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RESEARCH ARTICLE

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Understanding network travel time reliability with on-demand ride service data

Abstract Travel time reliability is of increasing importance for travelers, shippers, and transportation managers because traffic congestion has become worse in major urban areas in recent years. To better evaluate the urban network-wide travel time reliability, five indices based on the emerging on-demand ride service data are proposed: network free flow time rate (NFFTR), network travel time rate (NTTR), network planning time rate (NPTR), network buffer time rate (NBTR), and network buffer time rate index (NBTRI). These indices take into account the probability distribution of the travel time rate (i.e., travel time spent for the unit distance, in min/km) of each origin-destination (OD) pair in the road network. We use real-world data extracted from DiDi-Chuxing, which is the largest on-demand ride service platform in China. For demonstrative purposes, the network-wide travel time reliability of Beijing is analyzed in detail from two dimensions of time and space. The results show that the road network is more unreliable in AM/PM peaks than other time periods, and the most reliable time period is the early morning. Additionally, we can find that the central region is more unreliable than other regions of the city based on the spatial analysis results. The proposed network travel time reliability indices provide insights for the comprehensive evaluation of the road network traffic dynamics and day-to-day travel time variations.

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1 Introduction

Travel time reliability is defined as the consistency of travel time in certain sections and regions in a given period of time. More formally, it represents "*the consistency or dependability in travel times, as measured from day to day or across different times of the day*" (Federal Highway Administration, 2006). Travel time reliability is one of the fundamental factors that influence travel behavior. Travelers consider the existence of travel time uncertainties in multidimensional choices, e.g., departure time, route, mode, and destination, for a trip.

Reliability is commonly used to refer to the level of consistency in transportation services for a mode, trip, route or corridor for a certain time period. Typically, reliability is viewed by travelers in relation to their experience. In this paper, we use reliability for the purposes of reporting performance measures to the public, since it may have a "marketable" connotation (Lomax et al., 2003).

The road network travel time reliability that presents spatial and temporal features of traffic dynamics can be affected by numerous factors, such as traffic incidents, temporary traffic control, and sudden natural disasters, which bring great uncertainty to road traffic. Meanwhile, random factors may reduce the reliability of traffic operations and have negative impacts on the development of transportation infrastructure. From the perspective of travel behavior, travel time unreliability makes a trip difficult to complete within the estimated or pre-scheduled travel time; also, it makes the whole state of the urban transportation system unstable. Therefore, a smooth and reliable road transportation system provides the basis for the realization of traveling purposes and benefits efficient urban traffic management.

Reliability is an important measure of the transportation system's health. The introduction of travel time reliability makes a significant difference in improving the efficient usage of transportation systems. Despite its importance, transportation planners typically use other measures such as congestion as well as accessibility, mobility, connectivity, and safety to evaluate transportation systems.

This paper aims to develop travel time reliability measures with the emerging on-demand ride service data in the hope of coming to a better understanding of the dynamics and variations of the transportation systems. The contributions of this paper include:

(i) Multiple evaluation indices for the network-wide travel time reliability. Based on the on-demand ride service data, the proposed indices (refer to Section 3) consider the probability distribution of the travel time rate (i.e., travel time spent for the unit distance, in min/km) of each origin-destination (OD) pair in the road network. The network is divided into grids and analyzed for specific time periods. The network-wide travel time reliability indices are calculated by weighting the percentiles of the travel time rate distribution for each OD pair. Those indices are more diversified, reasonable, and reliable for the network-wide performance assessment. It avoids the limitation of the traditional evaluation that is mainly designed for specific paths or road segments.

(ii) Guidance for reliable travel planning. The concept of the travel time rate (in min/km) and travel time reliability indices help residents to plan travel in a more reliable way. Given information about a trip's origin, destination, trip distance, and departure time, the on-demand ride service platform offers residents opportunities to reserve extra travel time for ensuring the timely arrival at the destination.

The remainder of the paper is organized as follows. Section 2 briefly reviews the existing travel time reliability related studies. Section 3 proposes the network-wide travel time reliability indices based on OD pairs. Section 4 demonstrates applications of the proposed indices to a real-world large-scale road network and selected points of interest in Beijing by using the on-demand ride service data that are collected from the largest transportation network company in China, DiDi Chuxing. Section 5 concludes the paper.

2 Literature review

A large quantity of research on the travel time variability has been conducted over the past decades. Gaver Jr (1968) introduced a theoretical framework based on the utility maximization for describing travel time variability in trip-scheduling decisions. Statistical estimation procedures (non-parametric and parametric) were provided to estimate the probability density distribution of the trip delay, and it was found that a traveler would plan an earlier departure time when facing travel time variability, compared with the circumstances given known certain travel times. Knight (1974) proposed a "safety margin" hypothesis to explain a similar response of travelers to travel time unreliability. This safety margin allowed the reduction of the probability of late arrivals, and implied that travelers had a preference of arriving early to work. Chen et al. (2002) studied how the fluctuations of the capacity affected the reliability. Bell and Cassir (2002) used the method of sensitivity analysis to solve the distribution problem by changing the traffic volume. In that research, the method was applied in conjunction with the Monte Carlo method to estimate the reliability in more complex situations. Hou and Jiang (2002) used traffic simulation to calculate the reliability of the road network, and believed that the roads were unreliable due to the arrival of vehicles close to or beyond the intersection capacity. A comprehensive review of the theoretical and empirical studies on the travel time reliability valuation appears in Carrion and Levinson (2012).

The travel time rate represents the travel time per unit distance, and it is used to characterize travel time distributions for different OD pairs in this paper. Richardson and Taylor (1978) first investigated the use of unit travel time to indicate the relationship between congestion and the variability of travel times. Taylor (1982) confirmed and extended the theory developed by Herman and Lam (1974), which proposed that when travel times on different links were independent and identically distributed, the standard deviation was proportional to the average travel time. Lam and Small (2001) used the standard deviation of travel time to represent variability and included it into the route choice utility function to study the value of reliability. Sen et al. (2001) proposed a mean-variance multi-objective model to study travelers' route choice behavior, in which travel time variability was expressed as the variance of travel time. Lomax et al. (2003) proposed calculating the buffer time by using the difference between the 95th percent travel time and average travel time for a trip, for measuring the extra time travelers needed to arrive in time. The travel time rate helped exclude the source of variability coming from the trip distance and focused on the travel time variability caused by the variation of speed (Mahmassani et al., 2013).

Measurements of the travel time reliability can be based on stated preference (SP) data (Noland and Polak, 2002), revealed preference (RP) data (Lam and Small, 2001), or combined RP and SP studies (Small et al., 2005). Lomax et al. (2003) generated three basic approaches for travel time analyses, namely, the travel time data collected from floating cars or other vehicle-based sampling procedures, data from traffic operations center archives, and estimation or modeling techniques. Uno et al. (2009) proposed a methodology for evaluating the road network from the viewpoint of travel time stability and reliability using bus probe data. In that research, the level of service of road networks was evaluated based on the concept of travel time reliability. Devarasetty et al. (2012) designed the SP survey of travelers on Houston's Katy Freeway. Gan and Bai (2014) studied the effect of travel time variability on route choice behavior. An SP survey was conducted to collect behavioral data on Shanghai drivers' choices. A generalized linear mixed model was applied to quantify trade-offs between travel time and travel time variability. Abir (2016) used data collected by automated vehicle identification sensors from the Katy Freeway travelers to measure the value of travel time reliability. Today, on-demand ride services have spread rapidly across regions all over the world due to the development of communication technologies, and they generate the big data that are more comprehensive and abundant than traditional survey-based studies.

In the literature, two network travel time reliability measures were introduced, namely, the path travel time reliability (e.g., Rakha et al., 2006; Lyman and Bertini, 2008; Bhouri and Kauppila, 2011), and OD travel time reliability (e.g., Asakura and Kashiwadani, 1991; Asakura et al., 2003; Clark and Watling, 2005). When monitoring reliability, it is important to distinguish the network operators' perspective from the travelers' perspective. For the network operators, the focus is on the network-wide performance (that is provided and/or planned), while for the travelers, the concern is how the variability of travel time is experienced. In this paper, the proposed travel time reliability indices are based on the OD travel time reliability and thus take the travelers' perspective, which bridges a research gap in that the emerging data of on-demand service platform have seldom been used to reveal the network-wide travel time reliability for large-scale urban areas.

3 Network travel time reliability indices

The travel time rate represents the travel time per unit distance. In this paper, it is defined as

$$\tau_{ijk} = \frac{t_{ijk}}{d_{ijk}},\ i \in I,\ j \in J,\ 1 \leqslant k \leqslant n_{ij} \tag{1}$$

where τ_{ijk} represents the travel time rate (min/km) of the kth trip from origin i to destination j, t_{ijk} and d_{ijk} are the corresponding travel time (min) and trip distance (km), respectively. I and J denote the origin and destination sets, respectively. n_{ij} is the number of the completed trips from OD pair(i, j).

For a certain OD pair (i, j), let the probability density function of τ_{ijk}, $1 \leqslant k \leqslant n_{ijk}$ be $f_{ij}(\tau)$. Then, the αpercentile of the travel time rate at the confidence level of α can be calculated by the cumulative distribution function $F_{ij}(\tau)$, given by:

$$\tau_{ij,\alpha} = F^{-1}{}_{ij}(\alpha),\ 0 \leqslant \alpha \leqslant 100\%. \tag{2}$$

Based on Eq. (2), percentiles of the travel time rate for OD pair (i, j) at the confidence level of 5%, 50%, and 95% can be expressed as $\tau_{ij,5\%}$, $\tau_{ij,50\%}$ and $\tau_{ij,95\%}$, respectively. Thus, $\tau_{ij,5\%}$ represents the free flow travel time rate of OD pair (i, j), which means the ideal traffic situation under uncongested conditions. $\tau_{ij,50\%}$ represents the median travel time rate indicating the average traffic conditions. $\tau_{ij,95\%}$ represents the planning travel time rate if travelers aim to arrive at the destination on time under most circumstances. It can be seen that all of the aforementioned percentiles are estimated for the certain OD pair (i, j). In this paper, the network mobility and reliability features proposed are geared to the needs of describing the network-wide travel time reliability. For convenience, the road network will be divided into 1 km^2 grids. The attributes for the network mobility and reliability features of each OD pair is determined by w_{ij}, which is the total trip distance for OD pair (i, j), given by:

$$w_{ij} = \sum_{k=1}^{n_{ij}} d_{ijk}. \tag{3}$$

The network free-flow travel time rate (NFFTR) is defined as:

$$\text{NFFTR} = \frac{\sum_i \sum_j w_{ij} \times \tau_{ij,5\%}}{\sum_i \sum_j w_{ij}}. \tag{4}$$

The network travel time rate (NTTR) is defined as:

$$\text{NTTR} = \frac{\sum_i \sum_j w_{ij} \times \tau_{ij,50\%}}{\sum_i \sum_j w_{ij}}. \tag{5}$$

The network planning time rate (NPTR) is defined as:

$$\text{NPTR} = \frac{\sum_i \sum_j w_{ij} \times \tau_{ij,95\%}}{\sum_i \sum_j w_{ij}}. \tag{6}$$

All three indices above calculate the network-wide travel time rate percentiles, which can describe how the road network performs under different situations. For instance, NFFTR represents the overall free-flow travel time rate of the whole region, while NTTR and NPTR represent the overall average travel time rate and the planning travel time rate of the region, respectively.

In addition to the aforementioned indices, as shown in Fig. 1, the buffer time quantifies the extra percentage of travel time due to travel time variability on a trip that a

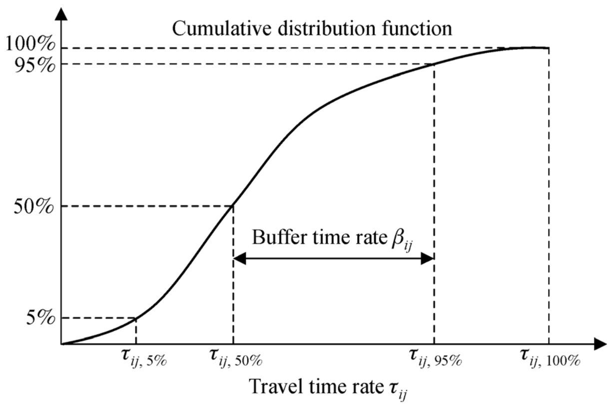

Fig. 1 An illustration of the travel time rate distribution for each OD pair

traveler should take into account in order to arrive on time. As a result, the buffer time rate β_{ij} is defined as the extra travel time rate the traveler plans to add to the median travel time rate for arrival on time with a confidence level of 95%. To standardize the measure, the buffer time rate index η_{ij} is defined as the ratio between the buffer time rate and the median travel time rate. Both indices are useful in the assessment of uncertainties in travel conditions, given by:

$$\tau_{ij,95\%} - \tau_{ij,50\%} = \beta_{ij}, \tag{7}$$

$$\eta_{ij} = \frac{\beta_{ij}}{\tau_{ij,50\%}}. \tag{8}$$

The buffer indices for the urban road network, i.e., the network buffer time rate (NBTR) and network buffer time rate index (NBTRI) are calculated as:

$$\mathrm{NBTR} = \frac{\sum_i \sum_j w_{ij} \times \beta_{ij}}{\sum_i \sum_j w_{ij}}, \tag{9}$$

$$\mathrm{NBTRI} = \frac{\sum_i \sum_j w_{ij} \times \eta_{ij}}{\sum_i \sum_j w_{ij}}. \tag{10}$$

4 Case study

4.1 Data description

The data set used in this paper was extracted from the on-demand ride service platform DiDi Chuxing in Beijing, China, from January 1, 2016, to December 31, 2016. DiDi was founded in 2012 as a taxi-hailing App and later developed private-car hailing business, and currently, it is the largest transportation network company in China (Chen et al., 2017). The total number of ride orders is 4058138 (including 750398 invalid orders with missing information that have been excluded from the subsequent analyses of this paper). The data were randomly sampled from all of the on-demand ride requests that have been serviced via the platform. Each ride order includes the pickup and drop-off locations and time, order ID, driver ID, trip ID, passenger ID, travel distance, travel time, and city ID. The spatial distribution of the ride request origins is shown in Fig. 2, according to the origin longitude and latitude, which covers most of the urban area of Beijing. The spatial distribution of the request origins shows that most requests are mainly distributed within the urban central region or

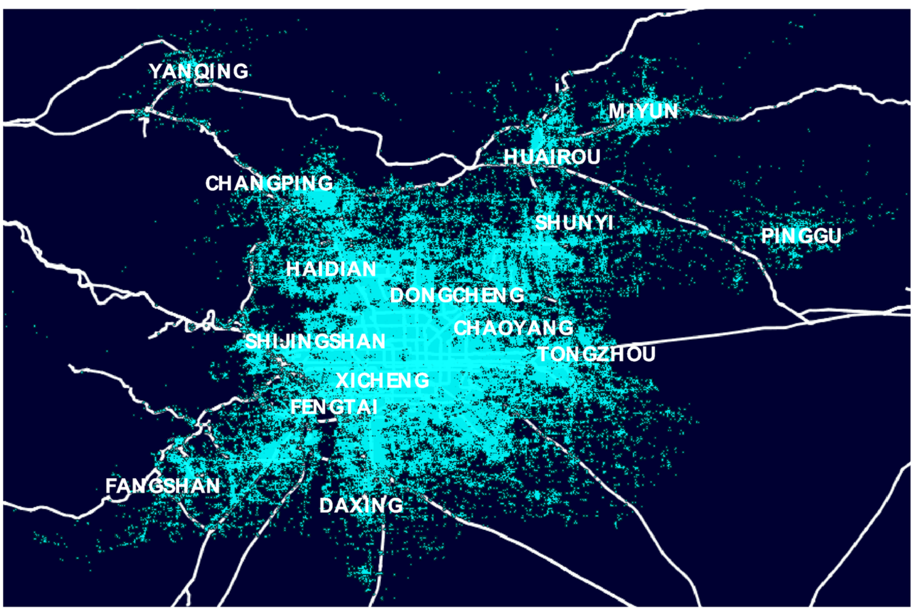

Fig. 2 Spatial distribution of on-demand ride request origins in Beijing for the year 2016

residential areas. Further, the request origins also have several centers scattering around the core area of Beijing, and these scattering centers match the location of municipal districts well. Here, we weaken the boundary of municipal districts because it is difficult to distinguish the boundary when processing a large amount of data.

4.2 Results

We apply the real-world on-demand ride service data to calculate the proposed network travel time reliability indices for the metropolitan area of Beijing. For demonstrative purposes, the travel time reliability indices of selected points of interest will also be presented.

4.2.1 Temporal distributions of network-wide travel time reliability indices

As shown in Table 1, the proposed five indices are calculated based on the emerging on-demand ride service data. NFFTR reflects the time needed per kilometer in the free-flow condition. The NFFTR value is equal to 1.52 min/km, that is, vehicles usually spend 1.52 min per kilometer when the network is unblocked. NTTR reflects the average travel time per kilometer. Travelers in Beijing usually spend 2.38 min/km on average across the network wide. NPTR refers to the planning time for travelers. It means the travel time per kilometer in a congested network. To ensure arriving at the destination in time, travelers should take NPTR into account, the value of which is 4.17 min/km to ensure arriving in time under 95% of circumstances in Beijing. NBTR refers to the extra travel time rate that should be reserved for travelers to ensure on-time arrivals at their destinations, which is 1.78 min/km. Similarly, NBTRI is the ratio of NBTR to NPTR. A higher NBTRI implies the lower reliability of the network.

Figure 3 illustrates the monthly distribution of the five indices of Beijing in 2016. The value of NBTRI slightly fluctuates through the whole year except December, and the value of NBTR fluctuates approximately 1.5 min/km. In February, all values of the five indices drop down due to the Spring Festival when travel demand is lower than other months. The fewer vehicles running in the network make the road network more reliable.

As shown in Fig. 4, the travel time reliability indices on Monday are slightly higher, which indicates the frequent congestion on Monday due to workers' commutes. The congestion decreases the reliability and causes fluctuations of the travel time rate. Similarly, the reliability indices on Friday are the highest through the week, which indicates the routine of residents. On weekends, the indices are the lowest, indicating that travel demand on weekends is much lower than that on weekdays.

Figure 5 shows the trend of the travel time reliability in Beijing over 24 h. NBTRI is obviously high during the two peak periods of 7:00–9:00 and 17:00–19:00, respectively. During the early morning (0:00–6:00), the indices are significantly lower than those values in other periods due to the light traffic. Overall, NBTRI varies widely during 6:00–22:00. It is also found that the reliability in the daytime is less than that in the night.

4.2.2 Spatial distributions of origin-based travel time reliability indices

The indices proposed in Section 3 reflect the travel time reliability of the whole network. To define the travel time reliability of a specific point of interest, we propose another five similar origin-based indices: the free flow time rate (FFTR), median travel time rate (MTTR), planning time rate (PTR), buffer time rate (BTR), and buffer time rate index (BTRI). These origin-based indices are calculated in the same way as the network travel time reliability indices, but the on-demand ride services are selected and only the services with origins close to that specific point of interest are selected.

The BTR value for each region of Beijing is shown in Fig. 6. Different colors represent different BTR values, and the colors changing from green to red indicate that the BTR value gradually increases.

As shown in Table 2, the origin-based travel time reliability indices of Tiananmen are higher than the network-wide values shown in Table 1. It is reasonable because Tiananmen is one of the most prosperous and busiest points of interest in Beijing. The BTRI of Tiananmen is lower, however, which indicates that continuous congestion exists when passengers travel from Tiananmen to other places. The travel time reliability of Tiananmen shows the traffic environment around it. The passengers whose travel originates from Tiananmen may pass through prosperous business and shopping centers (i.e., Xidan and Dongdan) where there may be congested traffic conditions along their trips. This may cause the BTR to be slightly higher.

Table 3 presents the monthly variations of the origin-based travel time reliability indices and the sampling outflow of the origin-based on-demand ride services of Tiananmen. The outflow indicates the number of trips that originate from a certain grid in the sample. Compared to Fig. 3, the origin-based indices are higher than the network-wide average levels, which also implies more congested conditions around Tiananmen. Comparing the 12 months of the whole year, February has the lowest values of origin-based indices, which may be influenced by the Spring Festival. However, the BTR and BTRI show that February has a larger gap between FFTR (cars run almost at free speed) and PTR (the traffic is congested). This may also be due to the effect of the Spring Festival in February.

Table 1 Yearly travel time reliability indices for Beijing in 2016

NFFTR/(min·km^{-1})	NTTR/(min·km^{-1})	NPTR/(min·km^{-1})	NBTR/(min·km^{-1})	NBTRI
1.52	2.38	4.17	1.78	75.67%

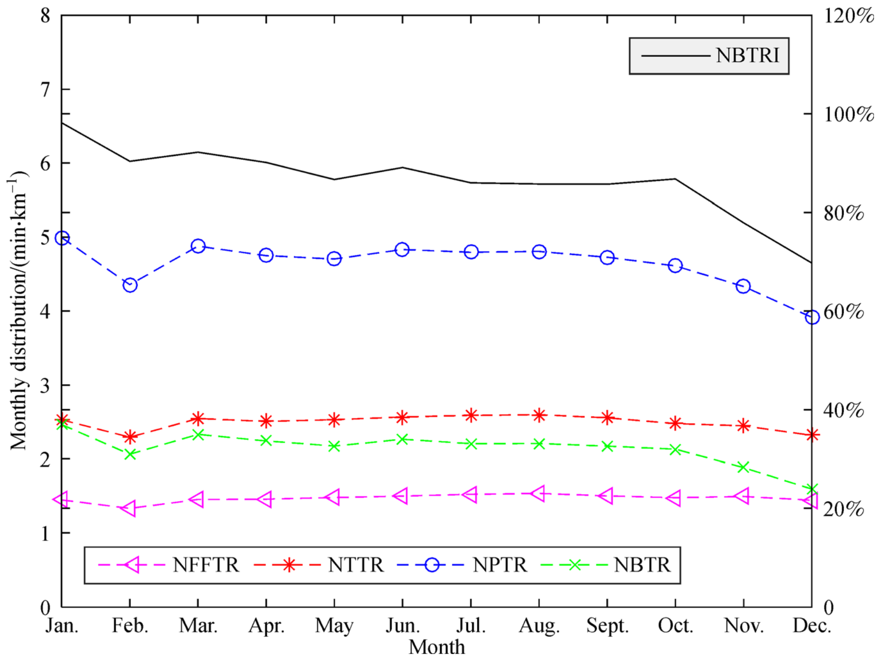

Fig. 3 Monthly distribution of travel time reliability indices in Beijing

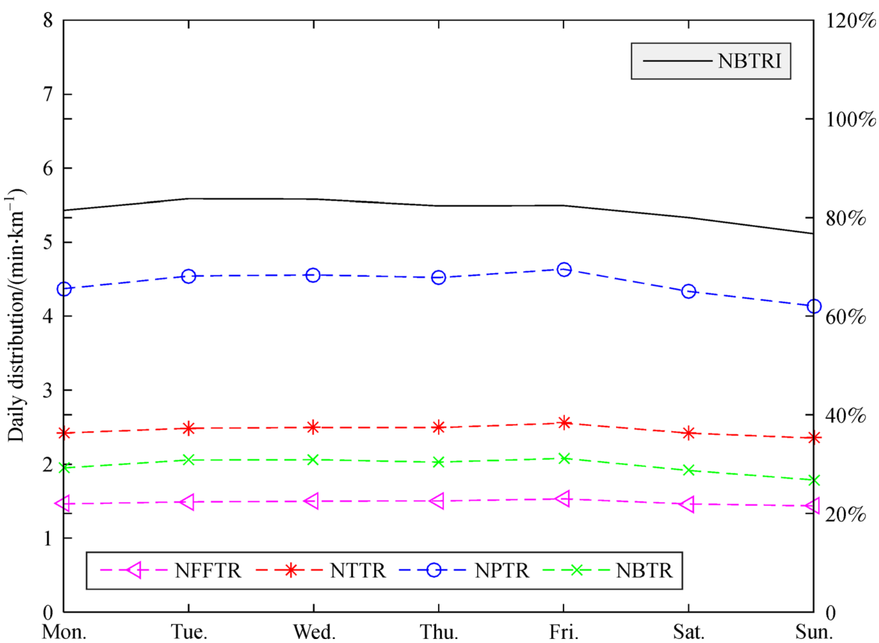

Fig. 4 Daily distribution of travel time reliability indices in Beijing

Table 4 presents the origin-based indices and the sampling outflow of the origin-based on-demand ride services of Tiananmen in terms of the day of the week. The time rate indices are higher than the network average levels. Because Tiananmen is a noted attraction in Beijing, the travel flows from Tiananmen mostly consist of tourists.

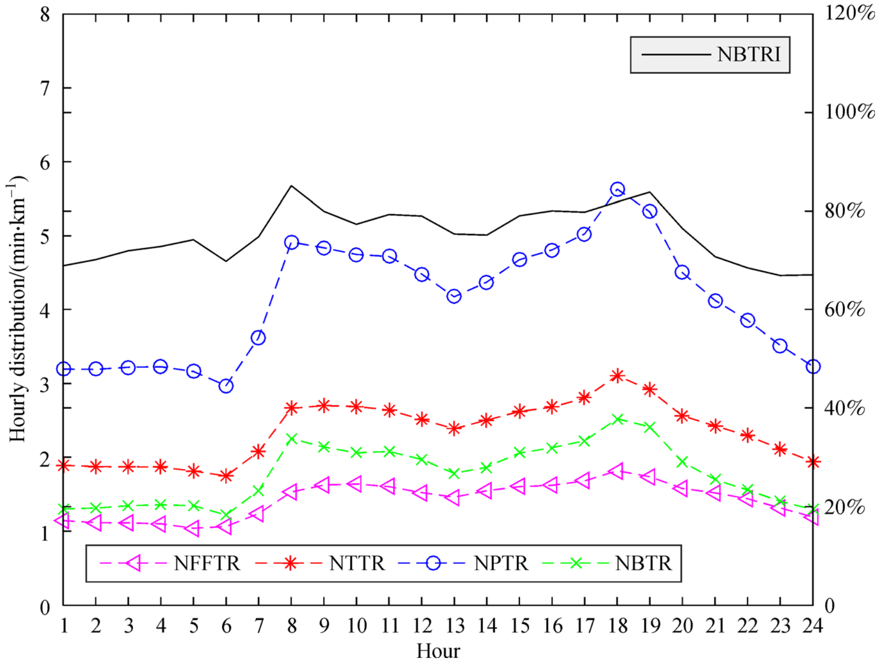

Fig. 5 Hourly distribution of travel time reliability indices in Beijing

Table 2 Origin-based travel time reliability indices of Tiananmen in Beijing (2016)

FFTR /(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI
1.91	2.94	5.00	2.07	71.03%

It is reasonable that Tiananmen attracts more visits on weekends, which is the opposite of the overall weekly trend in Beijing. The travel time reliability indices on Monday are slightly lower than the other days, which also indicates that there are more commute travels on Monday, instead of more tourism travels in Tiananmen. Thus, BTRI on Sunday is higher than the other days.

Table 5 presents the hourly origin-based indices that are higher than the network average level. The origin-based indices are obviously high in the morning for the following two reasons: first, the residents going to work in the morning increase the traffic congestion and travel time variations; and second, the flag-raising ceremony in the morning at Tiananmen attracts many tourists, which causes unreliability in morning travel times. In contrast, there is a steady stream of tourists departing Tiananmen throughout the day. As a result, the reliability in the evening does not rise like the overall trend.

We further analyze the reliability for the three representative categories of points of interest in Beijing, including transportation hubs (e.g., Capital International Airport, Beijing Railway Station, Beijing South Railway Station, Beijing North Railway Station, Beijing West Railway Station, and Beijing East Railway Station), tourist attractions (e.g., Temple of Heaven, the Summer Palace, 798 Art Zone and Sanlitun bar street), and business centers (e.g., Wangfujing, Dashilar, China World Mall, Oriental Plaza and Xidan).

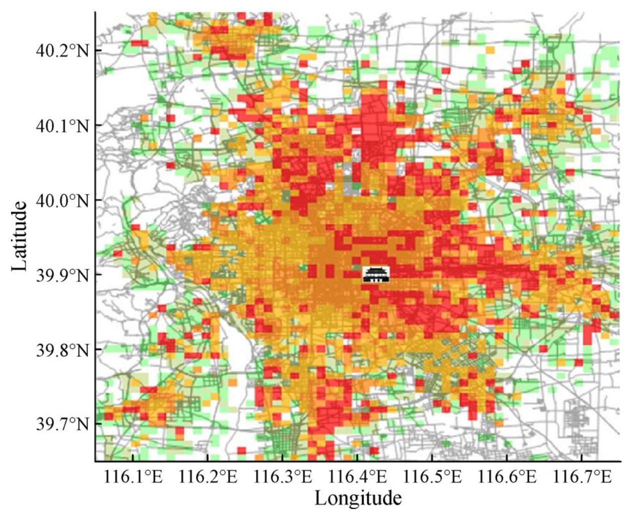

Fig. 6 Spatial distribution of the origin-based buffer time rate index in Beijing (red for low reliability, orange for median reliability, and green for high reliability)

Tables 6–8 present the origin-based travel time reliability indices and the origin-based on-demand ride services

Table 3 Monthly origin-based travel time reliability indices of Tiananmen in Beijing (2016)

Month	NFFTR/(min·km^{-1})	NTTR/(min·km^{-1})	NPTR/(min·km^{-1})	NBTR/(min·km^{-1})	NBTRI	Sampling outflow/ (trips·year^{-1})
January	2.26	3.67	5.70	2.03	56.03%	549
February	2.09	2.47	4.10	1.64	66.37%	274
March	2.97	3.65	5.00	1.36	36.91%	551
April	2.30	3.59	5.55	1.97	55.61%	806
May	2.57	3.76	5.75	1.99	51.94%	939
June	2.58	3.71	5.96	2.25	61.50%	911
July	2.63	3.88	5.83	1.96	53.07%	920
August	2.48	4.01	6.26	2.25	56.80%	817
September	2.41	3.42	5.00	1.59	47.00%	733
October	2.40	3.48	5.78	2.30	68.97%	669
November	2.32	3.22	4.97	1.75	56.49%	515
December	2.07	3.01	4.58	1.57	53.35%	545

Table 4 Daily origin-based travel time reliability indices of Tiananmen in Beijing (2016)

Day of week	FFTR/(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI	Sampling outflow /(trips·year^{-1})
Monday	2.14	3.14	4.92	1.78	56.07%	1243
Tuesday	2.26	3.26	5.23	1.97	62.34%	1128
Wednesday	2.29	3.41	5.27	1.85	55.09%	1132
Thursday	2.30	3.44	5.46	2.02	60.27%	1153
Friday	2.37	3.37	5.11	1.75	53.29%	1123
Saturday	2.29	3.50	5.57	2.07	58.50%	1132
Sunday	2.28	3.46	5.80	2.34	69.07%	1318

outflows of transportation hubs, tourist attractions, and business centers, respectively. It is easy to see that Beijing Railway Station, Sanlitun Bar Street, and the China World Mall are the most unreliable locations. The outflows of these three locations are almost the largest in the selected points of interests. These places are more crowded than the others. Their FFTR values are smaller while the NPTR values are larger than the other selected points of interest, which implies the three locations are much more variable in travel time than the other ones. This phenomenon also shows that travel reliability may change over time. For the time when there are few vehicles on the road, the reliability indices are small, and thus the road network is more reliable. Comparing the BTR of the three categories, the value of the business centers is the largest, because this type is the most obvious one to show the routine of life and work for citizens.

5 Conclusions

Smooth and reliable urban traffic is not only the way for residents to realize their travel purposes but also formulates one of the goals of urban traffic management. This paper examines the road network travel time reliability and establishes five travel time reliability indices (i.e., NFFTR, NTTR, NPTR, NBTR, and NBTRI) based on the emerging on-demand ride service data to better understand the dynamics and variations of urban road transportation systems. The indices take into account the probability distribution of the travel time rate of each OD pair in the road network. We use real-world data extracted from Didi-Chuxing, which is the largest on-demand ride service platform in China. The proposed indices are applied to Beijing for evaluating both the network-wide and specific locations' travel time reliability. The analyses are conducted temporally and spatially. The results show that the road network is more unreliable in the AM/PM peaks than other time periods, and the most reliable time period is the early morning. Additionally, the central region is more unreliable than other regions of the city based on the spatial analysis results.

Under the big data platform of on-demand ride services, the travel time reliability indices proposed in this study can better evaluate the regional and urban traffic variations and provide guidance for transportation participants. The reliability indices can fit different levels of users, including travelers and traffic managers, and have the potential to

Table 5 Hourly origin-based travel time reliability indices of Tiananmen in Beijing (2016)

Hour	FFTR/(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI	Sampling outflow /(trips·year^{-1})
0 h	2.20	3.18	4.80	1.61	51.76%	348
1 h	2.23	3.10	4.85	1.75	56.85%	207
2 h	2.34	3.22	4.88	1.66	52.69%	116
3 h	2.28	3.15	4.81	1.66	52.79%	72
4 h	2.15	2.96	4.34	1.38	47.54%	40
5 h	2.32	3.20	4.86	1.66	53.14%	41
6 h	2.41	3.26	5.05	1.79	55.88%	79
7 h	2.44	3.30	5.07	1.77	54.40%	228
8 h	2.44	3.42	5.15	1.73	51.19%	349
9 h	2.60	3.73	5.59	1.85	50.93%	445
10 h	2.39	3.37	5.14	1.77	53.30%	425
11 h	2.21	2.97	4.29	1.32	45.36%	434
12 h	2.15	2.87	4.14	1.27	45.18%	436
13 h	2.07	2.74	3.81	1.07	39.06%	441
14 h	1.90	2.48	3.54	1.06	43.77%	472
15 h	1.66	2.12	2.92	0.80	37.70%	444
16 h	1.85	2.27	3.14	0.87	36.56%	430
17 h	1.94	2.28	3.71	1.43	59.11%	451
18 h	1.83	2.17	2.88	0.72	33.52%	406
19 h	1.81	2.27	3.60	1.33	46.12%	393
20 h	1.91	2.58	3.36	0.78	30.38%	420
21 h	1.91	2.29	3.17	0.87	35.93%	527
22 h	1.95	2.53	3.77	1.23	46.62%	535
23 h	2.32	3.40	5.27	1.87	56.30%	490

Table 6 Origin-based travel time reliability indices of transportation hubs

Location	FFTR/(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI	Sampling outflow/(trips·year^{-1})
Capital International Airport	1.20	1.67	2.74	1.07	65.16%	1781
Beijing Railway Station	1.78	2.83	4.95	2.11	75.49%	21919
Beijing South Railway Station	1.54	2.33	3.96	1.63	71.22%	10829
Beijing North Railway Station	1.67	2.58	4.37	1.79	70.84%	14791
Beijing West Railway Station	1.48	2.32	4.08	1.76	76.62%	13479
Beijing East Railway Station	1.70	2.82	5.01	2.19	78.88%	27188

Table 7 Origin-based travel time reliability indices of tourist attractions

Location	FFTR/(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI	Sampling outflow/(trips·year^{-1})
Tiananmen	1.91	2.94	5.00	2.07	71.03%	8229
Temple of Heaven	1.87	2.81	4.65	1.84	66.58%	7113
The Summer Palace	1.76	2.50	4.34	1.84	73.75%	1185
798 Art Zone	1.78	2.75	4.70	1.95	71.43%	14901
Sanlitun Bar Street	1.73	2.84	5.08	2.24	79.91%	27658

Table 8 Origin-based travel time reliability indices of business centers

Location	FFTR/(min·km^{-1})	TTR/(min·km^{-1})	PTR/(min·km^{-1})	BTR/(min·km^{-1})	BTRI	Sampling outflow/(trips·year^{-1})
Wangfujing	1.93	3.01	5.13	2.12	70.23%	12429
Dashilar	1.95	2.95	4.90	1.95	65.81%	9093
China World Mall	1.78	2.97	5.28	2.31	79.45%	27503
Oriental Plaza	1.81	2.85	4.93	2.08	73.33%	17696
Xidan	1.87	2.93	4.94	2.02	69.19%	17994

help adjust individual travel strategies and improve the efficiency of traffic operations. In one word, the proposed network travel time reliability indices provide insights for the comprehensive evaluation of the road network traffic dynamics and day-to-day travel time variations. This paper has some shortcomings: the data we used are extracted from a single transportation network company, which may influence the final results. Thus, in future research, we expect to pay more attention to the collection of various data sources, e.g., GPS data, to refine the estimation of the travel time reliability indices.

Notations

i	The serial number of the origin grid
j	The serial number of the destination grid
k	the kth trip of a certain OD pair
d_{ijk}	Travel distance of trip k from origin i to destination j
τ	Random variable of travel time rate
τ_{ijk}	Travel time rate of the trip k from origin i to destination j
$\overline{\tau}_{ij}$	Mean travel time rate of the OD pair (i, j)
$\tau_{ij,\alpha}$	Travel time rate percentile at the confidence level of α for the OD pair (i, j)
$f_{ij,}(\tau)$	Probability density function of τ for the OD pair (i, j)
$F_{ij,}(\tau)$	Cumulative distribution function of τ for the OD pair (i, j)
n_{ij}	Number of trips from origin i to destination j
t_{ijk}	Travel time of trip k from origin i to destination j
w_{ij}	Weight of the OD pair (i, j)
β_{ij}	Buffer time rate of the OD pair (i, j)
η_{ij}	Buffer time rate index of the OD pair (i, j)
NBTR	Network buffer time rate
NBTRI	Network buffer time rate index
NFFTR	Network free-flow travel time rate
NPTR	Network planning time rate
NTTR	Network travel time rate

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