pairs.

Weibull [41] provided a framework for deriving accessibility measurements that considered destination opportunities and travel impedance. However, the proposed framework lacked consideration of individual travel behavior. Accessibility measures should directly analyze the benefit of the individuals, either in utility or budgets. Utility-maximizing choice behavior is interpreted as individuals receiving the maximum benefits from the available choice set. Based on the individual’s location utility, the utility-based model was built [25]. Utility-based models have the advantage of capturing the random characteristics of individual preferences. For calculating travel impedance in a given OD pair, the utility-based model interprets accessibility as the outcome of a set of optional travel mode choices. Habib [42] developed the utility-based econometric model to analyze the factors that affect older people’s travel mode choices and travel distance demand. Nassir et al. [26] used the Nested Logit (NL) model with reasonable path options to evaluate public transit accessibility in OD pairs.

For specific destinations, which in most cities are often singular (e.g., high-speed railway stations or airports), the utility-based model can capture the travel behavior and the benefits of different travelers in reaching the destination through the transportation network. Harvey [43] was the first author to consider mode choice behavior in researching airport accessibility. He used the Multinomial Logit (MNL) model to analyze travelers’ travel behavior to the airport in the San Francisco Bay area. The results show that business travelers are more sensitive to the whole travel time, while the perception of travel cost is not much different between business travelers and non-business travelers. Alhussein [44] adopted the binary logit model to analyze mode choice for accessing King Khaled International Airport in Riyadh, and the results show that total travel time is more important in decision-making. Tam et al. [45] developed the MNL model to analyze the impact of travel time reliability on air travelers’ mode choice behavior and found that waiting time, travel time, and travel time reliability have a significant impact on travelers’ mode choice. It can be seen that for specific transportation hubs like airports, travelers pay more attention to travel time due to the timeliness of the travel.

In conclusion, existing studies neglect the impact of spatiotemporal constraints on individual travel mode choices in measuring accessibility. To fill this gap, this study proposes an integrated method to measure reliable accessibility to specific transportation hubs under travel time uncertainty. The findings from this study can be adopted by transportation planning departments and urban mobility policymakers to evaluate and improve transportation accessibility.

3. Methodology

In this section, we propose a method to integrate the multimodal STP and the utility-based model to measure reliable accessibility under travel time uncertainty. First, considering different individual risk attitudes, we develop a reliable multimodal STP to obtain the corresponding possible travel mode choice set for certain travel time budgets. Second, we construct a mean–standard deviation logit model to capture the perceived utility of

each travel mode and derive a log-sum function for accessibility measurement. Finally, the integration for measuring reliable accessibility is achieved by the above-mentioned log-sum function, constrained by the possible travel mode choice set generated by the reliable multimodal STP. Figure 1 shows the framework of this study, including data collection and model construction.

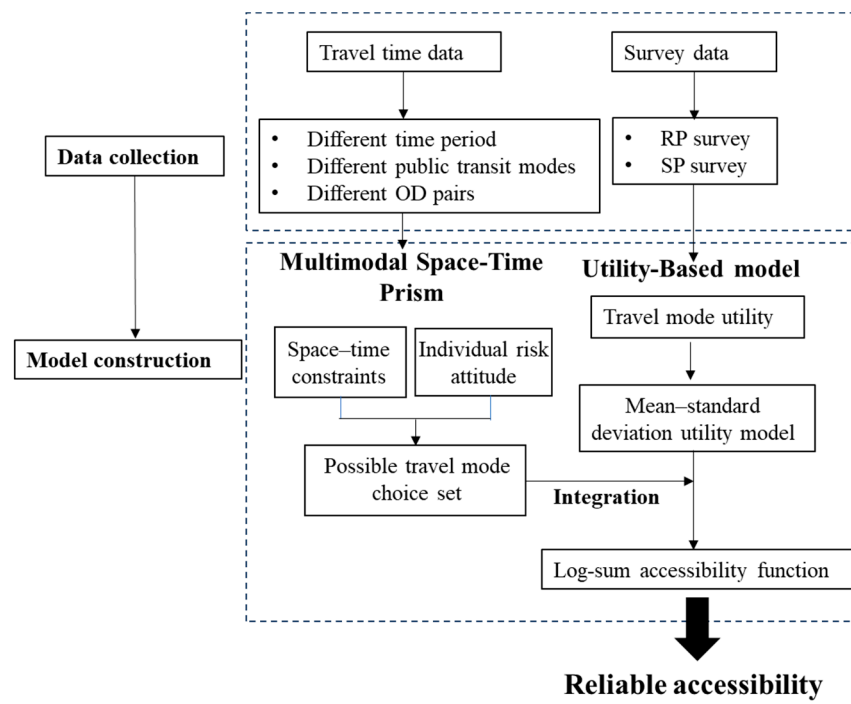


Figure 1. The framework of the model.

3.1. Reliable Multimodal Space–Time Prism

For various reasons, travel times of different travel modes have some uncertainties, leading to risky travel mode choices. Under these circumstances, it is imperative to take into account not just the mean travel time but also its standard deviation. Different travelers may have different attitudes toward the risk associated with the standard deviation of travel time. Travel time budgets [46] refer to a planned travel time that guarantees a certain probability of arriving at the destination on time. It is calculated as the mean travel time plus an additional margin. This margin is typically expressed as the product of a parameter and the standard deviation of travel time. This study uses individual risk attitudes to characterize the uncertainty of individual travel time. The travel time budget can be expressed as follows:

$$b_{ij} = \mu_{ij}^k + \lambda \sigma_{ij}^k \quad (1)$$

where μ_{ij}^k is the mean travel time under the travel mode k from location i to j , σ_{ij}^k is the standard deviation of travel time under the travel mode k from location i to j , and λ is a parameter indicating individual risk attitudes.

The individual risk attitude can be conceived as the parameter λ , which multiplies the standard deviation to represent the uncertainty travel time. For example, if travel time with the mode k conforms to a normal distribution $N(\mu_{ij}^k, \sigma_{ij}^k)$, $\lambda = 1.96$ corresponds to a 95% probability that the individual arrives at the destination on time. If the mean travel time is 20 min and the standard deviation is 5 min, the travel time budget is 29.8 min. This means that the individual will take 29.8 min to reach the destination with at least a 95% probability. It can be seen that with an increasing risk attitude, the travel time budgets are also increasing due to the requirement of higher reliability.

To explore the possible travel choice set, this study develops a reliable multimodal STP. The reliable multimodal STP can depict the range of activity under spatiotemporal constraints with different risk attitudes.

Figure 2 shows different reliable multimodal STPs under the risk attitudes of 5% and 95% for 60 min. It can be seen that the possible travel choice set changes with the individual risk attitude. For example, all of the taxi, subway, and bus options can arrive at the destination under a 5% risk attitude for a 60-minute travel time constraint. However, with the risk attitude increasing to 95%, only the subway can arrive at the destination, which changes the possible travel choice set.

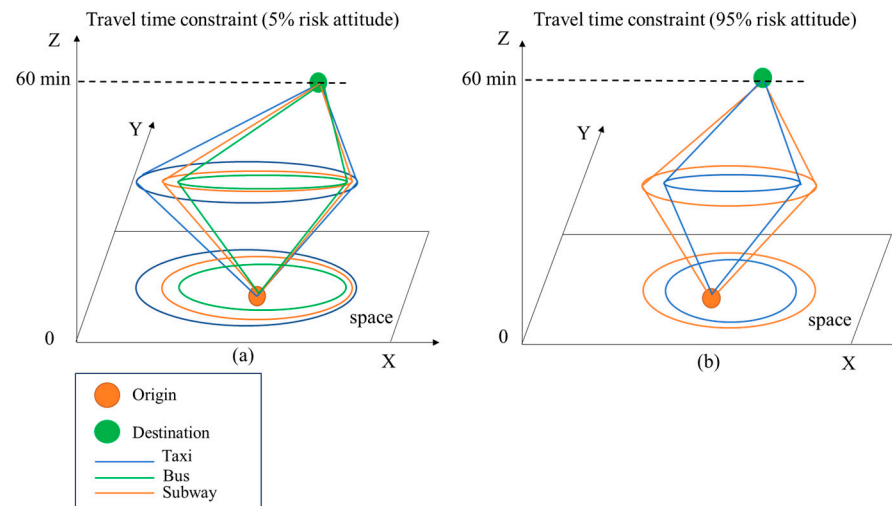


Figure 2. Multimodal STPs in a given OD pair. (a) STP under the risk attitude of 5%; (b) STP under the risk attitude of 95%.

Figure 3 shows the multimodal STP of the subway for 30 min and 60 min. It can be seen that the accessible range for the 60 min time constraint is much larger than that for 30 min.

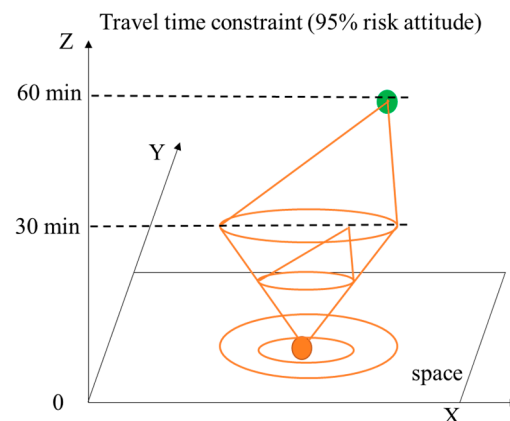


Figure 3. Multimodal STPs under the travel time constraint of 30 min and 60 min.

The analysis can be summarized according to the following two aspects:

1. With the same risk attitude, the travel time constraint impacts the possible travel choice set. For example, the taxi cannot arrive at the destination within 30 min with a 95% risk attitude. However, with the travel time constraint increasing to 60 min, the accessibility of the taxi also expands and can arrive at the destination on time.
2. With the same travel time constraint, the possible travel choice set varies as the risk attitude changes. For example, at a 5% risk attitude, the accessibility of the taxi is

higher than that of the subway. However, when the risk attitude changes to 95%, the accessibility of the taxi drastically decreases due to the high uncertainty in the road network and is lower than that of the subway. As risk attitude increases, the possible travel choice set may correspondingly decrease.

Due to the travel time uncertainty among different travel modes, the risk attitude has a significant impact on the possible travel choice sets and further affects reliable accessibility. Therefore, the reliable multimodal STP model is developed as a function of the travel time budget to determine the possible travel mode choice set under different risk attitudes. The function of the multimodal STP can be expressed as follows:

$$STP(t) = \left\{ k \in K \mid \mu_{ij}^k + \lambda \sigma_{ij}^k < t \right\} \quad (2)$$

where K is the whole travel choice set.

3.2. Utility-Based Model

To capture the individual travel behavior and perception of different modes' utility, the mean–standard deviation utility-based model is established for a given OD pair. According to random utility theory, the utility function that the traveler from the origin i to the destination j chooses for the travel mode k is as follows:

$$U_{ij}^k = V_{ij}^k + \varepsilon_{ij}^k \quad (3)$$

$$V_{ij}^k = \mu_{ij}^k \beta_1 + \sigma_{ij}^k \beta_2 + \sum_{n=3}^N X_n \beta_n \quad (4)$$

where ε_{ij}^k is the random error, X_n is the n th characteristic variable of travel mode k , and β_n is the corresponding coefficient.

With each utility of travel mode, the mean–standard deviation utility-based model can be expressed as the log-sum function to calculate the accessibility. The log-sum function is shown in Equation (5):

$$A_i = \ln \left(\sum_{k=1}^K e^{V_k} \right) \quad (5)$$

3.3. Integration Model

With the given travel time budgets, the possible travel mode choice set differs among individuals due to their varying risk attitudes, resulting in different accessibility levels in the same area. Utilizing the multimodal reliable STP for specified origin–destination pairs, a log-sum accessibility function constrained by the possible travel mode choice set is constructed to obtain reliable accessibility. This function can be expressed by Equation (6).

$$A_i = \ln \left(\sum_{k \in STP(t)} \exp[\mu_{ij}^k \beta_1 + \sigma_{ij}^k \beta_2 + \sum_{n=3}^N X_n \beta_n] \right) \quad (6)$$

4. Case Study

4.1. Study Area

This study measures the reliable accessibility of each sub-district from Beijing's 5th Ring Road to Beijing South Railway Station. The area in the 5th Ring Road is the core district of Beijing, and Beijing South Railway Station, a primary transportation hub, handles a significant portion of Beijing's intercity travel demand. The location of Beijing South Railway Station and the study area are shown in Figure 4.

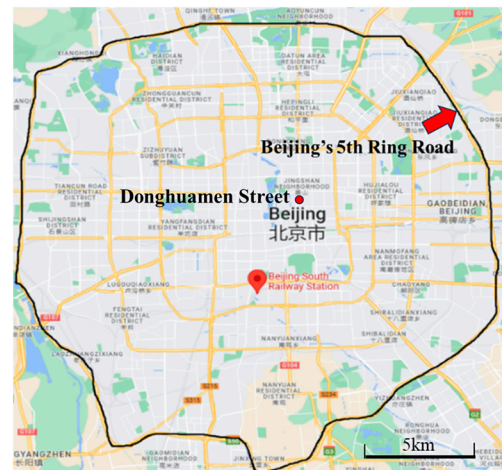


Figure 4. Study area and location of Beijing South Railway Station.

4.2. Data

The data in this study consist of three parts: travel time data from each sub-district to Beijing South Railway Station, Revealed Preference (RP) data, and Stated Preference (SP) data. The travel time data for each travel mode are obtained through Amap, a comprehensive mapping and navigation service developed by Alibaba Group. Amap provides detailed maps, real-time traffic information, route planning, and location-based services. Using Amap, we obtained a total of 48,816 travel time data points for 339 administrative districts over three days. In reality, there are various travel modes available for residents. For this study, public transit is chosen as the travel choice to explore reliable accessibility. Taking Donghuamen, which is marked in Figure 4, as an example, the travel time and distribution by taxi are shown in Figure 5.

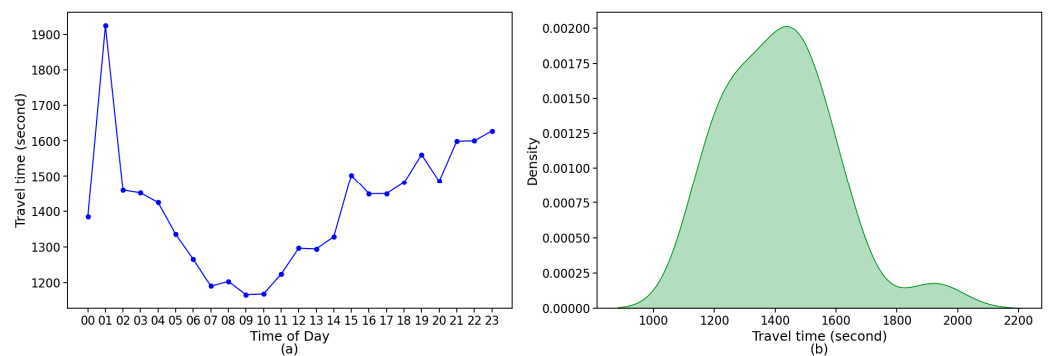


Figure 5. The statistical results of the collected travel time data. (a) The variation in travel time by taxi in a day from Donghuamen Street to Beijing South Railway Station. (b) Travel time distribution from Donghuamen Street to Beijing South Railway Station.

The travel time from Donghuamen Street to Beijing South Railway Station exhibits variability and tends to follow a normal distribution, primarily ranging from 20 to 30 min, with occasional instances exceeding this range. This suggests the need to consider daily travel time fluctuations and uncertainty in accessibility analysis.

In this study, the RP survey primarily collected respondents' basic personal information and details about a specific trip to Beijing South Railway Station. Basic personal information includes age, gender, education, income level, and occupation. Travel details include travel mode choice, travel time budgets, and the respondent's origin. The SP survey explores travelers' choice behavior in hypothetical scenarios, examining six key attributes: mean travel time, travel time variability (standard deviation), punctuality needs, travel

cost, comfort level, and the number of transfers. Respondents were asked to choose the travel modes that best fit their characteristics and preferences in these scenarios.

We used the Wenjuanxing platform to distribute the survey and obtained 280 valid questionnaires, resulting in a total of 1116 data points. Figure 6 shows the statistical results of the survey.

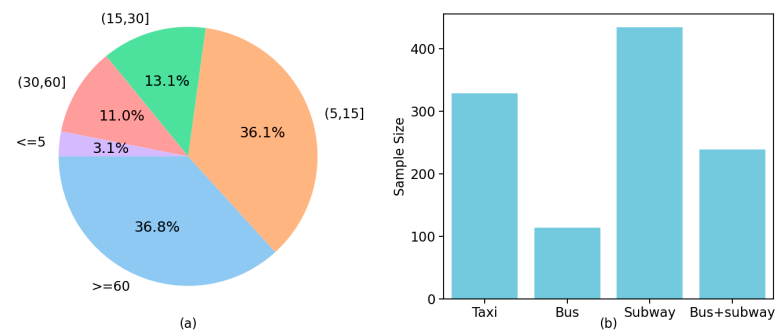


Figure 6. The statistical results of the survey data. (a) The proportion of travel time budgets. (b) The sample size of different public transit modes.

4.3. Estimation

The developed utility-based accessibility model employs maximum likelihood estimation for calibration. After multiple rounds of statistical testing, the combination of mean travel time (min), the standard deviation of travel time (min), and travel cost (CNY) shows the best predictive performance. Therefore, this study adopts these three variables to analyze travel choice behavior in this situation. The first two variables are calculated based on three days of travel time data obtained through Amap's Application Programming Interface (API), while the latter includes only the travel mode fares directly obtained through the API according to the mode choice and distance. To illustrate the impact of travel time uncertainty on individual choice behavior, this study compares a model that includes the standard deviation of travel time as a characteristic variable (M2 model) with one that does not (M1 model).

In Table 1, most estimates show a significant t-value higher than 1.96. The parameters for mean travel time, the standard deviation of travel time, and travel cost in both models are negative. Besides mean travel time, travelers demonstrate strong sensitivity to the standard deviation of travel time. Comparatively, the model considering travel time uncertainty has a higher Adjusted Rho-square, indicating that travel time uncertainty significantly impacts choice behavior.

Table 1. Comparison results for two models.

Variables	M1 (t-Value)	M2 (t-Value)
Subway constant	0.982 (5.06)	−0.084 (−4.46)
Bus constant	−0.352 (−1.78)	0.025 (1.88)
Bus and subway constant	−0.293 (2.75)	−0.454 (−3.73)
Mean travel time (min)	−0.542 (−0.39)	−0.124 (−3.13)
Travel cost (CNY)	−0.049 (−2.71)	−0.017 (−1.92)
The standard deviation of travel time (min)	-	−3.83 (−2.57)
Sample size	1116	1116
Log likelihood at zero	−883.107	−840.12
Log likelihood at convergence	−710.218	−607.78
Rho-square	0.285	0.370
Adjusted Rho-square	0.257	0.344

To test the prediction accuracy of the calibrated model, Table 2 compares the predicted mode vales with the actual values.

Table 2. A comparison of the predicted values and the actual values.

Travel Mode	Taxi	Subway	Bus	Bus and Subway
Predicted (%)	29.67	38.73	10.22	21.37
Actual (%)	29.48	38.89	10.22	21.42

It can be seen that the accuracy is higher than 95% in each travel mode, which indicates that the model can capture the traveler's mode choice and further analyze the accessibility.

4.4. Results

4.4.1. Accessibility Measurement at Different Reliability Levels

This case measures the reliable accessibility under the 30-minute travel time budget. Reliable accessibility can be defined as the likelihood that a traveler can reach their destination within a certain probability. This probability is derived from the travel time distribution, as explained in Section 3.1. Figure 7 illustrates the accessibility for each area at the 10%, 50%, and 90% reliability levels.

**Figure 7.** Accessibility at different reliability levels.

Ground transportation is often affected by changes in road capacity for the transportation network, leading to significant fluctuations in travel time. In contrast, underground transportation typically offers more stable travel times. At a 10% reliability level, accessibility is generally high in most areas, and travelers perceive travel time optimistically. This reliability level reflects optimal traffic conditions, where travel times are lower compared to other situations, but the associated risk is also higher. Accessibility at a 50% reliability level represents the normal operational condition of the road network. For this reliability level, accessibility is relatively high in the 2nd Ring Road and inside the South 4th Ring Road, but significantly reduced outside the North 4th Ring Road. Reduced accessibility in these areas indicates greater travel time uncertainty due to their distance from the destination. At a 90% reliability level, accessibility in most northern areas decreases significantly, suggesting that reliable accessibility is more distance-sensitive. In areas with high reliability, those far from the destination lack suitable travel modes to reach their destinations for the allocated travel time budgets.

4.4.2. Accessibility Measurement for Different Travel Time Budgets

In this case, we measure the accessibility with different travel time budgets. To make the change in the accessibility level more obvious, we choose the 90% reliability level in which many travel modes are possible for this study. The result is shown in Figure 8.

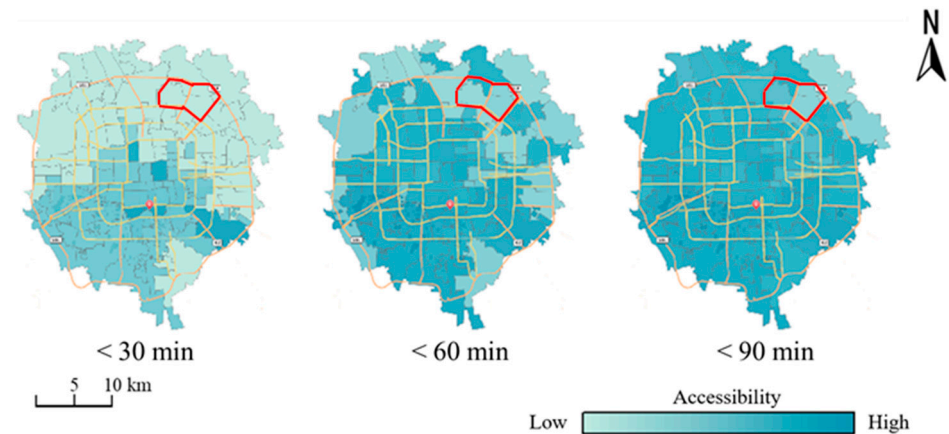


Figure 8. Accessibility for different travel time budgets.

With the increase in the travel time budgets, the range of possible travel mode choices has increased, leading to an increase in the accessibility level of most areas. Near Beijing South Railway Station, the travel times for various modes are relatively short, and the set of possible choices does not change much. Therefore, the accessibility from these areas to Beijing South Railway Station has changed little. When the travel time budgets increase from 60 min to 90 min, the accessibility level of most areas changes slightly, indicating that most areas can reach Beijing South Railway Station in 60 min. It can also be observed that under different travel time budgets, the accessibility of Wangjing, which is marked by a red line, has little changed. Moreover, the accessibility in this area is relatively lower than in other areas within the same ring road. Therefore, transportation conditions in the Wangjing area need urgent improvement.

4.5. Policy Implications

Based on the preceding analysis, when the travel time budget is set at 30 min, the accessibility of areas farther from Beijing South Station is zero because there are no possible mode choices that can reach the destination within this time constraint. Conversely, the 90 min travel time budget is overly generous, as most areas have a high probability of reaching Beijing South Station in this situation. It is advisable to analyze macro-level accessibility for the 60 min travel time budget for areas within the 5th Ring Road in Beijing to derive relevant policy implications. Figure 9 illustrates the accessibility for the 60 min time budget at different reliability levels.



Figure 9. Accessibility with different risk attitudes for 60 min travel time budget.

The accessibility for the 60 min budget at a 10% reliability level is generally high, indicating that most areas can reach the destination under optimal traffic conditions. For areas where accessibility changes significantly with reliability, improvements should focus

on both the travel modes and the travelers themselves. Encouraging high punctuality and faster travel modes such as subways or dedicated buses can enhance reliability for all travelers. Additionally, providing travelers with timely travel information can help them understand the current transportation situation and make better decisions.

Accessibility changes little with the travel time budgets, indicating long travel times to the destination. Possible reasons for these long travel times include serious transportation congestion or long travel distances. Due to the distance from the destination, improving reliable accessibility in these areas is crucial for ensuring a fair and efficient transportation network. Optimizing the road network structure is necessary to enhance transportation effectiveness. Advocating public transportation that can alleviate road congestion and improve travel efficiency is also important.

Looking at accessibility in the three areas that have the same straight line distance (about 20 km) from the destination, we can find a difference between them. The locations of the three areas are highlighted in Figure 10. It can be seen that the National Stadium generally exhibits higher accessibility levels than the other two areas. One possible reason for this difference is that the three areas have different routes to the destination, resulting in varying travel times. Additionally, the subway system serving the National Stadium offers lower travel times and higher reliability compared to the other areas, making it more convenient.

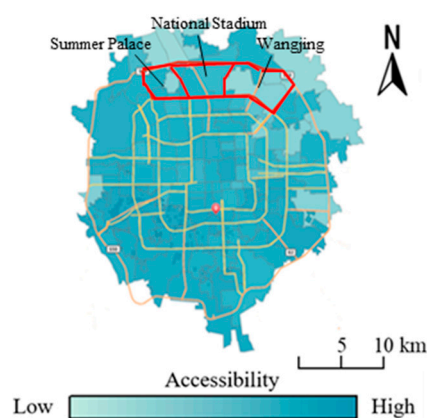


Figure 10. A comparison of accessibility in the Summer Palace, the National Stadium, and the Wangjing area.

For areas with differing accessibility levels situated at the same distance to the destination, attention should be given to the reasonable allocation of road transportation resources. Transportation guidance can be adopted to balance network transportation and fully utilize existing road resources. The above-mentioned applications can be adopted by transportation planning departments and urban mobility policymakers to improve accessibility.

5. Conclusions

This study introduces a method integrating a multimodal space–time prism and a utility-based model to measure reliable accessibility to high-speed railway stations. The results highlight the meanings and contributions of the proposed model in measuring reliable accessibility in both theory and practice. From a theoretical perspective, this study proposes an integration method by combining the possible travel mode choice set constrained by space and individual travel time budgets with the mean–standard deviation utility-based accessibility function. Moreover, the impact of travel time uncertainty on travel time budgets is considered in the integration by involving individual risk attitudes. From a practical perspective, the method can be applied by the built utility-based model with travel time data which can be easily collected by Amap in real-time for practical operation and evaluation.

One limitation of this study is using prior information for the travel time distribution of each travel mode, which could potentially introduce bias into the accessibility analysis. In reality, it is possible to estimate the travel time distribution of each travel mode based on the large size of available travel time data. Considering that this study focuses on the integration method, travel time distribution is estimated as a normal distribution for simplicity. The second limitation of this study is that the utility-based model does not take into account the varying levels of onboard congestion experienced across different travel modes, which can influence individual perceptions. For instance, taxis offer more comfortable personal space compared to other modes, and this dissimilarity can impact individual choice behavior. The third limitation is not distinguishing the travel time uncertainty between specific times of the day and different days. This variability is a critical aspect of travel time uncertainty.

In the future, one possible research direction involves exploring various socio-demographic groups' preferences toward risk attitude and behavior to assess the equity of accessibility among different populations. Furthermore, besides public travel modes, other travel modes and their associated factors that could influence individual choice behavior and subjective perceptions can be considered to provide a more thorough assessment of accessibility. Thirdly, varying travel time uncertainty should be considered to explore dynamic accessibility.

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References

1. Hansen, W.G. How Accessibility Shapes Land Use. *J. Am. Inst. Plan.* **1959**, *25*, 73–76. [\[CrossRef\]](#)
2. Hero, R.E. The Urban Service Delivery Literature: Some Questions & Considerations. *Polity* **1986**, *18*, 659–677. [\[CrossRef\]](#)
3. Kwan, M.-P.; Weber, J. Scale and Accessibility: Implications for the Analysis of Land Use–Travel Interaction. *Appl. Geogr.* **2008**, *28*, 110–123. [\[CrossRef\]](#)
4. Wu, T.; Li, M.; Zhou, Y. Measuring Metro Accessibility: An Exploratory Study of Wuhan Based on Multi-Source Urban Data. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 18. [\[CrossRef\]](#)
5. Wang, Y. Measuring Temporal Variation of Location-Based Accessibility Using Space-Time Utility Perspective. *J. Transp. Geogr.* **2018**, *12*, 13–24. [\[CrossRef\]](#)
6. Singh, S.S.; Sarkar, B. Cumulative Opportunity-Based Accessibility Measurement Framework in Rural India. *Transp. Policy* **2022**, *117*, 138–151. [\[CrossRef\]](#)
7. Geurs, K.T.; van Wee, B. Accessibility Evaluation of Land-Use and Transport Strategies: Review and Research Directions. *J. Transp. Geogr.* **2004**, *12*, 127–140. [\[CrossRef\]](#)
8. Neutens, T. Accessibility, Equity and Health Care: Review and Research Directions for Transport Geographers. *J. Transp. Geogr.* **2015**, *43*, 14–27. [\[CrossRef\]](#)
9. Chen, Y.; Jia, S.; Xu, Q.; Xiao, Z.; Zhang, S. Measuring the Dynamic Accessibility to COVID-19 Testing Sites in the 15-Min City: A Focus on Service Congestion and Mobility Difference. *J. Transp. Geogr.* **2023**, *111*, 103670. [\[CrossRef\]](#)
10. Faghihinejad, F.; Zoghifard, M.; Amiri, A.M.; Monajem, S. Evaluating Social and Spatial Equity in Public Transport: A Case Study. *Transp. Lett.* **2022**, *10*, 1420–1429. [\[CrossRef\]](#)

11. Qi, Z.; Lim, S.; Hossein Rashidi, T. Assessment of Transport Equity to Central Business District (CBD) in Sydney, Australia. *Transp. Lett.* **2020**, *12*, 246–256. [\[CrossRef\]](#)
12. Cheng, L.; Caset, F.; De Vos, J.; Derudder, B.; Witlox, F. Investigating Walking Accessibility to Recreational Amenities for Elderly People in Nanjing, China. *Transp. Res. Part D Transp. Environ.* **2019**, *76*, 85–99. [\[CrossRef\]](#)
13. Basu, R.; Ferreira, J. Can Increased Accessibility from Emerging Mobility Services Create a Car-Lite Future? Evidence from Singapore Using LUTI Microsimulation. *Transp. Lett.* **2022**, *14*, 332–338. [\[CrossRef\]](#)
14. Shen, Y.; Zhao, J.; de Abreu e Silva, J.; Martínez, L.M. From Accessibility Improvement to Land Development: A Comparative Study on the Impacts of Madrid-Seville High-Speed Rail. *Transp. Lett.* **2017**, *9*, 187–201. [\[CrossRef\]](#)
15. Liu, L.; Yu, H.; Zhao, J.; Wu, H.; Peng, Z.; Wang, R. Multiscale Effects of Multimodal Public Facilities Accessibility on Housing Prices Based on MGWR: A Case Study of Wuhan, China. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 57. [\[CrossRef\]](#)
16. Wang, Y.; Liu, Y.; Xing, L.; Zhang, Z. An Improved Accessibility-Based Model to Evaluate Educational Equity: A Case Study in the City of Wuhan. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 458. [\[CrossRef\]](#)
17. Cui, L.; Li, T.; Qiu, M.; Cao, X. Applying Decision Trees to Examine the Nonlinear Effects of Multiscale Transport Accessibility on Rural Poverty in China. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 352. [\[CrossRef\]](#)
18. Carrion, C.; Levinson, D. Value of Travel Time Reliability: A Review of Current Evidence. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 720–741. [\[CrossRef\]](#)
19. Taylor, M.A.P. Travel through Time: The Story of Research on Travel Time Reliability. *Transp. B Transp. Dyn.* **2013**, *1*, 174–194. [\[CrossRef\]](#)
20. Abdel-Aty, M.A.; Kitamura, R.; Jovanis, P.P. Investigating Effect Of Travel Time Variability On Route Choice Using Repeated-Measurement Stated Preference Data. *Transp. Res. Rec.* **1995**, *1493*, 39–45.
21. Bates, J.; Polak, J.; Jones, P.; Cook, A. The Valuation of Reliability for Personal Travel. *Transp. Res. Part E Logist. Transp. Rev.* **2001**, *37*, 191–229. [\[CrossRef\]](#)
22. Tam, M.L.; Lam, W.H.K.; Lo, H.P. Modeling Air Passenger Travel Behavior on Airport Ground Access Mode Choices. *Transportmetrica* **2008**, *4*, 135–153. [\[CrossRef\]](#)
23. Hall, R.W. Travel Outcome and Performance: The Effect of Uncertainty on Accessibility. *Transp. Res. Part B Methodol.* **1983**, *17*, 275–290. [\[CrossRef\]](#)
24. Chen, B.Y.; Li, Q.; Wang, D.; Shaw, S.-L.; Lam, W.H.K.; Yuan, H.; Fang, Z. Reliable Space-Time Prisms Under Travel Time Uncertainty. *Ann. Assoc. Am. Geogr.* **2013**, *103*, 1502–1521. [\[CrossRef\]](#)
25. Ben-Akiva, M.E.; Lerman, S.R. *Disaggregate Travel and Mobility Choice Models and Measures of Accessibility*; Taylor & Francis Group: Abingdon, UK, 1979.
26. Nassir, N.; Hickman, M.; Malekzadeh, A.; Irannezhad, E. A Utility-Based Travel Impedance Measure for Public Transit Network Accessibility. *Transp. Res. Part A Policy Pract.* **2016**, *88*, 26–39. [\[CrossRef\]](#)
27. Luo, S.; Jiang, H.; Yi, D.; Liu, R.; Qin, J.; Liu, Y.; Zhang, J. PM2SFCA: Spatial Access to Urban Parks, Based on Park Perceptions and Multi-Travel Modes. A Case Study in Beijing. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 488. [\[CrossRef\]](#)
28. Park, J.; Goldberg, D.W. A Review of Recent Spatial Accessibility Studies That Benefitted from Advanced Geospatial Information: Multimodal Transportation and Spatiotemporal Disaggregation. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 532. [\[CrossRef\]](#)
29. Moniruzzaman, M.; Paez, A. Accessibility to Transit, by Transit, and Mode Share: Application of a Logistic Model with Spatial Filters. *J. Transp. Geogr.* **2012**, *24*, 198–205. [\[CrossRef\]](#)
30. O'Sullivan, D.; Morrison, A.; Shearer, J. Using Desktop GIS for the Investigation of Accessibility by Public Transport: An Isochrone Approach. *Int. J. Geogr. Inf. Sci.* **2000**, *14*, 85–104. [\[CrossRef\]](#)
31. Mavoa, S.; Witten, K.; McCreanor, T.; O'Sullivan, D. GIS Based Destination Accessibility via Public Transit and Walking in Auckland, New Zealand. *J. Transp. Geogr.* **2012**, *20*, 15–22. [\[CrossRef\]](#)
32. Tribby, C.P.; Zandbergen, P.A. High-Resolution Spatio-Temporal Modeling of Public Transit Accessibility. *Appl. Geogr.* **2012**, *34*, 345–355. [\[CrossRef\]](#)
33. Yu, W.; Sun, H.; Feng, T.; Wu, J.; Lv, Y.; Xin, G. A Data-Based Bi-Objective Approach to Explore the Accessibility of Multimodal Public Transport Networks. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 758. [\[CrossRef\]](#)
34. Dao, T.H.D.; Thill, J.-C. Metric, Topological, and Syntactic Accessibility in Three-Dimensional Urban Networked Spaces: Modeling Options and Visualization. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 467. [\[CrossRef\]](#)
35. Karner, A. Assessing Public Transit Service Equity Using Route-Level Accessibility Measures and Public Data. *J. Transp. Geogr.* **2018**, *67*, 24–32. [\[CrossRef\]](#)
36. Lei, T.L.; Chen, Y.; Goulias, K.G. Opportunity-Based Dynamic Transit Accessibility in Southern California Measurement, Findings, and Comparison with Automobile Accessibility. *Transp. Res. Rec.* **2012**, *2276*, 26–37. [\[CrossRef\]](#)
37. Lei, T.L.; Church, R.L. Mapping Transit-Based Access: Integrating GIS, Routes and Schedules. *Int. J. Geogr. Inf. Sci.* **2010**, *24*, 283–304. [\[CrossRef\]](#)
38. Lucas Albuquerque-Oliveira, J.; Moraes Oliveira-Neto, F.; Pereira, R.H.M. A Novel Route-Based Accessibility Measure and Its Association with Transit Ridership. *Transp. Res. Part A Policy Pract.* **2024**, *179*, 103916. [\[CrossRef\]](#)
39. Salonen, M.; Toivonen, T. Modelling Travel Time in Urban Networks: Comparable Measures for Private Car and Public Transport. *J. Transp. Geogr.* **2013**, *31*, 143–153. [\[CrossRef\]](#)
40. Liao, F.; van Wee, B. Accessibility Measures for Robustness of the Transport System. *Transportation* **2017**, *44*, 1213–1233. [\[CrossRef\]](#)

41. Weibull, J.W. An Axiomatic Approach to the Measurement of Accessibility. *Reg. Sci. Urban Econ.* **1976**, *6*, 357–379. [[CrossRef](#)]
42. Habib, K.N. An Investigation on Mode Choice and Travel Distance Demand of Older People in the National Capital Region (NCR) of Canada: Application of a Utility Theoretic Joint Econometric Model. *Transportation* **2015**, *42*, 143–161. [[CrossRef](#)]
43. Harvey, G. Study of Airport Access Mode Choice. *J. Transp. Eng.-ASCE* **1986**, *112*, 525–545. [[CrossRef](#)]
44. Alhussein, S.N. Analysis of Ground Access Modes Choice King Khaled International Airport, Riyadh, Saudi Arabia. *J. Transp. Geogr.* **2011**, *19*, 1361–1367. [[CrossRef](#)]
45. Tam, M.-L.; Lam, W.H.K.; Lo, H.-P. The Impact of Travel Time Reliability and Perceived Service Quality on Airport Ground Access Mode Choice. *J. Choice Model.* **2011**, *4*, 49–69. [[CrossRef](#)]
46. Lo, H.K.; Luo, X.W.; Siu, B.W.Y. Degradable Transport Network: Travel Time Budgets of Travelers with Heterogeneous Risk Aversion. *Transp. Res. Part B Methodol.* **2006**, *40*, 792–806. [[CrossRef](#)]

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