Bus Travel Time Reliability Incorporating Stop Waiting Time and In-vehicle Travel Time with AVL Data

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Abstract

Improving bus operation quality can attract more commuters to use bus transit, and therefore reduces the share of car and alleviates traffic congestion. One important index of bus operation quality is the bus travel time reliability, which in this paper is defined to be the probability when the sum of bus stop waiting time and in-vehicle travel time is less than a certain threshold. We formulate the bus travel time reliability by the convolution of independent events' probabilities, and elaborate the calculation method using Automatic Vehicle Location (AVL) data. Next, the No.63 Bus Line in Harbin City is used to test the applicability of the proposed method, and analyze the influence factors of the bus travel time reliability. The numerical results show that factors such as weather, workday, departure time, travel distance, and the distance from the boarding stop to the bus departure station will significantly affect the travel time reliability. At last, some general conclusions and future research are summarized.

1. Introduction

Bus transit plays an important role in the urban transportation system because of its positive effects on reducing traffic congestion. When traveling by bus, "arriving as planned" is the main requirement for all travelers (Nakanishi, 2002). While the operation of a bus is more likely to suffer from a range of factors, such as traffic congestion and weather, which often cause more unreliability for operations and undermine the attractiveness of bus service. Therefore, establishing an effective evaluation system for bus service quality (which is often measured by time reliability/stability) can be greatly helpful to improve traffic efficiency (Hassan et al., 2013).

Multiple reliability criteria can be used for the evaluation and optimization of bus transit system's performance. Lin et al. (2008) proposed a quality control framework based on headway. Gittens and Shalaby (2015) used multiple deviation indexes to evaluate bus reliability. Yao et al. (2015) proposed an evaluation method for exclusive bus lanes to consider travel time disturbance affected by road degradation. Ma et al. (2017) established a bus travel time reliability model focusing on average travel time, buffer time and coefficient of variation of travel time. For the optimization of bus transit systems, Xuan et al. (2011) analyzed dynamic bus holding strategy and proposed an optimal method by taking the bus arrival time as a single parameter. Yao et al. (2014) presented a transit network optimization method considering travel time reliability. These studies are all based on reliability; although the definition of reliability is different, the travel time reliability is indeed an indispensable part of these studies.

The ambiguity of passengers' perception and the evaluation of bus travel time reliability are two major difficulties in evaluating transit system's reliability. Koster et al. (2011) analyzed the cost of travel time variability for travelers to the airport, which shows that due to the uncertainty of in-vehicle travel time, passengers are willing to spend about 30% of the additional travel costs to avoid flight delays. Asensio and Matas (2007) studied commuters' valuation of travel time variability, and proposed a relationship between the reduction of bus travel time and the saving of commuter costs; the study shows that due to the heterogeneity among travelers, the values of travel time are significantly different. The above researches on passengers’ perceived fuzziness demonstrate that there is a relationship between passengers’ attributes and the maximum reliable travel time they can tolerate. Recently, the widespread of Automatic Vehicle Location (AVL) equipment has brought a new era to the research of transit systems reliability. Chen et al. (2009) analyzed urban bus service reliability by using bus arriving time deviation’s punctuality index; the research pointed out that the bus service reliability in Beijing is highly correlated with route distance, bus headway, distance from boarding stop to bus departure station, and the implementation of exclusive bus lanes. Tao et al. (2016) used smart card data and detailed weather measurement data to explore the impact of Brisbane’s weather conditions on both bus passengers and bus services. Chang (2010) proposed a method based on the logit model to assess the travel time reliability, and discussed the impact of travel time uncertainty on the assessment of travel time reliability. Sun (2015) used public transportation smart card data to evaluate the public transportation reliability in Singapore, and established reliability models based on passengers' waiting time at stops and bus departure time. Chakrabarti (2015) demonstrated that high-reliability bus lines meet passengers’ travel needs better by using real-time geo-referenced vehicle location data. Barabino et al. (2013) considered the reliability at bus stops by using AVL data and proposed that the percentage of passengers receiving regular service and punctual service can be used to evaluate bus travel time reliability. Meng and Qu (2013) established a probabilistic model to predict the bus dwell time at the bus bay, and the prediction process is a standard regenerative stochastic process involving arrival passengers and the traffic on shoulder lane. However, the existing researches have not combined the fuzziness of passengers’ perception in the evaluation of bus travel time reliability, which may cause some limitations in evaluating different passenger groups.

In this paper, the probability when the bus travel time is less than a certain threshold is formulated to measure the bus travel time reliability. A case study based on AVL data is conducted to quantitatively evaluate the bus travel time reliability of a bus line in Harbin under different conditions. The purpose of this work is to better understand the relationship between the different factors and the bus travel time reliability, then guide bus service providers to improve the quality of bus services by handing/optimizing the most unfavorable factors. In addition, the bus travel time reliability of different bus lines can be compared using the proposed model.

The remainder of this paper is organized as follows. Section 2 establishes the bus travel time reliability model, in which both travelers’ stop waiting time and in-vehicle travel time are considered. Section 3 illustrates how to calculate the proposed bus travel time reliability based on raw AVL data. In Section 4, a case study of Harbin No.63 Bus Line is conducted to show how the factors, such as the travel time threshold, weather and workday, affect the bus travel time reliability. Finally, some general conclusions and further researches are summarized and discussed in the last section.

2. Model Establishment

2.1 Composition of Bus Travel Time

A complete bus travel time consists of stop waiting time, in-vehicle travel time and walking time. Usually, walking time does not affect the reliability of bus transit. Thus, in this paper the bus travel time is defined to be the sum of the stop waiting time and the in-vehicle travel time:

$$T_{BT} = T_{SW} + T_{IT} (1)$$

where:

T_{BT} is bus travel time;

T_{SW} is stop waiting time;

T_{IT} is in-vehicle travel time;

2.2 Definition of Bus Travel Time Reliability

In reality, it is common that the unpredictable interference factors delay the stop waiting time and the in-vehicle travel time. Considering the travel time threshold T_{TT} is the travellers' maximum expected bus travel time, the bus travel time reliability can be defined as the probability of the case when the actual bus travel time is less than T_{TT}:

$$R_{BT} = P\left(T_{SW} + T_{IT} \leq T_{TT}\right) (2)$$

where:

T_{TT} is bus travel time threshold;

2.3 Calculation of Bus Travel Time Distribution Function

In a short period of time, stop waiting time and in-vehicle travel time for travelers are independent (HyunhoChang et al., 2010; Mazloumi et al., 2011; Ran, 2004). According to the convolution theorem, the probability density function of bus travel time can be expressed as:

$$f_{BT}(T) = \int_0^T f_{SW}(T - t) f_{IT}(t)\, dt (3)$$

where:

f_{BT} is the probability density function of bus travel time;

f_{SW} is the probability density function of stop waiting time;

f_{IT} is the probability density function of in-vehicle travel time;

T is the bus travel time;

Stop waiting time is mainly influenced by the time when passenger and bus arrive at the stop, the probability density function of stop waiting time can be shown as:

$$f_{SW}^{'}(T) = \int_{T}^{+\infty} f_{headway}\left(t_{headway}\right) f_{PA}\left(t_{headway} - T\right) dt_{headway} \quad (4)$$

$$f_{PA}\left(t_{headway} - T\right) = \frac{N_{PA}\left(t_{headway} - T\right)}{\int_{0}^{T_{SI}} N_{PA}(t)\, dt} \quad (5)$$

$$f_{SW}(T) = \frac{f_{SW}^{'}(T)}{\int_{-\infty}^{+\infty} f_{SW}^{'}(T)} \quad (6)$$

where:

$f_{SW}^{'}$ is the probability density function of stop waiting time before normalization;

f_{PA} is the probability density function of passenger arrival time;

$f_{headway}$ is the probability density function of headway;

N_{PA} is the number of passengers arriving at the stop when the time between the latest bus departure and the passenger arrival at the stop is t;

T is the passenger stop waiting time;

T_{SI} is the schedule bus departure interval;

$t_{headway}$ is the time of headway.

If bus arrives with high frequency, the passengers' arrival frequency will satisfy the uniform distribution (Amin-Naseri and Baradaran, 2015):

$$N_{PA}(t) = \frac{1}{T_p} \quad (7)$$

$$f_{PA}(t) = \frac{1}{T_{SI}} \quad (8)$$

$$f_{SW}^{'}(T) = \frac{1}{T_{SI}} \int_{T}^{+\infty} f_{headway}\left(t_{headway}\right) dt_{headway} \quad (9)$$

$$f_{SW}(T') = \frac{\int_{T'}^{+\infty} f_{headway}\left(t_{headway}\right) dt_{headway}}{\int_{-\infty}^{+\infty}\int_{T'}^{+\infty} f_{headway}\left(t_{headway}\right) dt_{headway}} (10)$$

where:

T_p is the passenger arrival time interval;

In-vehicle travel time is the time from the boarding stop to getting off stop. The probability density function of headway $f_{headway}$ and the in-vehicle travel time density function f_{IT} can be obtained by data fitting.

2.4 Measurement of Bus Travel Time Threshold

Bus travel time threshold is usually related to traveler's travel experience, and travelers with different travel purposes often have different bus travel time thresholds. In this paper, the bus travel time threshold is considered to be related to expected stop waiting time based on scheduled headway, free flow in-vehicle time, average delays in waiting for traffic lights and travelers' psychology index, which is shown as below:

$$T_{TT} = \left(T_{EW} + T_{MT} + T_{TL}\right) \times \gamma (11)$$

where:

T_{EW} is the expected stop waiting time based on the scheduled headway;

T_{MT} is the minimum in-vehicle travel time;

T_{TL} is the average delays in waiting for traffic lights.

γ is traveler's psychology index. Generally, γ is larger than 1.

When the bus arrival is uniform distributed at fixed-time controlled intersections, and we ignore the time loss by vehicle start, T_{TL} is:

$$T_{TL} = \frac{{t_{red}}^2}{2C} (12)$$

where:

C is the traffic light cycle;

t_{red} is the red light time;

Bus travel time threshold is affected by bus arrival interval. High and low frequency of bus services should be distinguished (Barabino et al., 2017; Chen et al., 2010), which is usually measured by a threshold of 10-12 minutes of bus interval (Barabino et al., 2017; Yao et al., 2014; Eboli and Mazzulla, 2011). For high frequency, passenger arrival frequency usually satisfies the uniform distribution (Amin-Naseri and Baradaran, 2015; Zheng et al., 2017). If the bus arrival frequency is low, passengers will deliberately control their arrival time based on timetable so that they can reduce the stop waiting time, accordingly, the passenger arrival frequency could not satisfy the uniform distribution. For convenience, this paper only studies the case with high bus arrival frequency.

The best case for bus travelling is that buses run in accordance with timetable strictly, then the headway is fixed, and the average stop waiting time is minimal theoretically, which is often defined as expected stop waiting time. According to the uniform distribution formula (Osuna and Newell, 1972), the expected stop waiting time is half of the schedule bus departure interval as:

$$T_{EW} = \frac{1}{2} T_{SI} (13)$$

where:

T_{SI} is the schedule bus departure interval;

The in-vehicle travel time under the best traffic conditions can be set as the minimum value among the historical data:

$$T_{MT} = min\left(T_{IT}\right)$$

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2.5 Calculation of bus travel time reliability

According to the above definitions, the bus travel time reliability can be expressed as:

$$R_P = \int_{-\infty}^{T_{TT}} f_{BT}(t)\, dt (15)$$

Note that actual bus travel time must be nonnegative, the tail of the utilized distribution function less than zero is very small, and it almost has no effect on the result.

3. Ral Avl Data Processing

AVL recorder is a kind of digital electronic recording device, which can record vehicle speed, time, location, stations, and other vehicle-related status information by using the integrated GPS positioning module and GPRS communication module. Different AVL recorders have different data format, therefore it is necessary to perform a preliminary processing to the parameters. The following part will use the AVL data obtained from Harbin Public Transport Administration as an example.

The main field names of AVL data and their descriptions are shown in Table 1:

Table 1
Field names of AVL data

Field Name	Description
O_LINENAME	Line ID
O_BUSNAME	Bus ID
O_ARRIVETIME	Arrival Time
O_UP	Direction
O_STATIONNO	Stop ID
O_DATE	Date

The data process procedures are as follows:

First, extract data in the fields shown in Table 1, and fill in missing data by three-layer neural network prediction method (HyunhoChang et al., 2010; Mazloumi et al., 2011; Ran, 2004).

Second, combine the "Arrival Time" and "Date" fields to "Time" field. The bus travel time reliability is calculated in the interval of hour, and data is grouped according to the "Time" field. The data with bus arrival time from t to $t+1$ are pushed in a set s_t and arranged in ascending order. If there are n members in the vector s_t, the headway set $S_{headway}$ can be calculated as:

$$S_{headway}(t) = \{s_t(i+1) - s_t(i) | i = 1, \ldots, n-1\} (16)$$

By fitting the headway, the headway probability density function $f_{headway}$ is obtained.

Passenger arrival frequency conforms to uniform distribution, so there is:

$$f_{SW}(T) = \frac{\int_{T}^{+\infty} f_{headway}\left(t_{headway}\right) dt_{headway}}{\int_{-\infty}^{+\infty}\int_{T}^{+\infty} f_{headway}\left(t_{headway}\right) dt_{headway}} (10)$$

Bus bunching exists in bus transit system. The arrival time arranged in time series is not matched with bus IDs, so the in-vehicle travel time needs to be dealt separately.

Arrange the data in ascending order according to "Time" field for the departure stop (passengers' origin). Mark $b_i(k)$ as the time when the k^{th} bus leaves the departure i^{th} stop and $b_j(k)$ to be the time when the k^{th} bus arrives at j^{th} stop. $S_{IT}(t)$ is the in-vehicle travel time set for all the bus trips from i^{th} stop to j^{th} stop, it can be described as:

$$S_{IT}(t) = \left\{ b_j(k) - b_i(k) \mid, k = 1, \ldots, n \right\} (17)$$

Then the probability density function f_{IT} can be obtained by fitting the in-vehicle travel time.

Finally, based on the scheduled bus headway, the expected stop waiting time could be obtained. And the calculation of all parameters in bus travel time reliability has finished.

4. Case Study

This section uses an actual AVL data set to demonstrate analysis process and results of the bus travel time reliability. Furthermore, how the related parameters/factors such as travel time threshold, weather, workday, time periods within a day, travel distance, and distance from the traveler's origin stop to the origin terminal affect the results is also conducted.

The AVL data of Harbin in December 2012 is obtained from Harbin Xiantong Bus Company. In the position close to the origin-terminal station, because the high-rise blocked the GPS signal or drivers stalled the buses too early, the AVL system failed to correctly work when the vehicle on the stop, which may result in the missing of about 30% of the data. We use the three-layer neural network to learn the data, 70% of the valid AVL data is used to train the network, leaving 30% for accuracy verification, and then the missing data will be predicted and completed. Through comparison at the same hour, the data after completion is basically reliable and can be used for the next calculation.

4.1 Background Parameters

The No.63 bus line of Harbin City is taken as an example to do these demonstrations. As shown in Fig. (1), it includes 20 bus stops with a total mileage of 10.8 km from Jiangong Community to Dajiang Community, and the main street passed by the line is named West Dazhi Street.

4.2 Parameter Calculation and Function Fitting

The procedure of calculating the bus travel time reliability is shown in the following example, which is performed by the data of the origin-destination (O-D) pair from the 5th stop to the 18th stop on December 4th .

4.2.1 AVL Data Preprocessing

Firstly, the neural network prediction method is applied to fill in the missing data, then in order to facilitate data analysis, the fields named O_WEEKEND and O_WEATHER are manually added into the AVL data by referring to the historical weather and weekends.

4.2.2 Fitting of the Actual Travel Time Function

After data preprocessing, the headway sets and in-vehicle travel time sets of this O-D pair are obtained by using the sorted group. The sets divided by an hour of one day have too few elements to get a reasonable fitting result, while the sets divided by the same hour of the month ignore the factors such as weather and weekends, so the set divided by a day is used when function fitting.

The mean value of headway $T_{headway} = 299.7s$, and the detailed results with different fitting functions are shown in Table 2:

Table2. The fitting results with different functions for headway

Function Name	SSE	R-square	Adjusted R-square	RMSE
Normal	0.0024	0.9535	0.9443	0.0156
Exponential	0.0458	0.1308	0.0518	0.0645
Uniform	0.0286	0.5057	0.4704	0.0320

It is clear that the normal function gives the best result. The normal function satisfies:

$$f_{headway}(T) = 0.1775exp\left(-\left(\frac{T-229.0}{157.0}\right)^2\right)(18)$$

Similarly, as shown in Table 3, the fitting results of the in-vehicle travel time from 5th stop to 18th stop show that the Normal distribution function still has the highest fitting degree.

Table 3
The fitting results with different functions for in-vehicle travel time

Function Name	SSE	R-square	Adjusted R-square	RMSE
Normal	0.0025	0.9702	0.9669	0.0118
Exponential	0.0596	0.2865	0.1606	0.0592
Uniform	0.1056	0.2636	0.2034	0.0709

The fitted Normal function equation is as:

$$f_{IT}(t) = 0.1875exp\left(-\left(\frac{t-1985}{291.9}\right)^2\right)(19)$$

According to the analysis above, it's clear that the Normal distribution function can fit more accurate results. Therefore, the Normal distribution function will be used to fit the probability density function of stop waiting time and in-vehicle travel time.

4.2.3 Calculation of Excepted Bus Travel Time

The departure interval of No.63 bus is controlled by schedule. The schedule bus departure is 5 minutes, that is $T_{SI} = 300$s, and the excepted stop waiting time T_{EW} is $\frac{T_{SI}}{2} = 150s$.

According to Eq. (12) and Eq. (14), the minimum in-vehicle travel time $T_{MT} = 1807.8s$, $\sum T_{TL} = 300.0s$, then the bus travel time threshold T_{TT}=$2257.8s \times \gamma$.

4.3 Evaluation of Bus Travel Time Reliability

In this section, the correlation between bus travel time reliability and the following parameters/factors are analyzed: 1) The value of γ; 2) Weather, workday and time periods within a day; 3) Travel distance; 4) Distance from the origin terminal to the traveler's origin stop.

The concept of bus travel time reliability is defined for time periods. Therefore, in the later part of the paper, the value corresponding to time t represents the bus travel time reliability from t to $t+1$; the value corresponding to date t represents the hourly average bus travel time reliability at day t.

4.3.1 The Influence of γ Value

Eq. (11) shows that the value of γ is related to travelers' tolerance for delays in bus travel. It has a direct impact on the bus travel time reliability. A suitable γ value can not only clearly distinguish different traffic conditions, but also fit passengers' travel experience.

How γ affects the bus travel time reliability is shown in Fig. (2).

As shown in Fig. (2), too high or low γ will result in a smaller range of bus travel time reliability in a day. And γ is derived from the reasonable judgment of passengers' in bus travel time fluctuations, so it has a fuzzy range of values.

Note that when $\gamma = 1.8$, the bus travel time reliability from 5th stop to 18th stop on December 4th is 0.8738, which is a relatively high result, and it could be reasonable to consider that the result can exactly correspond to the actual situation (according to the historical data, we can know that the traffic conditions on that day were better). Therefore, γ will be fixed to 1.8 in the following part.

When comparing the bus travel time reliability between different cities, the bus travel time threshold can be calculated by the same γ so as to compare the overall differences in bus travel time reliability between different cities by the same evaluation procedure.

4.3.2 The Influence of Weather, Workday and Time Periods within a Day

In order to evaluate the bus travel time reliability of the same O-D pair in different situations, the 5th stop and the 18th stop are selected as origin stop and destination stop respectively. The mean and standard deviation of bus travel time and bus travel time reliability in different time period is shown in Fig. (3) and Fig. (4) respectively.

As shown in Fig. (3), the mean of the in-vehicle travel time has a bigger fluctuation, especially in the morning and evening peak hours. But the mean of stop waiting time is relatively smoother, which implies that the stop waiting time is less affected by peak hours. Besides, it also can be seen that with the change of time periods, the standard deviation of the in-vehicle travel time and stop waiting time has the similar trend, which is also similar to the change trend of the mean of the in-vehicle travel time.

Fig. (4) shows that the bus travel time reliability is low in peak hours (8 am to 11 am17 pm to 19 pm), especially in evening peak hours. It is consistent with overall variance of in-vehicle travel time and the stop waiting time in Fig. (3). Both of them illustrate the traffic condition is bad in the peak hours, especially for the evening peak hours.

Then in order to evaluate the influence of weather and workday, the bus travel time reliability of each day in December 2012 is shown in Fig. (5), which is calculated by the average hourly bus travel time reliability of the whole day.

Table 4. The bus travel time reliability in December 2012

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
BTTR's median < 0.9	1	2	3				7					12		14						20			23	24				28	29		31
Snow	1	2	3				7					12		14						20			23	24				28	29		31
Non-snow				4	5	6		8	9	10	11		13		15	16	17	18	19		21	22			25	26	27			30	31
Workday	1	2						8	9						15	16						22	23						29	30	
Weekend			3	4	5	6	7			10	11	12	13	14			17	18	19	20	21			24	25	26	27				31
BTTR's fluctuation > 0.25	1	2	3				7				11		13							20			23	24				28	29		31
Abnormal BTTS						6		8		10			13		15		17	18	19		21	22									

BTTR: bus travel time reliability

It is shown in Fig. (5) that the bus travel time reliability in some days are lower than 0.9. It could because of the day features, e.g., weekend/workday, snow/non-snow.

By referring to the historical weather data, the snow days and other information are shown in Table 4. We find that for all the days with snow, the bus travel time reliability is lower than 0.9, which indicates a relationship between snowfall and the decrease of bus travel time reliability. For the weekends shown in Table 4, there are both high and low bus travel time reliability in these days, it cannot be intuitively inferred that it has a relationship with weekends/workdays. However, comparing the daily average bus travel time reliability on day 16 with on day 17, on day 23 with on day 24 in the same weather but different in workdays/weekends as shown in Fig. (5), it can be found that the bus travel time reliability on weekends is slightly higher than that on workdays under the same weather conditions.

In addition, it can be also seen from Fig. (5) and Table 4 that for most of the days with snow, the bus travel time reliability fluctuation is higher than 0.25, and most of the extreme bus travel time reliability data points appear on the working day, which are all low points. This shows that snow will lead to greater differences in bus travel time reliability during the day, and peak hours on work day will lead extreme low bus travel time reliability.

There are many factors that affect the bus travel time reliability, and how the related factors affect the travel time reliability together can be evaluated by comparisons. Fig. (6) and Fig. (7) give more details by considering time periods within a day simultaneously.

Fig. (6) and Fig. (7) show that the snow clearly leads a reduction of the bus travel time reliability under the same condition of weekday/weekend. The bus travel time reliability of workdays and weekends could be completely different when considering time periods within a day as shown in Fig. (7). It can be concluded that the snow/non-snow will affect the overall daily travel time reliability and the workdays/weekends will affect the travel time reliability considering time periods within a day in details.

4.3.3 The Influence of Different Travel Distance

Usually, for different in-vehicle travel distance, the effect of stop waiting time and in-vehicle travel time on bus travel time reliability is also different.

In order to explore under different travel distance, how the bus travel time reliability can be affected by the stop waiting time and the in-vehicle travel time, the bus transit travel from 5th stop to different stops is tested. In this case, 5th stop is set as the origin. Although the O-D pairs that destination is 6th stop have no practical significance due to too short distance, it is included for the convenience of evaluation. The stop waiting time reliability is defined as the bus travel time reliability when the in-vehicle travel time is zero. Similarly, the in-vehicle travel time reliability is defined as the bus travel time reliability when the stop waiting time is zero.

In addition, in order to demonstrate the impact of the two on the bus travel time reliability, it will be separately discussed according to whether it is a peak hour. The definition of peak hour is determined by referring to Fig. (7): The time period where the bus travel time reliability is always lower than 0.8 is considered as the peak hour, otherwise it is the off-peak hour. And all these reliability is calculated as monthly average value.

The result is shown as follows:

It can be seen from Fig. (8) that after the 6th stop, the bus travel time reliability has a short sharp decline due to the low in-vehicle travel time reliability. But the bus travel time reliability in the short bus trip, such as the 6th, 7th and 8th stop is still pretty high because the high stop waiting time reliability.

Actually, the influence of stop waiting time and in-vehicle travel time on the bus travel time reliability varies with the bus travel distance. In short bus travel distance, the stop waiting time occupies a greater proportion of the bus travel time, so the in-vehicle travel time reliability has little effect on the bus travel time reliability, and the bus travel time is closer to the stop waiting time reliability; with the increase of travel distance, the in-vehicle travel time takes a higher proportion in the bus travel time. At this time, the bus travel time reliability will tend to be closer to the in-vehicle travel time. We can clearly see in Fig. (8) that as the bus travel distance increases, the bus travel time reliability curve gradually changes from the stop waiting time reliability curve to the in-vehicle travel time curve.

The tendency of the bus travel time reliability formed by the model consists with the fact that in short-distance travel, people pay more attention to the stop waiting time; conversely, in long-distance travel, people pay more attention to in-vehicle travel time. Therefore, the stability of bus arrival frequency will largely affect the feel of short-distance travel passengers, and the real-time traffic conditions will more easily affect the long-distance bus travel time reliability. The in-vehicle travel time reliability at 15th stop in Fig. (8) has a significant decrease, which clearly influence the bus travel reliability curve in that point.

4.3.4 The Influence of the Distance between the Boarding Stop and the Departure Station

Because the uncertainty of bus arrival time accumulates as a bus goes along, the stability of in-stop waiting time usually decreases with the increase of the distance between the boarding stop and the departure station, especially under poor bus operation condition. In order to examine such effect, three O-

D pairs (1st stop to 6th stop, 9th stop to 13th stop, 14th stop to 18th stop) with comparable lengths but at different segments of the No.63 Bus Line are extracted for analyzing, as shown in Fig. (9). Lengths of the three O-D pairs are 2094m, 2160m and 2010m respectively. The fluctuations of bus travel time reliability caused by the distance between the boarding stop and the departure station are analyzed in this section.

The hourly bus travel time reliabilities of the three O-D pairs are calculated and shown in Fig. (10), it is clear that under similar bus travel distances, the closer the boarding stop to the departure station, the higher the bus travel time reliability will be.

Note that the bus travel time reliabilities of O-D 2 and O-D 3 have less difference. Further, they are decomposed into waiting time reliability and in-vehicle travel time reliability, as shown in Fig. (11). The dash lines represent the waiting time reliabilities, and the dash-dot lines are the in-vehicle travel time reliability; O-D 2 and O-D 3 are marked in dot and cross markers respectively. It is conspicuous that there is a noticeable discrepancy between the stop waiting time reliabilities of the two O-D pairs; the O-D 3 whose boarding stop is farther from departure station has smaller waiting time reliability. On the other hand, the in-vehicle travel time reliability of O-D 2 is smaller than that of O-D 3 because of higher road congestion level in O-D 2. Thus, the relative differences of the bus travel time reliabilities of O-D 2 and O-D 3 become small.

5. Conclusions And Discussions

This paper proposes a new method to evaluate the bus travel time reliability by calculating the probability when the sum of bus stop waiting time and in-vehicle travel time is less than a certain threshold. It is formulated by the convolution of independent events' probability and calculated by AVL data. Based on the analysis of the case study, the general conclusions are summarized as follows:

(1) A reasonable bus travel time threshold is the key to evaluate the bus travel time reliability and its value should be adjusted for different evaluation purposes.

(2) Bus travel time reliability is closely related to weekends/workdays, weather and time periods within a day. Generally speaking, bus travel time reliability often decreases significantly in snowy days and peak hours; bus travel time reliability in workday and weekend have different temporal patterns.

(3) The effect of the stop waiting time and the in-vehicle travel time on bus travel time reliability depends on the distance of the bus trip. The bus travel time reliability of short trips is more likely to be affected by the stop waiting time, while longer trips are more susceptible to in-vehicle travel time.

(4) Under similar bus travel conditions, the bus travel time reliability gets worse with the increasing of the distance from the boarding stop to the departure station.

Further research includes: (1) Analysis of the relationship between bus travel time reliability and the city's network traffic volume; (2) Evaluation of bus travel time reliability when considering bus transfer behavior; (3) Optimal bus investment strategy based on bus travel time reliability; (4) The impact of real-time bus travel time estimation on passengers' bus travel time reliability.

Ethical approval: I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by International Journal of Coal Science & Technology. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support our conclusions. No data, text, or theories by others are presented as if they were our own.

Declarations

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Authors' contribtuions: The authors confirm contribution to the paper as follows: project initiator: Jia Yao; model design: Jia Yao; data collection: Zixu Zhuang, Jian Wang and Zhanhong Cheng; data processing: Zixu Zhuang; analysis and interpretation of results: Jia Yao, Zhanhong Cheng; Jian Wang, Shi An; draft manuscript preparation: Zhanhong Cheng, Zixu Zhuang and Jia Yao. All authors reviewed the results and approved the final version of the manuscript.

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical approval: I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while it is considered by International Journal of Coal Science & Technology. No data have been fabricated or manipulated (including images) to support our conclusions.

References

1. Amin-Naseri, M. R., & Baradaran, V. (2015). Accurate estimation of average waiting time in public transportation systems. Transportation Science, 49(2), 213-222.
2. Asensio, J., & Matas, A. (2008). Commuters' valuation of travel time variability. Transportation Research Part E: Logistics and Transportation Review, 44(6), 1074-1085.
3. Barabino, B., Lai, C., Casari, C., Demontis, R., & Mozzoni, S. (2017). Rethinking transit time reliability by integrating automated vehicle location data, passenger patterns, and web tools. IEEE Transactions on Intelligent Transportation Systems, 18(4), 756-766.
4. Bladikas, A., Tsai, F. M., & Chien, S. I. (2009). Evaluation of bus travel time and schedule adherence under adverse weather. Transportation Research Board 88th Annual Meeting, Washington DC, United States.

5. Chakrabarti, S. (2015). The demand for reliable transit service: New evidence using stop level data from the Los Angeles Metro bus system. Journal of Transport Geography, 48, 154-164.
6. Chang, J. S. (2010). Assessing travel time reliability in transport appraisal. Journal of Transport Geography, 18(3), 419-425.
7. Chen, M., Liu, X., Xia, J., & Chien, S. I. (2010). A dynamic bus-arrival time prediction model based on apc data. Computer-aided Civil & Infrastructure Engineering, 19(5), 364-376.
8. Chen, X., Yu, L., Zhang, Y., & Guo, J. (2009). Analyzing urban bus service reliability at the stop, route, and network levels. Transportation Research Part A, 43(8), 722-734.
9. Eboli, L., & Mazzulla, G. (2011). A methodology for evaluating transit service quality based on subjective and objective measures from the passenger's point of view. Transport Policy, 18(1), 172-181.
10. Hassan, M. N., Hawas, Y. E., & Ahmed, K. (2013). A multi-dimensional framework for evaluating the transit service performance. Transportation Research Part A, 50(2), 47-61.
11. HyunhoChang, DongjooPark, SeungjaeLee, HosangLee, & SeungkirlBaek. (2010). Dynamic multi-interval bus travel time prediction using bus transit data. Transportmetrica, 6(1), 19-38.
12. Koster, P., Kroes, E., & Verhoef, E. (2011). Travel time variability and airport accessibility. Transportation Research Part B, 45(10), 1545-1559.
13. Lin, J., Wang, P., & Barnum, D. T. (2008). A quality control framework for bus schedule reliability. Transportation Research Part E, 44(6), 1086-1098.
14. Mazloumi, E., Rose, G., Currie, G., & Moridpour, S. (2011). Prediction intervals to account for uncertainties in neural network predictions: methodology and application in bus travel time prediction. Engineering Applications of Artificial Intelligence, 24(3), 534-542.
15. Ma, Z., Ferreira, L., Mesbah, M., & Hojati, A. (2015). Modelling bus travel time reliability using supply and demand data from avl and smart card systems. Transportation Research Record, 2533, 17-27.
16. Meng, Q., & Qu, X. (2013). Bus dwell time estimation at bus bays: a probabilistic approach. Transportation Research Part C, 36(36), 61-71.
17. Nakanishi, Y. J. (1997). Bus performance indicators: on-time performance and service regularity. Transportation Research Record, 1571(1571), 1-13.
18. Osuna, E. E., & Newell, G. F. (1972). Control strategies for an idealized public transportation system. Transportation Science, 6(1), 52-72.
19. Jeong, R. H. (2005). The prediction of bus arrival time using automatic vehicle location systems data (Doctoral dissertation, Texas A&M University).
20. Shalaby, A. S., & Gittens, A. (2015). Evaluation of bus reliability measures and development of a new composite indicator. Transportation Research Record, 2533.
21. Sun, L. (2015). Research on Urban Transit Reliability Using Smart Card Data (Doctoral dissertation, National University of Singapore).

22. Tao, S., Corcoran, J., Hickman, M., & Stimson, R. (2016). The influence of weather on local geographical patterns of bus usage. Journal of Transport Geography, 54, 66-80.
23. Xuan, Y., Argote, J., & Daganzo, C. F. (2011). Dynamic bus holding strategies for schedule reliability optimal linear control and performance analysis. Transportation Research Part B, 45(10), 1831-1845.
24. Yao, B., Hu, P., Lu, X., Gao, J., & Zhang, M. (2014). Transit network design based on travel time reliability. Transportation Research Part C, 43, 233-248.
25. Yao, J., Shi, F., An, S., & Wang, J. (2015). Evaluation of exclusive bus lanes in a bi-modal degradable road network. Transportation Research Part C, 60, 36-51.
26. Zheng, F., Liu, X., Zuylen, H. V., Li, J., & Lu, C. (2017). Travel time reliability for urban networks: modelling and empirics. Journal of Advanced Transportation, 2017, 1-13.

Figures

Figure 1

The bus route

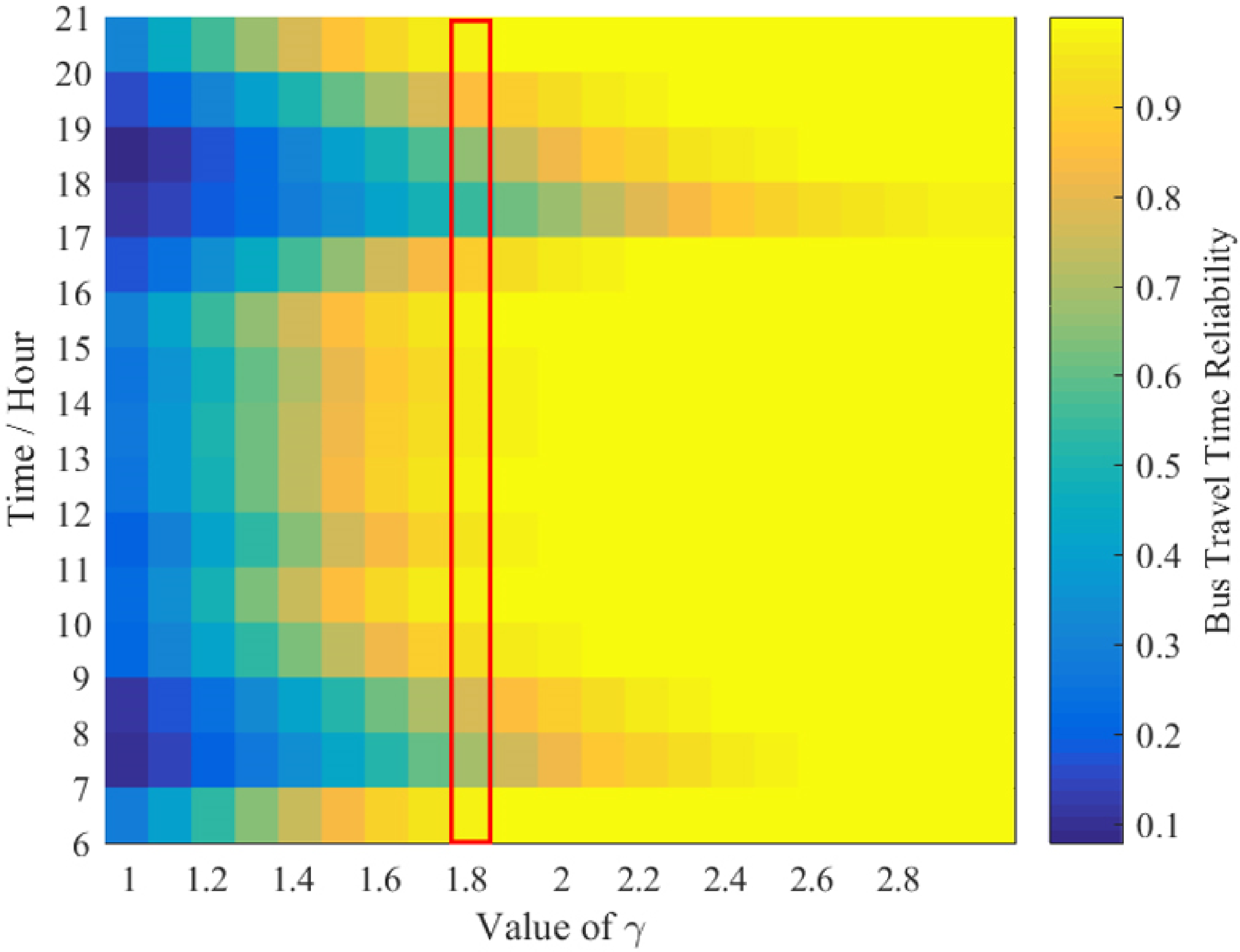

Figure 2

Bus travel time reliability with different γ

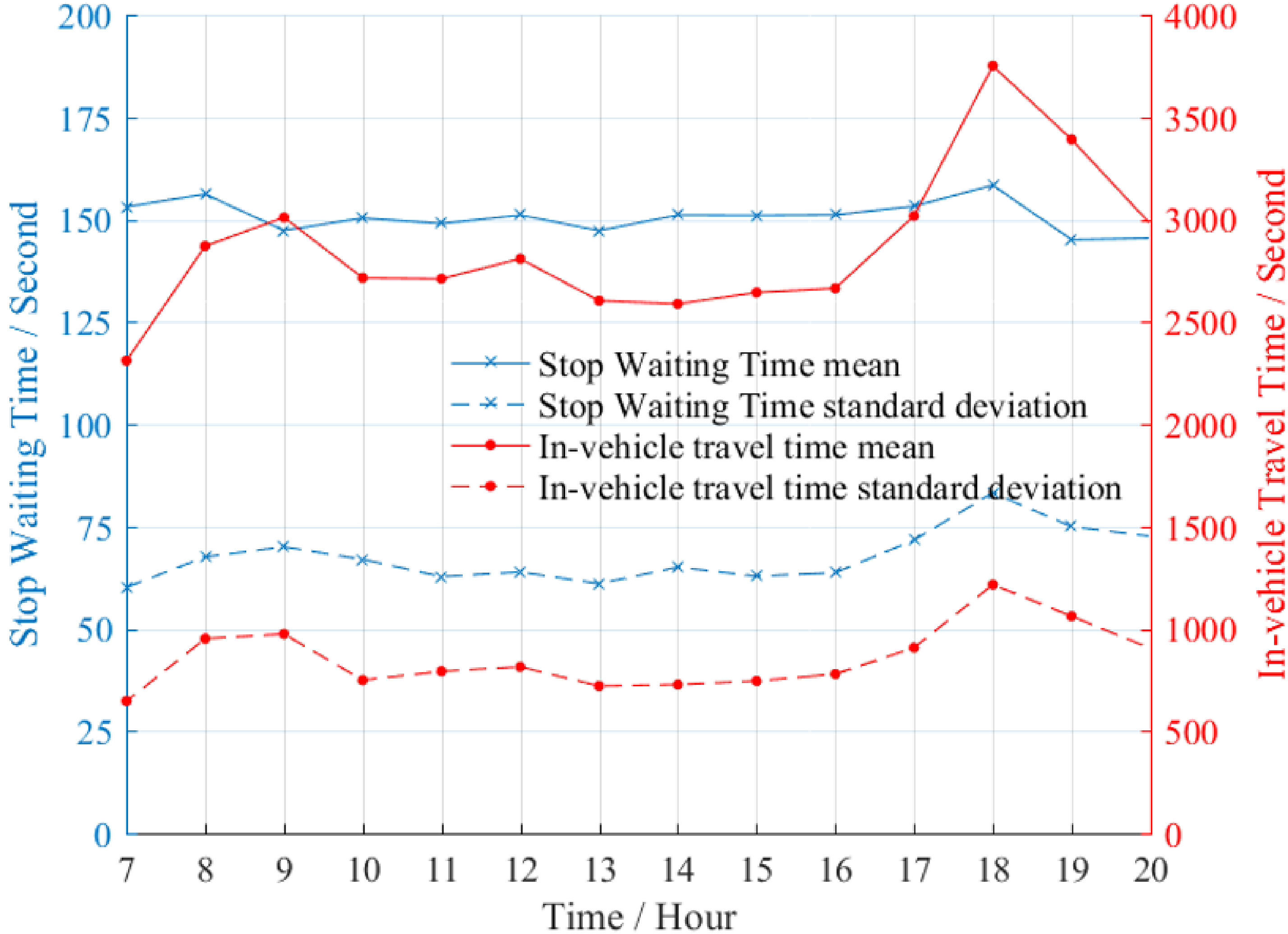

Figure 3

Bus travel time mean/standard deviation

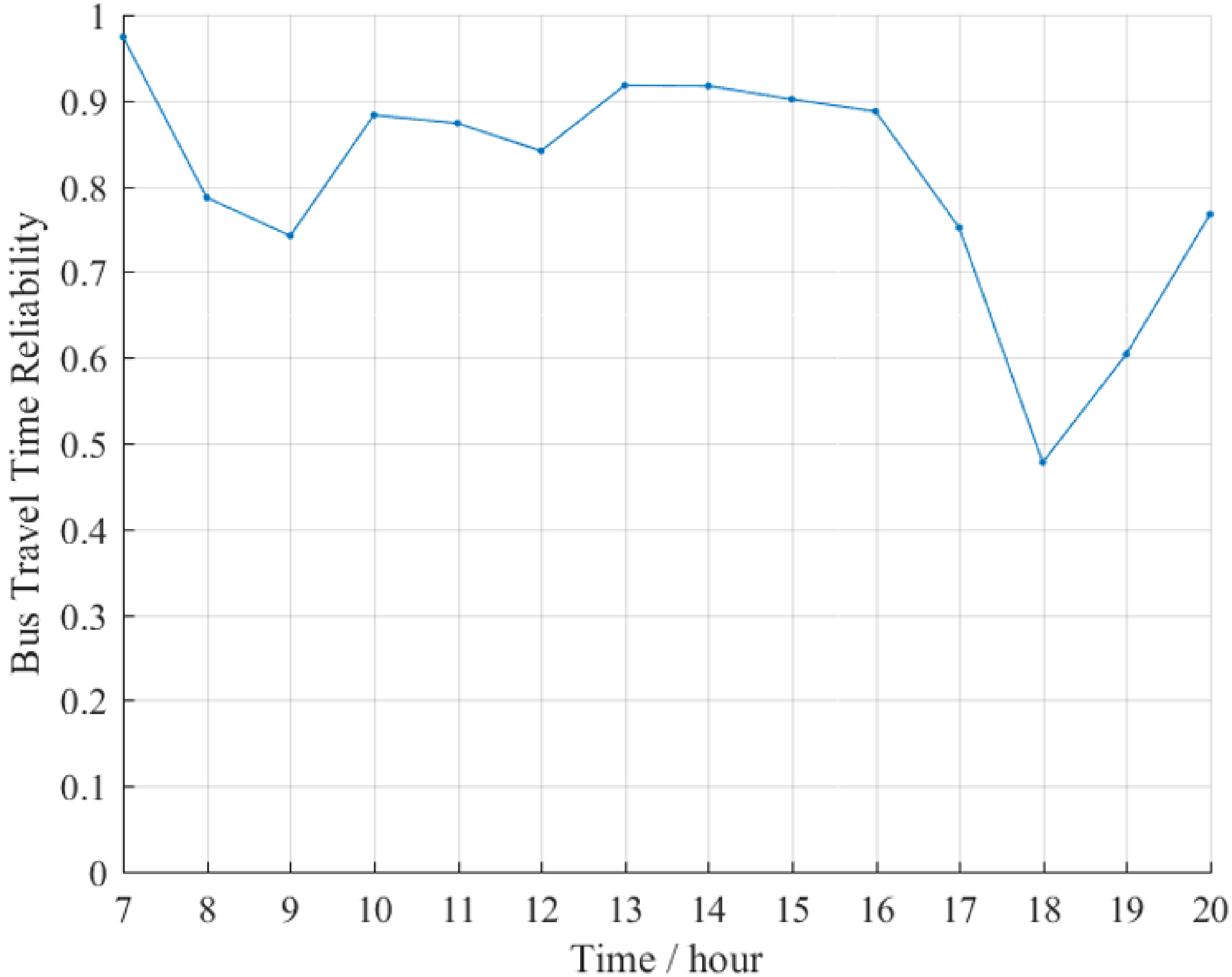

Figure 4

Bus travel time reliability

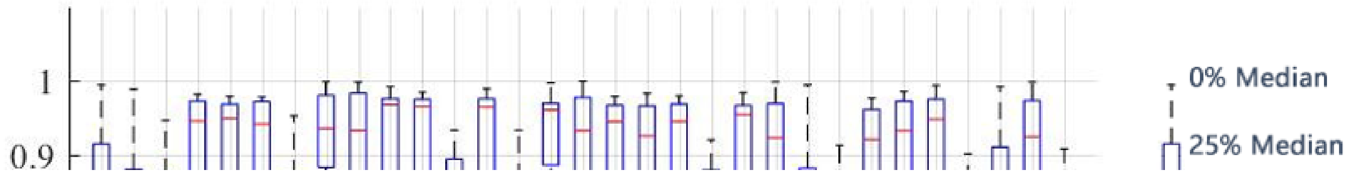

Figure 5

The bus travel time reliability in December 2012

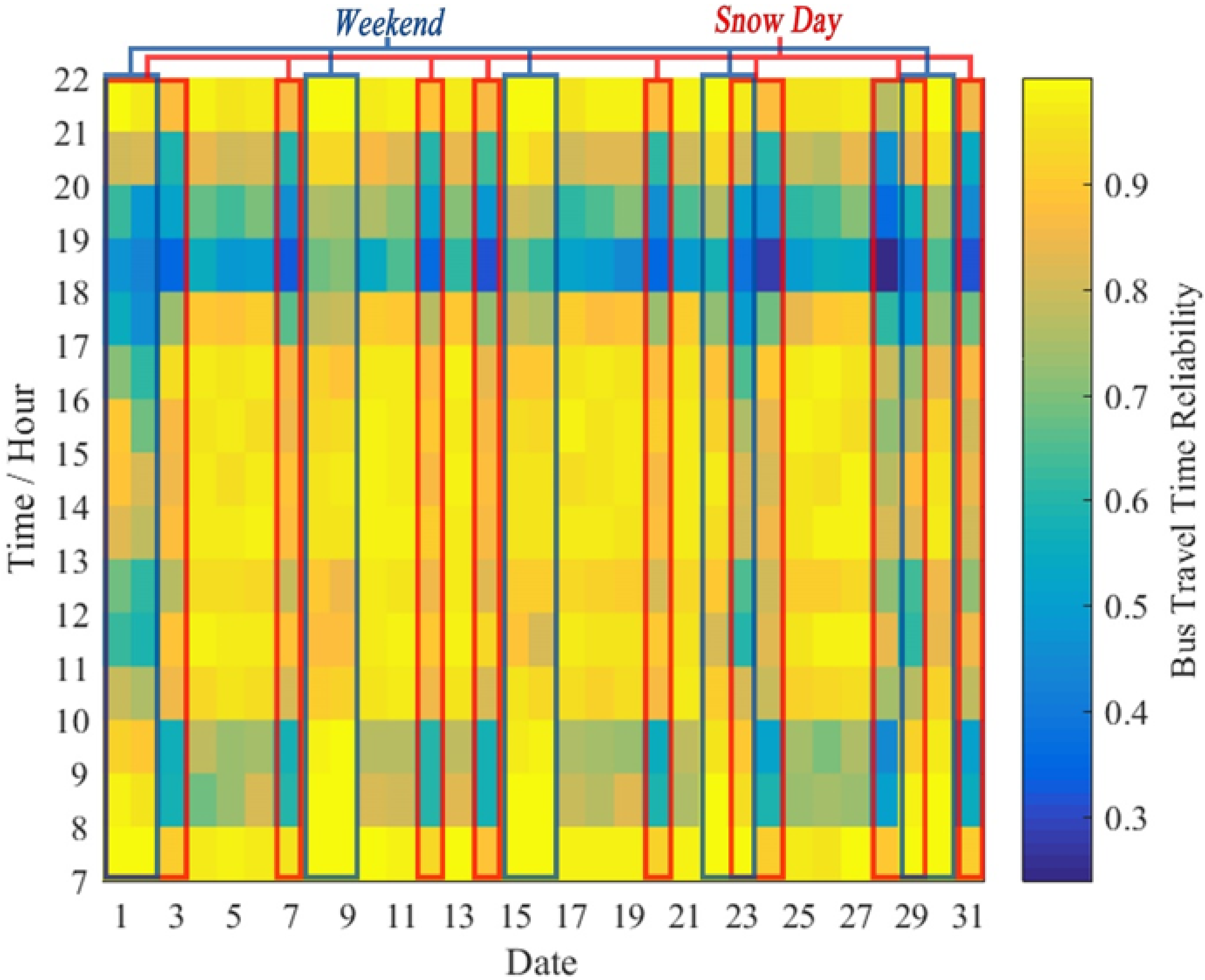

Figure 6

Bus travel time reliability in different conditions

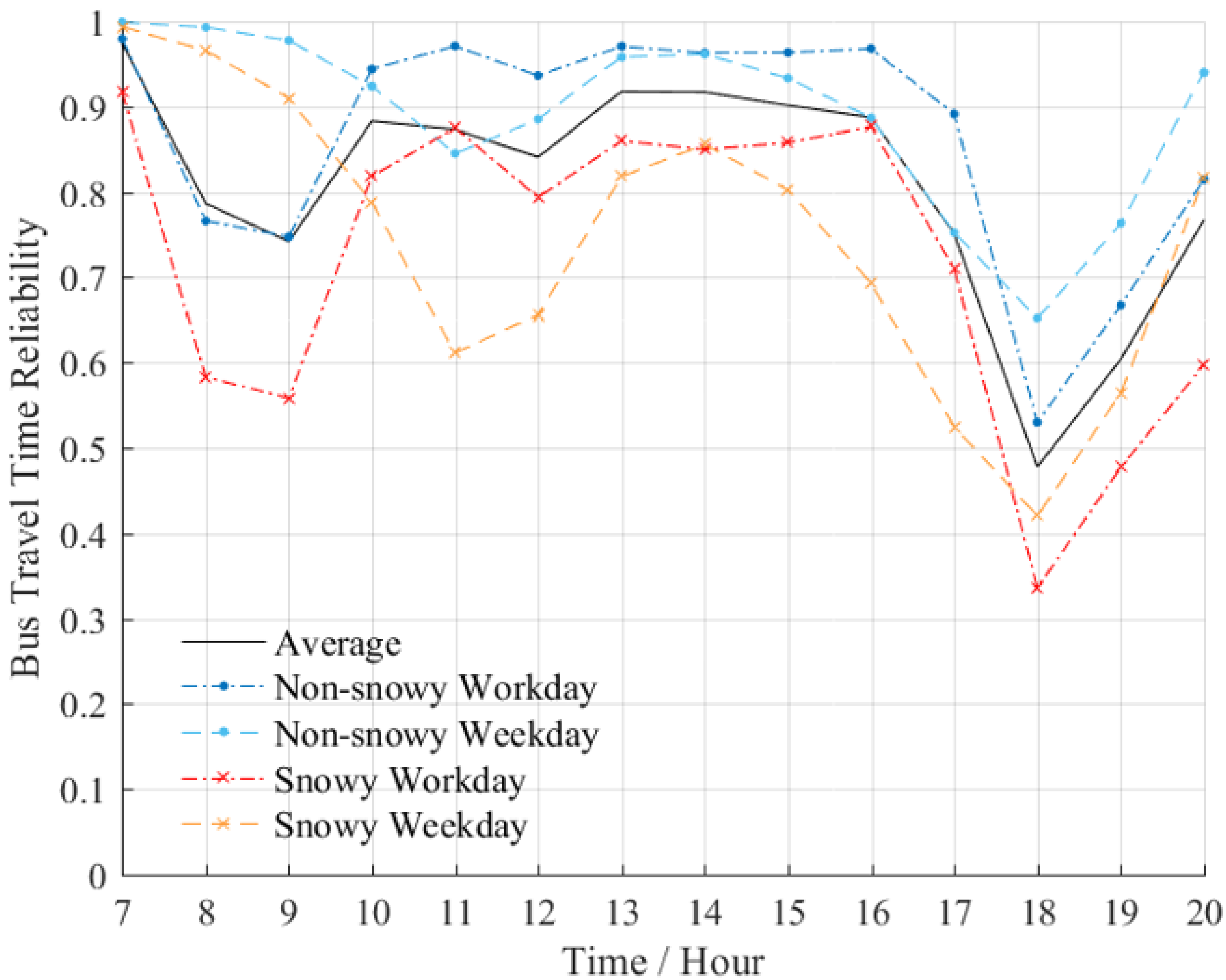

Figure 7

Bus travel time reliability in different conditions

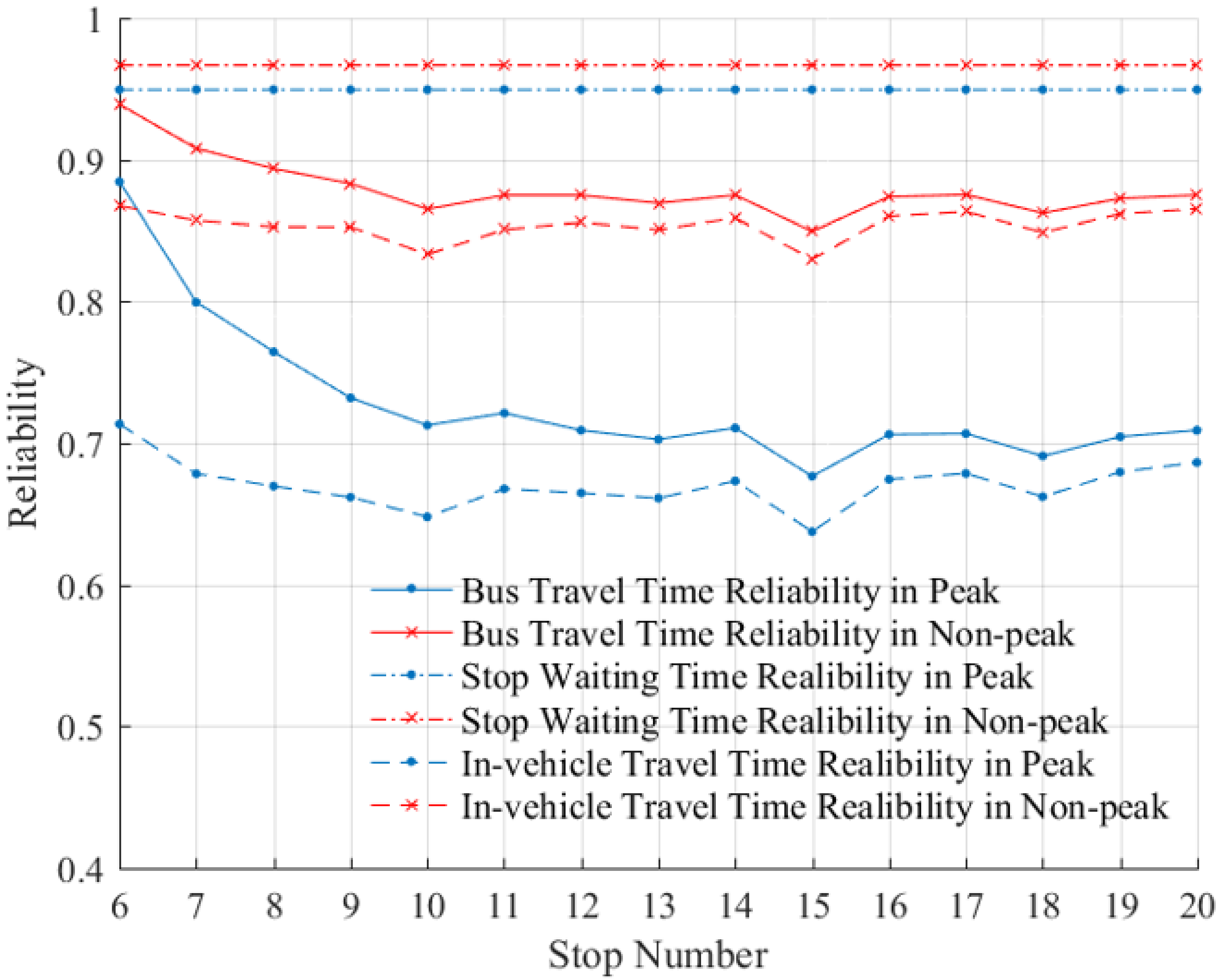

Figure 8

Bus travel time reliability in different conditions

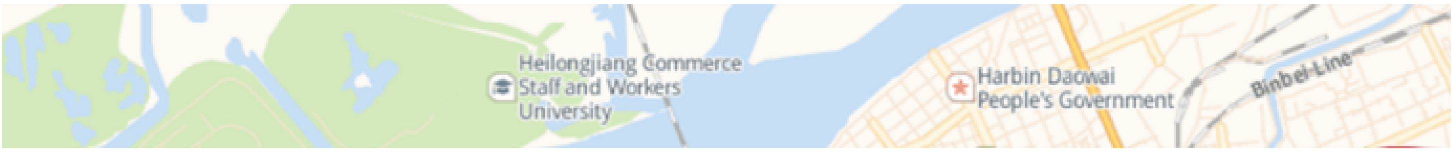

Figure 9

The selected O-D pairs (bus line segments)

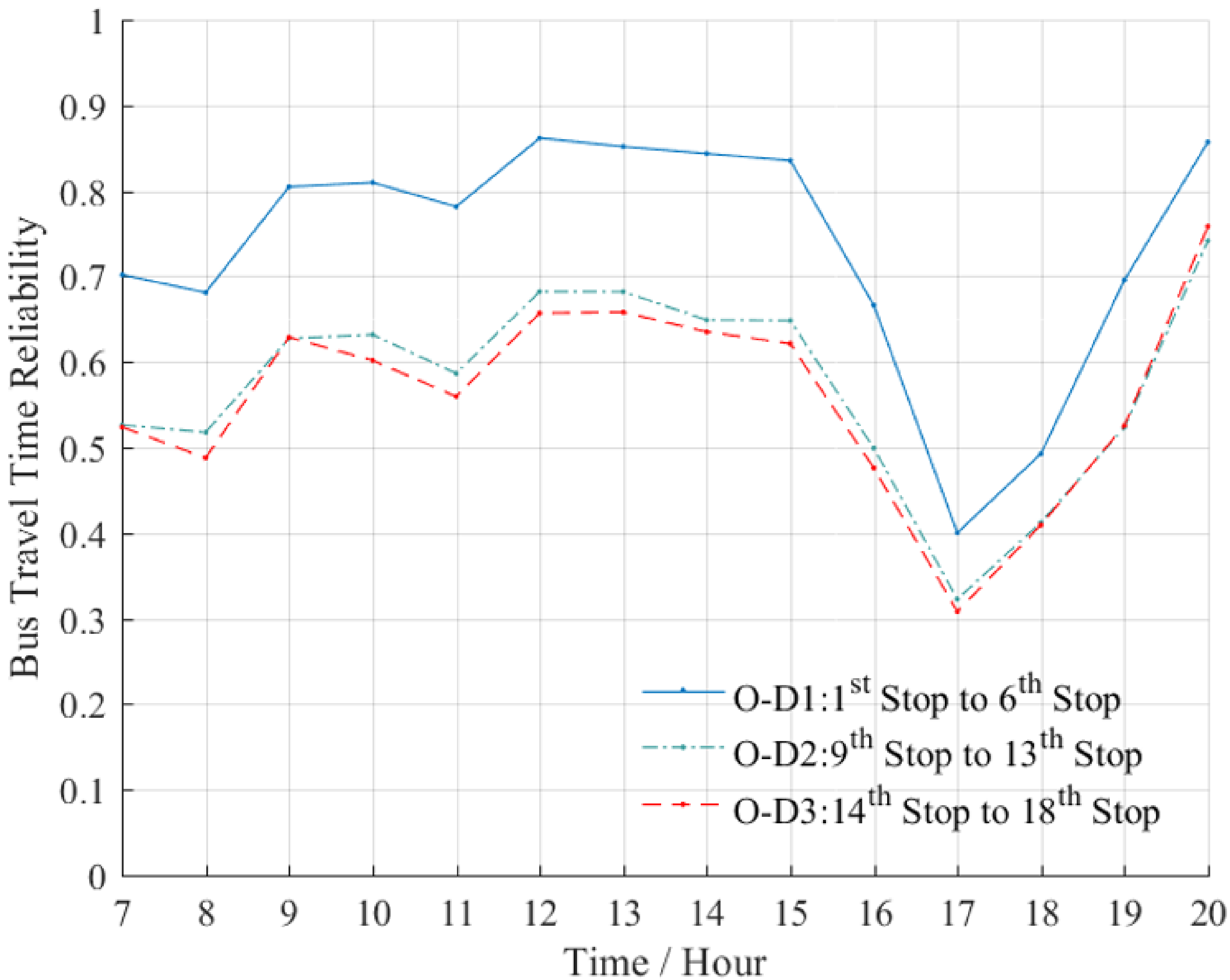

Figure 10

Bus travel time reliability of different O-D pairs

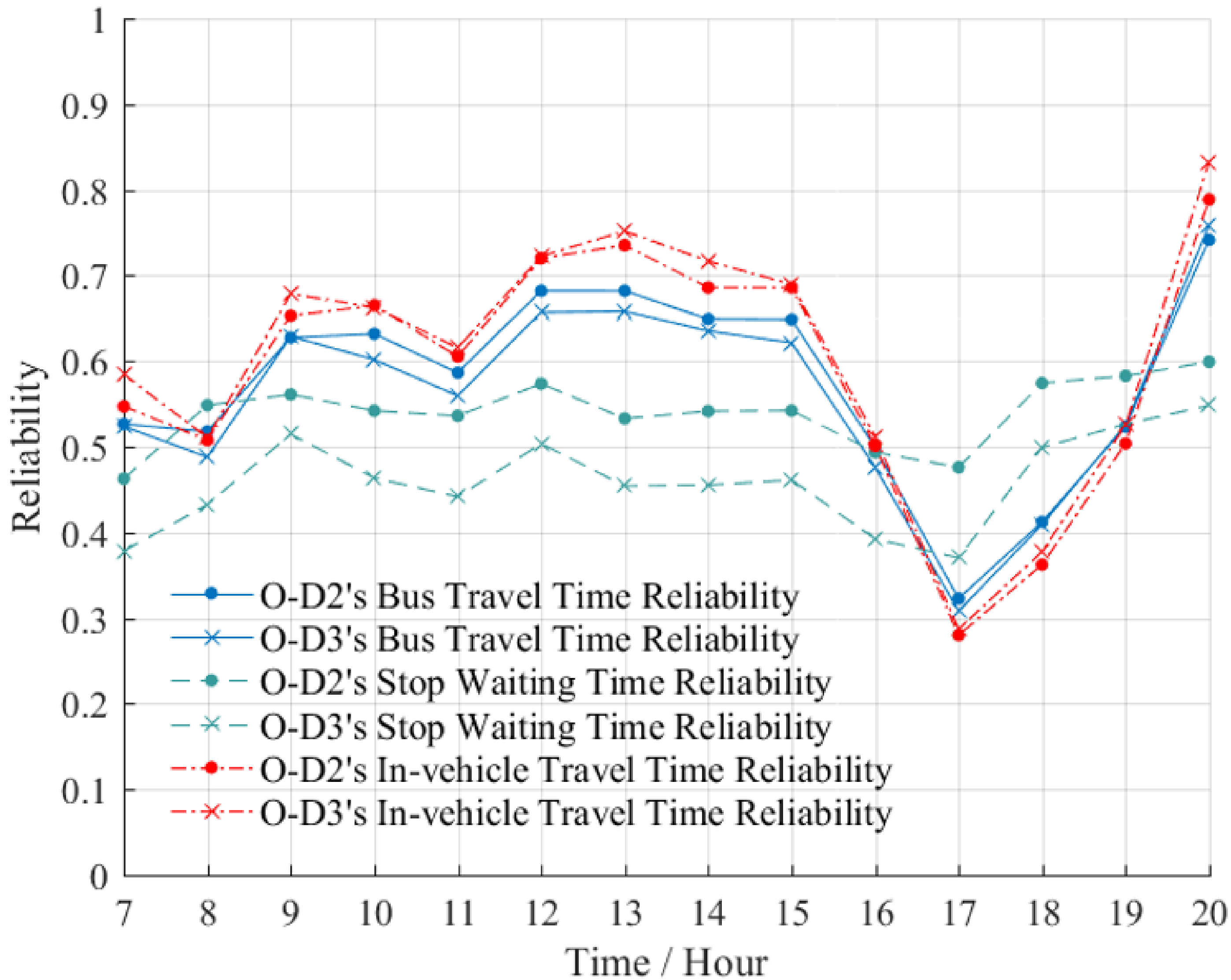

Figure 11

Reliability in different areas