UNDERSTANDING TRAVEL TIME UNCERTAINTY IMPACTS ON INDIVIDUAL ACCESSIBILITY

Bi Yu CHEN[a,b], Yafei WANG[a], Donggen WANG[c], William H. K. LAM[b] and Hui-Ping CHEN[b]
[a]State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China
Email: chen.biyu@whu.edu.cn
[b]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University
Email: william.lam@polyu.edu.hk
[c]Department of Geography, Hong Kong Baptist University
Email: dgwang@hkbu.edu.hk

ABSTRACT

Most existing individual accessibility studies ignore travel time uncertainties commonly encountered in congested road networks. This study investigates the impacts of travel time uncertainties on the equity of individual accessibility using spatiotemporal big data collected in Shenzhen, China. The collected big data are utilized to extract travel time distribution information and mobility data of a large number of individual samples across the entire study area. Two reliability-based individual accessibility measures are proposed to evaluate individual accessibility by explicitly considering the individual's reliability constraint in the activity-travel scheduling. The proposed measures are further applied to quantify the travel time uncertainty impacts on individual accessibility to healthy food retailers in Shenzhen. Results of this study suggest that travel time uncertainties have distinct impacts of travel time uncertainties on accessibility of different people groups; and underscore that traditional accessibility measures ignoring travel time uncertainties can lead to significant bias on the evaluation of individual accessibility and associated equity issues.

Keywords: Accessibility equity; individual accessibility; travel time uncertainty; social exclusion; spatiotemporal big data

1. INTRODUCTION

Accessibility is a key measure in urban planning and other related fields. A sufficient level of accessibility to urban services, such as job, food, healthcare and education services, is essential for citizens' quality of life and well-beings. Conversely, the lack of accessibility could dramatically increase the amount of effort individuals need to endure to organize their daily life; or in the extreme case could lead to a certain degree of transport-related social exclusion. It is, therefore, crucial for policymakers to evaluate the equity of accessibility among peoples in different socio-spatial groups.

Accessibility level of an individual depends on the interactions of land use, transport, and people components. Land use component describes the spatial distribution of urban services; transport component represents the travel cost required to access urban services; and people component reflects distinct human mobility patterns for people in different regions and socioeconomic groups (Geurs and van Wee, 2004). This triad of land use, transport and people, however, has rarely been fully considered for individual accessibility studies in large study areas. Most existing studies rely on activity-diary surveys to collect individual-level mobility information. However, conducting activity-diary surveys for a large number of individual samples could be very expensive and time-consuming (Kwan 1998). Consequently, most existing studies were restricted to a relatively small area using a few samples, and made it impossible to investigate the accessibility equity in the entire study area.

Further, existing individual accessibility studies assumed that travel times in transport networks were deterministic (Kwan 1998; Yang et al., 2017). Travel times in real transport networks, however, are highly stochastic, due to random demand fluctuations and supply degradations. The significant impacts of travel time uncertainties on individuals' activity-travel behaviors have been widely recognized by transport planners and researchers (Chen, 2013). Therefore, it is necessary to incorporate individuals' reliability concerns on individual accessibility studies. Existing individual accessibility studies, ignoring travel time uncertainties, could lead to significant bias on individual accessibility patterns and associated equity issues.

Recent advancements of information and communication technologies have made it possible to collect and assemble huge amounts of spatiotemporal big data, such as taxi trajectories, mobile phone data, social media data, and etc. (Yuan et al., 2018). These spatiotemporal big data have been widely recognized as ideal data sources for collecting human mobility information of massive individuals in the entire study area, and for monitoring travel time distribution information in large-scale transport networks (Shi et al., 2017). Such spatiotemporal big data have provided unprecedented opportunities for individual accessibility studies, which are long constrained by the lack of data. Chen et al. (2018) conducted one of the first individual accessibility studies using the mobility information extracted from mobile phone big data. They demonstrated that the mobile phone tracking data allowed individual accessibility to be evaluated for massive users across the entire study area of a mega-city in China. They found that traditional place-based accessibility measures, ignoring human mobility, can lead to significant bias on the accessibility evaluation. Incorporating human mobility can either improve or reduce individual accessibility depending on land use characteristics. Although the spatial equity of accessibility was examined in a fine spatial resolution by aggregating accessibility of all users in cellular towers, the equity of accessibility has not been investigated at a disaggregated individual level. In addition, travel time uncertainties were ignored in their study.

Using spatiotemporal big data, a few studies recently have been carried out to investigate travel time uncertainty impact on the place-based accessibility. Chen et al. (2017) proposed reliable place-based accessibility measures by considering reliability constraint for performing activities at facilities under travel time uncertainties. Zhang et al. (2018) further extended these proposed measures to public transport networks. However, these reliable accessibility measures were to evaluate place-based accessibility rather than individual accessibility.

This study seeks to fill two gaps in accessibility and equity studies. It extends the previous equity studies by using spatiotemporal big data to evaluate accessibility equity of a large number of individual samples across a large study area. It also examines travel time uncertainty impacts on individual accessibility of people in different socio-spatial groups. To achieve these research objectives, comprehensive sets of taxi trajectory data and mobile phone tracking data are collected in Shenzhen, China. Two reliability-based individual accessibility measures are proposed to evaluate individual accessibility by explicitly considering the individual's reliability constraint in the activity-travel scheduling. The proposed measures are further applied to quantify the travel time uncertainty impacts on the equity of accessing healthy food retailers. Results of this study will enrich understandings of how the transport component shapes the accessibility of people in different socio-spatial groups, and also advance methodologies in the evaluation of individual accessibility and associated equity issues.

2. RELIABILITY-BASED INDIVIDUAL ACCESSIBILITY MEASURES UNDER TRAVEL TIME UNCERTAINTIES

This section introduces the developed new measures for evaluating individual accessibility under travel time uncertainties. A road network with uncertain travel times can be represented as a directed graph $G=(V,E)$ comprising a set of nodes V and a set of links E. Each link $e \in E$ has a random travel time distribution T_e.

Under travel time uncertainties, the friction of distance between individuals and activity locations is stochastic rather than deterministic. Let p_0^{rf} be a path from an individual's origin r to a network location x, consisting of a set of consecutive links. The path travel time distribution, T_0^{rx}, can be calculated as the summation of corresponding travel times of links along the path:

$$T_0^{rx} = \sum_{\forall e} T_e \delta_e^{rx,0} \tag{1}$$

where $\delta_e^{rx,0}$ is the path-link incidence variable; $\delta_e^{rx,0}=1$ means that link e is on the path, and $\delta_e^{rx,0}=0$ otherwise. Since the path travel time is random variable, the probability (dented by α) of the individual reaching the facility within travel time budget b can be expressed as the following cumulative distribution function (CDF):

$$\alpha = \Phi_{T_0^{rx}}(b) \tag{2}$$

where $\Phi_{T_0^{rx}}(b)$ is the CDF of path travel time distribution T_0^{rx} . This on-time arrival probability, $\alpha \in (0,1)$, reflects the individual's risk attitude for being late to perform activities at the facility (Chen et al., 2013). $\alpha > 0.5$, α=0.5 and $\alpha < 0.5$ respectively represent the individual's risk-averse, risk-neutral and risk-seeking attitudes. Such on-time arrival probability generally can be pre-determined by the individual as the reliability constraint for activity participations, according to the activity type. Accordingly, given a pre-determined α constraint, the required travel time budget b can be expressed as

$$b = \Phi_{T_0^{rx}}^{-1}(\alpha) \tag{3}$$

where $\Phi_{T_0^{rx}}^{-1}(\alpha)$ is the inverse of CDF of path travel time distribution T_0^{rx} at α confidence level. Let P^{rx} be the set of all paths from origin r to network location x. Among all paths, the path with the least travel time budget is defined as the reliable shortest path p^{rx} (Chen et al., 2012). This least travel time budget of reliable shortest path, i.e. $\Phi_{T^{rx}}^{-1}(\alpha)$, can well quantify the friction of distance for the individual's activity scheduling in face of travel time uncertainties.

Due to the stochasticity of the friction of distance, the individual's potential activity-space is also stochastic. As illustrated in Figure 1, the individual's potential space relies on his or her daily activity schedule, consisting of n fixed (or mandatory) activities, denoted by $\{\mathrm{v}_1,...,\mathrm{v}_i,....\mathrm{v}_n\}$, which also referred as the anchor points in the time geography literature. Between each two subsequent anchor points, v_i and v_j , a flexible (or discretionary) activity could be scheduled. Built on the reliable shortest path concept, Chen et al. (2013) proposed a reliable space-time prism (RSTP) model to delimit all feasible space-time locations for performing the flexible activity by explicitly considering the individual's reliability constraint. As shown in the figure, one fixed activity has been completed by the individual at origin v_i at time instance t_i , and another fixed activity will be performed at destination v_j at time instance t_j . Between these two fixed activities, a flexible activity might be scheduled at a location x at time instance t_x with minimum duration $c_{\min}$. The RSTP model delimits all feasible space-time locations, (x,t_x) , for performing the flexible activity and return to the destination v_j with at least α probability of on-time arrival. It can be expressed as Chen et al. (2013):

$$\mathrm{RSTP_i}(\alpha) = \mathrm{RFC_i}(\alpha) \cap \mathrm{RBC_i}(\alpha) \cap \mathrm{RC_i}(\alpha) \tag{4}$$

$$\mathrm{RFC_i}(\alpha) = \left\{ (x,t_x) \mid \Phi_{T^{ix}}^{-1}(\alpha) \le t_x - t_i, t_x \le t_j \right\} \tag{5}$$

$$\mathrm{RBC_i}(\alpha) = \left\{ (x,t_x) \mid \Phi_{T^{xj}}^{-1}(\alpha) \le t_j - t_x, t_x \ge t_i \right\} \tag{6}$$

$$\mathrm{RC_i}(\alpha) = \left\{ (x,t_x) \mid \Phi_{T^{ix}}^{-1}(\alpha) + \Phi_{T^{js}}^{-1}(\alpha) \le t_j - t_i - c_{\min}, t_i \le t_x \le t_j \right\} \tag{7}$$

where $\Phi_{T^{ix}}^{-1}(\alpha)$ is the least travel time budget from the origin v_i to location x, and $\Phi_{T^{xj}}^{-1}(\alpha)$ is the least travel time budget from location x to the destination v_j. The height of RSTP at location x represents the maximum activity duration, denoted by $c_x(\alpha)$, which can be calculated as

$$c_x^i(\alpha) = t_s - t_r - \Phi_{T^{rx}}^{-1}(\alpha) - \Phi_{T^{xs}}^{-1}(\alpha) \tag{8}$$

The projection of RSTP onto two-dimensional (2D) geographical space forms the reliable potential path area (RPPA).

Given an individual's activity schedule consisting of n fixed activities, a series of RSTPs, $\mathrm{RSTP}_1(\alpha),...,\mathrm{RSTP}_i(\alpha),...,\mathrm{RSTP}_{n-1}(\alpha)$ can be constructed for $n-1$ successive pairs of fixed activities. All these RSTPs can be superimposed to create a daily reliable space-time prism (DRSTP), which can be represented as the individual's 3D potential activity-space for activity participations. The projection of DRSTP into the 2D geographical space forms a daily reliable potential path area (DRPPA) as the individual's 2D potential activity-space. The size of potential activity-space depends on not only traffic conditions but also the individual's reliability constraint α. When $\alpha = 0.5$, the DRSTP and DRPPA are equivalent to the traditional daily space-time prism and daily potential path area, which consider only median travel time and ignore travel time uncertainties. With the increase of α value, the individual reserves larger travel time safety margins to ensure a higher probability of arriving on time, leading to the reduction of potential activity-space size.

Based on the individual's potential activity-space in terms of DRSTP and DRPPA, two reliability-based individual accessibility measures are proposed to evaluate the accessibility of the individual in face of travel time uncertainties. Let $F = \{..., f, ...\}$ be the set of service facilities for individuals to perform activities. The first measure, denoted by $\mathrm{RCUM}(\alpha)$, is related to the number of facilities within the individual's 2D potential activity-space as

$$\mathrm{RCUM}(\alpha) = \sum_{\forall f} \delta_f \tag{9}$$

$$\delta_f = \begin{cases} 1, & \text{if } f \in \mathrm{DRPPA} \\ 0, & \textit{otherwise} \end{cases} \tag{10}$$

where δ_f is a binary variable indicating whether facility f is within DRPPA. The second measure, denoted by $\mathrm{RDUR}(\alpha)$, is the cumulative activity durations at feasible facilities within the individual's 3D potential activity-space as

$$\mathrm{RDUR}(\alpha) = \sum_{\forall f} \sum_{\forall RSTP_i} c_f^i(\alpha)\delta_f \tag{11}$$

This $\mathrm{RDUR}(\alpha)$ measure extends the $\mathrm{RCUM}(\alpha)$ measure by explicitly considering the time dimension, in terms of time availability for activity participations.

The proposed $\mathrm{RCUM}(\alpha)$ and $\mathrm{RDUR}(\alpha)$ measures can well capture the individuals' various reliability constraint, $\forall \alpha \in (0,1)$. The reliability constraint has significant impacts on the individual's accessibility. With an increase of α value, the individual becomes more risk-averse and tends to reserve more travel time budgets to ensure a higher probability of on-time arrival at locations for performing fixed activities. This could reduce the individual's potential activity-space, in terms of DRPPA and DRSTP; and consequently further reduce the individual's accessibility level. These proposed $\mathrm{RCUM}(\alpha)$ and $RDUR(\alpha)$ measures, thus, provide a flexible means for evaluating the accessibility of individuals in face of travel time uncertainties.

Let CUM and DUR be traditional individual accessibility measures, in terms of the cumulative number of facilities within the daily potential path area and the cumulative time durations at accessible facilities within the daily space-time prism, respectively (Kwan, 1998). The proposed $RCUM(\alpha)$ and $\mathrm{RDUR}(\alpha)$ measures generalize these two traditional measures by incorporating the individual's various reliability constraint, $\forall \alpha \in (0,1)$, for performing activities. Such traditional measures, ignoring travel time uncertainties, can be regarded as a special case of $\mathrm{RCUM}(\alpha)$ and $\mathrm{RDUR}(\alpha)$ measures by setting the reliability constraint to be 0.5. In following sections, we will apply the proposed accessibility measures to investigate travel time uncertainty impacts on individual accessibility of different people groups and associated equity issues.

3. STUDY AREA AND DATA COLLECTION

The study area of this study is a mega-city in China, i.e., Shenzhen, which is located in the southern China and adjacent to Hong Kong. By the end of 2013, Shenzhen covers an area of 1,996 km^2, and has a population of approximately 10.54 million inhabitants and more than 70% of them are migrants. Shenzhen consists of ten administrative districts with diverse land use characteristics. Luohu, Futian, and Nanshan are core urban areas with dense population and service facilities; Yantian, Bao'an, Longgang, and Longhua are suburban areas with some new towns and several electronics factories; and Guangming, Pingshan, and Dapeng are rural areas with large hilly and agriculture lands (Chen et al., 2018). The diverse socioeconomic population and land use characteristics of Shenzhen makes it an interesting area for the accessibility study.

Three datasets collected for this study include mobile phone tracking data, road network data, and food retailer information. The mobile phone tracking dataset consisted of 5.33 million phone users and collected on a typical Friday (i.e. 23 March 2012). The location of each phone user was actively recorded approximately once every hour; and each phone user thereby had twenty-four records. This dataset consisted of 5,930 cellular towers. The average nearest distance among the cellular towers was approximately 300 m. The service area of a cellular tower was represented by the tower's Thiessen polygon.

The road network dataset included the major roads and arterial streets in Shenzhen city and consisted of 32,066 nodes and 40,809 links. The hourly link travel time distributions of the road network were estimated by trajectories of 17,406 taxis on the same day as mobile phone dataset (Chen et al. 2013). The link travel time variations was evaluated using coefficient of variation (CV; i.e., the ratio of the standard deviation to the mean). A larger CV value indicates larger link travel time variations and more uncertainty of the link travel time. It is found that the average CV value was equal to 0.33, and 13.82% of links in red with a CV value larger than 0.5. Therefore, travel times in Shenzhen network were highly stochastic, and the impacts of travel time uncertainty were necessary inclusions in the evaluation of individual accessibility in this study area.

The food retailer dataset comprised 3,657 supermarkets and grocery stores in Shenzhen City. The distributions of supermarkets and grocery stores are spatially uneven in the city, but rather clustered in the three core urban areas, particularly in Luohu district. This pattern confirmed the spatial inequity of healthy food provisions.

4. RESULTS

Individual healthy food accessibility, in terms of RDUR(0.95) measure, was calculated for all collected phone users in Shenzhen so as to investigate the accessibility inequity of different people groups across the entire study area. Figure 1 reports the histogram and Lorenz curve of all calculated accessibility values. The histogram in the figure shows a long tail distribution of individual accessibility, indicating a significant level of accessibility inequity among phone users in Shenzhen. The average individual accessibility value is 3455.6 hours. The bottom 10% of individuals' accessibility is within 645.4 hours (only 18.7% of mean), while the top 10% individuals' accessibility is beyond 7573.9 hours (219.2% of mean). This significant level of accessibility inequity is also evidenced in the Lorenz curve with $GC = 0.43$ and $CV = 0.77$.

Figure 2 shows the spatial disparities of individual accessibility in the entire region of Shenzhen in a fine spatial resolution of cellular tower. As shown in Figure 2(a), the highest levels of accessibility are found for people living in core urban areas (particularly Luohu and Futian districts), where there is a higher density of healthy food retailers. Conversely, the lowest levels of accessibility are observed for people living in rural areas (particularly Dapeng and Pingshan districts) with a lower density of healthy food retailers. Figure 2(b) shows the inter-personal variation of accessibility for people living in the same residential area. People living in most core urban areas have a lower inter-personal variation with a CV value less than 0.3; while people in most suburban and rural areas have a higher inter-personal variation with a CV value larger than 0.6.

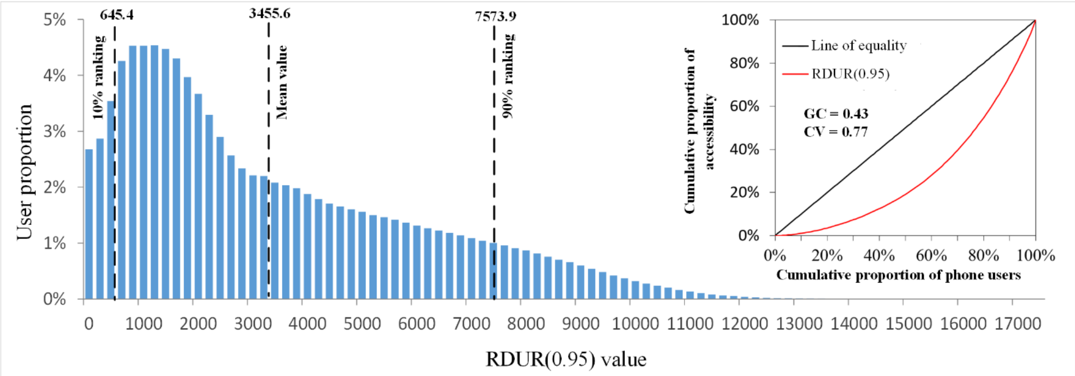

Figure 1. The histogram and Lorenz curve of individual accessibility in Shenzhen (GC: Gini coefficient; CV: Coefficient of variance).

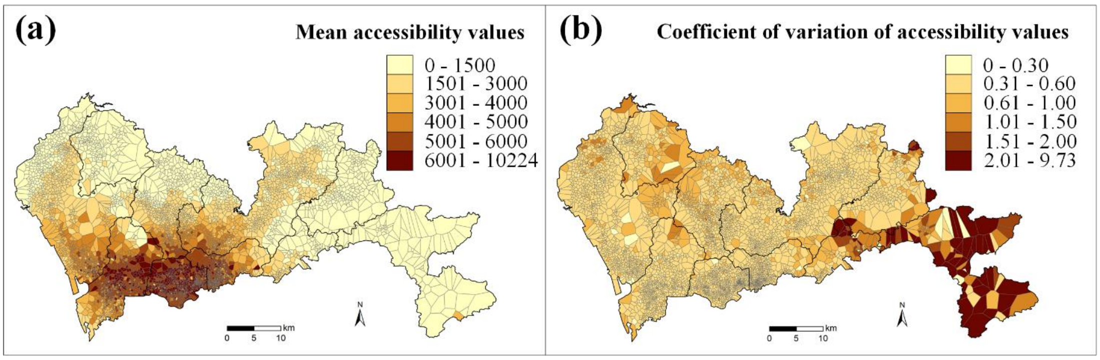

Figure 2. The spatial distribution of health food accessibility in Shenzhen.

The travel time uncertainty impacts on accessibility of each phone user were investigated by comparing the user's accessibility values of RDUR(0.95) and DUR measures. Figure 3shows the calculated accessibility reduction rate, R^{u}_{RDUR}, for all phone users in the entire study area. As shown, travel time uncertainties have significant negative impacts on users' accessibility with an average reduction rate of 13.02%. The CV of reduction rate distribution is 0.64, showing that such negative impacts vary considerably among phone users. Particularly, more than 13.8% of users' accessibility level are reduced by over 20%, and 0.77% of users are even reduced by over 50%.

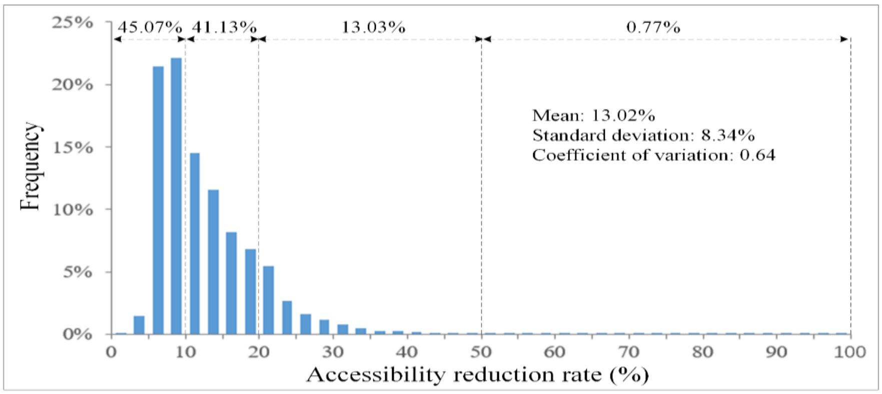

Figure 3. The histogram of accessibility reduction rates for all phone users

Then, the heterogeneous impacts of travel time uncertainties on individual activity-space and accessibility were further examined for three user subgroups in seven accessibility ranking categories. As summarized in Table 1, the negative impacts of travel time uncertainties on users' activity-space sizes are highly spatially uneven, i.e., more serious on rural and suburban than urban areas. For example, the average R_{DRSTP}^{u} for users in rural area is 20.41%, which is 2.32 times as large as that in urban areas (8.78%). This is mainly due to a lower density of the road network in rural and suburban areas in the Shenzhen city (Chen et al., 2018). More importantly, it is found that travel time uncertainties have more severe impacts on users in lower accessibility categories for all urban, suburban and rural subgroups. For example, R_{DRSTP}^{u} for rural users in the bottom 1% category is 46.94%, accounting for 4.59 times as large as that in the top 10% category (10.22%).

Table 2 summarizes the average accessibility reduction rates, $\mathrm{R}_{\mathrm{RDUR}}^{u}$, for users in different accessibility ranking categories and geographical regions. As expected, a similar pattern is observed between $\mathrm{R}_{\mathrm{RDUR}}^{u}$ and R_{DRSTP}^{u} among users in different categories and regions. This is obvious, because the reduction of an individual's activity-space directly degrade the individual's accessibility to healthy food retailers. By comparing Tables 1 and 2, it is found a relationship of $\mathrm{R}_{\mathrm{RDUR}}^{u} < \mathrm{R}_{DRSTP}^{u}$ for users ranking in the top 50% (i.e., 50%-80%, 80%-90%, and 90%-100% categories), while a relationship of $\mathrm{R}_{\mathrm{RDUR}}^{u} > \mathrm{R}_{DRSTP}^{u}$ for majority of users ranking in the bottom 50% (i.e., 0%-1%, 1%-10%, 10%-20%, and 20%-50% categories). It indicates that users in lower accessibility categories are more sensitive to the activity-space reduction. Therefore, these results underscore a key role of transport network reliability for disadvantaged people suffering from a low level of health food accessibility.

Table 1. The phone users' activity-space reduction rate distribution in three subgroups

Subgroups	Accessibility categories based raking in the whole user group							Mean reduction
	0%-1%	1%-10%	10%-20%	20%-50%	50%-80%	80%-90%	90%-100%	
Urban	25.93%	14.47%	10.69%	9.69%	8.87%	8.27%	7.72%	8.78%
Suburban	50.49%	20.07%	15.94%	14.01%	12.34%	10.61%	9.38%	14.36%
Rural	46.94%	22.63%	18.76%	15.14%	14.09%	12.18%	10.22%	20.41%

Table 2. The phone users' accessibility reduction rate distribution in three subgroups

Subgroups	Accessibility categories based raking in the whole user group							Mean reduction
	0%-1%	1%-10%	10%-20%	20%-50%	50%-80%	80%-90%	90%-100%	
Urban	32.78%	18.51%	15.22%	10.52%	8.19%	7.71%	7.09%	8.57%
Suburban	45.05%	22.60%	17.45%	14.53%	11.79%	8.85%	7.74%	14.65%
Rural	43.90%	23.59%	19.47%	15.55%	12.68%	7.79%	7.40%	20.90%

The travel time uncertainty impacts on the overall accessibility inequity was evaluated by comparing the values of Gini coefficient and CV between $\mathrm{RDUR}(0.95)$ and DUR measures. As calculated, the Gini coefficient and CV of $\mathrm{RDUR}(0.95)$ are increased by 4.88% (i.e., 1 – 0.43 / 0.41) and 4.05% (i.e., 1 – 0.77 / 0.74) respectively, compared to that of DUR. It suggests that incorporating travel time uncertainty impacts exaggerates the inequity of healthy food accessibility among different people groups in Shenzhen. This result is expected, because travel time uncertainties have more serious impacts on disadvantaged users with a lower level of accessibility to healthy food retailers (see Table 2).

5. CONCLUSIONS

This study investigated the travel time uncertainty impacts on the equity of individual accessibility by using a spatiotemporal big data analysis approach. Two reliability-based individual accessibility measures were proposed to generalize traditional individual accessibility measures by explicitly considering various individuals' reliability constraints in face of travel time uncertainties. The results of case study demonstrated the capabilities of using spatiotemporal big data to investigate the accessibility equity of large study areas in a disaggregated individual level approach. Further, the results of case study highlighted the distinct impacts of travel time uncertainties on accessibility of different people groups. Specially, travel time uncertainties have more severe impacts on disadvantaged people with a lower accessibility level; and exaggerate the overall accessibility inequity among all people groups. These results underscored the considerable bias of using traditional accessibility measures in the accessibility and equity evaluation.

There are some limitations that should be mentioned. First of all, this study estimated the potential activity-space of a phone user by constructing space-time regions of 20 min around multiple anchor points of hourly tracking data. However, the used anchor points may not exactly be fixed activity locations collected from activity-diary surveys, thus introducing a certain bias on the activity-space estimation. Although previous studies have demonstrated the effectiveness of this activity-space estimation method, further studies are required to quantify the bias on people with different mobility patterns. In addition, phone users' transport mode choice behaviors were not directly considered in this study by assuming all users with access to private cars or taxis. Further studies should be conducted to allow users make their trips by multiple transport modes, including walking, bicycling, private car, taxi and public transit modes.

6. ACKNOWLEDGEMENTS

The work described in this paper was supported by research grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (No. PolyU 152095/17E).

7. REFERENCES

Chen, B.Y., Lam, W.H.K., Sumalee, A. and Li, Z.L. (2012) Reliable shortest path finding in stochastic networks with spatial correlated link travel times. *International Journal of Geographical Information Science*, 26, pp. 365-386.

Chen, B.Y., Li, Q.Q., Wang, D.G., Shaw, S.-L., Lam, W.H.K., Yuan, H. and Fang, Z.X. (2013) Reliable space-time prisms under travel time uncertainty. *Annals of the Association of American Geographers*, 103, pp. 1502-1521.

Chen, B.Y., Yuan, H., Li, Q., Wang, D., Shaw, S.-L., Chen, H.-P. and Lam, W.H.K. (2017) Measuring place-based accessibility under travel time uncertainty. *International Journal of Geographical Information Science*, 31, pp. 783-804.

Chen, B.Y., Wang, Y., Wang, D., Li, Q., Lam, W.H.K. and Shaw, S.-L. (2018) Understanding the impacts of human mobility on accessibility using massive mobile phone tracking data. *Annals of the American Association of Geographers*, 108, pp. 1115-1133.

Geurs, K.T. and van Wee, B. (2004) Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12, pp. 127-140.

Kwan, M.P. (1998) Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geographical Analysis*, 30, pp. 191-216.

Shi, C., Chen, B.Y., Lam, W.H.K. and Li, Q.Q. (2017) Heterogeneous data fusion method to estimate travel time distributions in congested road networks. *Sensors*, 17, p. 2822.

Yang, W., Chen, B.Y., Cao, X., Li, T. and Li, P. (2017) The spatial characteristics and influencing factors of modal accessibility gaps: A case study for Guangzhou, China. *Journal of Transport Geography*, 60, pp. 21-32.

Yuan, H., Chen, B.Y., Li, Q.Q., Shaw, S.-L. and Lam, W.H.K. (2018) Toward space-time buffering for spatiotemporal proximity analysis of movement data. *International Journal of Geographical Information Science*, 32, pp. 1211-1246.

Zhang, T., Dong, S., Zeng, Z. and Li, J. (2018) Quantifying multi-modal public transit accessibility for large metropolitan areas: a time-dependent reliability modeling approach. *International Journal of Geographical Information Science*, 32, pp. 1649-1676.