



Bus travel time reliability incorporating stop waiting time and in-vehicle travel time with AVL data

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Received: 6 December 2021 / Accepted: 16 August 2022
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Abstract

Improving bus travel time reliability can attract more commuters to use bus transit, and therefore reduces the share of cars and alleviates traffic congestion. This paper formulates a new bus travel time reliability metric that jointly considers two stochastic processes: the in-stop waiting process and in-vehicle travel time process, and the bus travel time reliability function is calculated by the convolution of independent events' probabilities. The new reliability metric is defined as the probability when bus travel time is less than a certain threshold and can be used in both conditions with and without bus transfer. Next, Automatic Vehicle Location (AVL) data of the city of Harbin is used to demonstrate the applicability of the proposed method. Results show that factors such as weather, day of the week, departure time, travel distance, and the distance from the boarding stop to the bus departure station can significantly affect the travel time reliability. Then, a case with low bus departure frequency is analyzed to show the impact of travelers' arrival distribution on their bus travel time reliability. Further, it is demonstrated that the travel time reliabilities of two bus transfer schemes of the same Origin–Destination (O–D) pair can have significantly different patterns. Understanding the bus travel time reliability pattern of the alternative bus routes can help passengers to choose a more reliable bus route under different conditions. The proposed bus travel time reliability metric is tested to be sensitive to the effect of different factors and can be applied in bus route recommendation, bus service evaluation, and optimization.

Keywords Reliability · Bus travel time · Automatic vehicle location · Bus departure frequency

1 Introduction

Bus transit plays an important role in urban transportation. When traveling by bus, “arriving as planned” is the main requirement for all travelers (Nakanishi 1997). While a lot of factors, such as congestion, and weather often impair the reliability of bus service. Establishing a proper evaluation criterion for bus service quality (which is often measured by time reliability/stability) has wide application scenes (Hasan et al. 2013; Yao et al. 2015, 2014; Xuan et al. 2011; Lin et al. 2008) and can be helpful to improve the bus service.

Multiple criteria have been developed to evaluate the reliability of bus service; they can be roughly categorized into

route-based reliability and stop-based reliability (Chen et al. 2009). Route-based reliability models evaluate the stability of travel time between different bus stops, such as the inverse of the standard deviation of point-to-point travel (Sterman and Schofer 1976), and punctuality index based on routes (Chen et al. 2009) which is being used in most cities of China. Stop-based reliability is more common, as it can be extended to higher levels (i.e., the route or even the network level) by summing up according to the boarding-based weight. The most common three reliability criteria summarized in the Transit Capacity and Quality of Service Manual (TCQSM) (Kittelsohn & Assoc, Inc. et al. 2013) are all stop-based reliability; they are on-time performance, headway adherence, and excess wait time. There are also composite measures to evaluate the reliability of the bus system (Shalaby and Gittens 2015). Further, some researchers have assessed the properties of different measures (Trompet et al. 2011; Currie et al. 2012).

Although plenty in kind, existing reliability measures cannot jointly consider the reliability of route level and stop

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level. In another word, consider the in-stop waiting time and the in-vehicle travel time together. There are few methods to evaluate the impact of bus departure frequency and travelers' arrival distribution on bus travel time reliability. From the perspective of passengers, it is the time of total bus trip (rather than simply in-vehicle travel time or in-stop waiting time) that affects their travel experience. Therefore, combining route-based and stop-based measures can more accurately mark the impact of bus unreliability.

Recently, the widespread of Automatic Vehicle Location (AVL) equipment has brought a new era to the analysis of travel time reliability. Camus et al. (2005) used AVL data to develop a new reliability metric called weighted delay index. Sun (2015) used public transportation smart card data to evaluate the public transportation reliability in Singapore. Chakrabarti (2015) demonstrated that high-reliability bus lines meet passengers' travel needs better by using real-time geo-referenced vehicle location data. Ma et al. (2015) established a bus travel time reliability model using average travel time, buffer time, and coefficient of variation of travel time. 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. Barabino et al. (2017) suggested that the percentage of passengers receiving regular and punctual service can be a metric for the bus travel time reliability. Meng et al. (2018) analyzed the impact of travel time reliability to passengers' perceived travel time. Dixit et al. (2019) combined smart card data and AVL data to analyze passengers' travel time reliability in multimodal public transport. Kaewunruen et al. (2021) used a regression model to analyze the impact of 12 variables to the bus travel time reliability. Shelat et al. (2021, 2022) made empirical studies of bus travel time reliability using smart card data. A limitation of existing studies is that they used simple metrics to evaluate the bus travel time reliability, and these approaches typically lack a rigorous probabilistic foundation. The advantage of using AVL data is that bus headway and travel time between two stops can be easily calculated. However, AVL data does not contain information about how long a passenger had waited for a bus, which leaves difficulty in estimating the time of the whole bus trip (in-stop waiting time + in-vehicle travel time).

This paper tries to establish a bus travel time evaluation metric that jointly considers the in-stop waiting time and the in-vehicle travel time. The probability when the bus travel time is less than a certain threshold is defined to be the bus travel time reliability. The value of the threshold is determined by travelers' psychology or research needs. The methodology can also be applied to evaluate the reliability of bus trips with transfer behavior. Next, real AVL data is used to quantitatively evaluate the bus travel time reliabilities with and without transfer behavior of selected

bus lines in Harbin under different conditions. The case study shows that the proposed metric can sensitively depict the effects of different factors on the bus travel time reliability. The proposed bus travel time reliability metric can be used in bus route recommendation, bus travel time forecast, bus service evaluation, and optimization.

The rest of this article is organized as follows. Section 2 establishes a bus travel time reliability model. Section 3 demonstrates three case studies using Harbin's real AVL data. The first one is conducted on a high-frequency bus line with no transfer behavior, the second one has a low bus departure frequency, and the last considers the transfer behavior. The case studies also illustrate how to determine the bus travel time threshold, the influence of different travelers' arrival distribution on bus travel time reliability under low and high bus departure frequency, and the bus travel time reliability of two interchange schemes within the same O–D pair. Finally, the general conclusions and further research are summarized in the final section.

2 Methodology

2.1 Definition of bus travel time reliability

A complete bus trip includes four independent stochastic processes: an in-stop waiting process, an in-vehicle travel process, and two walking processes. The two walking processes are relatively stable and have less effect on bus travel time reliability. Therefore, the bus travel time T defined in this paper is simply the sum of the in-stop waiting time T_S and the in-vehicle travel time T_V as

$$T = T_S + T_V. \quad (1)$$

The travel time reliability is usually defined as the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day (FHWA 2010; Lo et al. 2006; Wisconsin Department of Transportation 2014). In other words, the reliability is the variability under a fixed on-time probability (usually 95% or 90%). However, this paper aims to investigate the impact of various factors on the bus travel on-time probability. The bus travel time reliability is defined as the probability when a bus travel time is less a fixed threshold T_T .

$$R = P(T \leq T_T), \quad (2)$$

where R is the bus travel time reliability defined in this paper, and T_T is a threshold beyond which the bus travel time becomes intolerable (unreliable).

2.2 Measurement of the bus travel time threshold

Usually, travelers will estimate bus travel time before they start bus trips to guarantee they will arrive on time. The travel time threshold for a bus trip is the maximum tolerable travel times in passengers' impression by an aggregated measure. When the actual travel time exceeds this threshold, a large percentage of travelers will think that the bus trip is not reliable.

Since bus travel time is directly related to traffic conditions, the ideal travel time occurs in the best traffic conditions: Bus arrives as scheduled and travels as free flow. It is close to the minimum travel time of the bus trip. When using ideal travel time as the travel time threshold, most bus trips will be unreliable. This is not appropriate, as passengers usually have some buffers in their trip time. The United States Department of Transportation-Federal Highway Administration (FHWA) defines planning time index as how much larger the total travel time is than the ideal or free-flow travel time (i.e., calculated as the ratio of the 95th percentile to the ideal) when using cars in a commuter route (FHWA 2010; Lo et al. 2006). Here we extend the definition to the bus travel time threshold as

$$T_T = \gamma(\widetilde{T}_S + \widetilde{T}_V) \tag{3}$$

where T_T is the travel time threshold, γ is the travel time index, and \widetilde{T}_S is the mean of in-stop waiting time when bus arrives as scheduled and \widetilde{T}_V is the minimal (free flow) in-vehicle travel time.

Bus travel time reliability is directly related to γ . The related research can be divided into two types according to methods: analysis of reliability under a fixed γ , and analysis of travel time budget under a fixed probability value (usually 95% or 90%). The purpose of the γ -fixed method is to understand the probability of travelers arriving on time with acceptable travel time budget, while the probability-fixed method considers how much the extra time is caused by the volatility of travel time (FHWA 2010; Lo et al. 2006; Wisconsin Department of Transportation 2014; Brown and Racca 2012). The probability-fixed method determines the value of γ with a fixed high arriving on-time arrival probability. The range of γ can be used to evaluate the reliability. Refer to Wisconsin Department of Transportation (2014), it is reliable when γ is between 1.0 and 1.3, moderately unreliable when γ is between 1.31 and 1.80, and unreliable when γ is over 1.80. With this method, γ has a direct link to the quality of transportation system service: lower γ represent higher service quality that can be obtained. The changes in γ throughout the day also reflect the stability of transportation system services. In this paper, the γ -fixed method is used to evaluate the bus travel time reliability. A data-driven approach is used to determine γ —as shown in the case study in Sect. 3.1.3—by maximizing the fluctuation of bus travel

time reliability within a day. Note that the value of γ could be different for different groups or different evaluation purposes.

2.3 Calculation of the bus travel time reliability without transfer behavior

For a bus trip without transfer behavior, the in-stop waiting process and the in-vehicle travel process for a traveler are independent (Jeong 2005; Chang et al. 2010; Mazloumi et al. 2011). Therefore, the probability density function (PDF) of bus travel time (without transfer behavior) is the convolution of the PDFs of T_S and T_V :

$$f(T) = \int_0^T f_V(t)f_S(T-t)dt, \tag{4}$$

where $f(\cdot)$ is the PDF of bus travel time without transfer behavior, $f_S(\cdot)$ is the PDF of in-stop waiting time, and $f_V(\cdot)$ is the PDF of in-vehicle travel time. Equation (4) holds because the PDF of the sum of two independent random variables is the convolution of their PDF (Hogg et al. 2005).

In calculating the PDF of in-stop waiting time f_S , one must distinguish high and low bus frequencies (Barabino et al. 2017; Chen et al. 2010), which is usually partitioned at 10–12 min of bus interval (Yao et al. 2014; Barabino et al. 2017; Eboli and Mazzulla 2011). For high bus frequency, the arrival of travelers usually satisfies the uniform distribution (Zheng et al. 2017); for low bus frequency, travelers will deliberately control their arrival time based on the timetable so that they can reduce the in-stop waiting time. Therefore, the travelers' arrival distribution does not satisfy the uniform distribution for low bus frequency. When a low-frequency bus passes the stop as scheduled, the informed travelers will arrive at the stop at the time of the upcoming departure, and the uninformed travelers will arrive at the stop randomly. Related studies (Fonzzone et al. 2015; Luethi et al. 2007; Zahir et al. 2000) have shown that the arriving distribution of informed travelers tends to be skewed distributed (like log-normal), and that of uninformed travelers tends to be uniformly distributed.

The PDF of in-vehicle travel time can be directly estimated from the AVL data, while the PDF of in-stop waiting time needs to be inferred from the PDF of the bus headway. Denote h to be the bus headway, and $t_a \in [0, h]$ to be the traveler's arrival time, then the in-stop waiting time $t = h - t_a$. Let $f_a(t_a|h)$ be the conditional distribution of arrival time given h . Then, the conditional distribution of in-stop waiting time given h is $f_a(h-t|h)$, and the PDF of in-stop waiting time can be derived as

$$f_S(t) = \int_0^{+\infty} f_a(h-t|h)f_h(h)dh, \tag{5}$$

where $f_h(\cdot)$ is the PDF of bus headway.

Finally, the bus travel time reliability without transfer behavior can be expressed as:

$$R = \int_0^{T_T} f(t) dt. \quad (6)$$

When using practical data to perform the calculation, numerical method is a straightforward and often the only feasible way. For the convolutions in Eqs. (4) and (5), their PDFs are first discretized to sequences to perform discrete convolution, then normalized (the sum of PDF is always 1). Next, the normalized sequences are used in a numerical integration to obtain the bus travel time reliability based on Eq. (6). The numerical method can not only calculate the bus travel reliability without transfer behavior quickly, but also can calculate the bus travel reliability with transfer behavior in the next case.

2.4 Calculation of bus travel time reliability with transfer behavior

If travelers are unable to reach their destination directly by one ride, they need to transfer. To model a bus trip with transfer behavior, define T_S^k and T_V^k to be the in-stop waiting time and the in-vehicle travel time of k th transfer, respectively. Then, the bus travel time with transfer behavior can be expressed as Eq. (7):

$$T_T = \gamma \sum_{k=0}^n (\widetilde{T}_S^k + \widetilde{T}_V^k) \quad (7)$$

where n is the total number of transfers.

when considering transfer behavior, T_S^0 , T_V^k , and T_T are similar to the non-transfer case. However, it is not reasonable to assume travelers arrive at the transfer stop as uniform distributed. The PDF of in-stop waiting time at k th transfer stop T_S^k ($k \neq 0$) should follow the distribution of the arrival interval between the previous and the next bus line, which can be estimated from AVL data. Because all T_S^k and T_V^k are generally considered to be independent in a bus trip (Jeong 2005; Chang et al. 2010; Mazloumi et al. 2011); the PDF of bus travel time considering n times ($n \geq 1$) transfer behavior can be expressed as

$$f(T) = \int_0^{T - \sum_{i=0}^{2n-1} t_i} \dots \int_0^{T-t_0} \int_0^T \prod_{i=0}^{n-1} (f_V^i(t_{2i}) f_S^i(t_{2i+1})) f_V^n(t_{2n}) f_S^n \left(T - \sum_{i=0}^{2n} t_i \right) dt_0 dt_1 \dots dt_{2n} \quad (8)$$

Where the even subscripts denote in-vehicle travel time and the odd subscripts denote in-stop waiting time. Finally, the bus travel time reliability considering transfer behavior can be obtained by Eq. (8).

3 Case study

Using the proposed model, this section analyzes the hourly bus travel time reliability. The AVL data used in this paper is obtained from Harbin Public Transport Administration, which records a month's bus operation information of Harbin in December 2012. First, a O-D pair in the No. 63 bus line of Harbin is used to study the bus travel time reliability without transfer behavior. The independence of the in-stop waiting process and the in-vehicle travel process is proven. And the influences of weather, weekday, departure time, travel distance, and the distance from the boarding stop to the bus departure station are analyzed. Next, a case of the No. 40 bus line of Harbin is used to understand the bus travel time reliability under low arrival frequency. Finally, when including transfer behavior, the bus travel time reliabilities of two bus routes are compared. The results show that the proposed model can sensitively capture the characteristics of bus travel time reliability.

3.1 The bus travel time reliability without transfer behavior

3.1.1 Introduction

As shown in Fig. 1, the No. 63 line passes the downtown area of Harbin with 20 bus stops and a total mileage of 10.8 km from Jiangong Community to Dajiang Community. The O-D pair from 5th Stop to 18th Stop is used to evaluate the bus travel time reliability without transfer behavior. Figure 1 also shows the major information contained in the AVL data, which can be used to estimate the distribution of bus headway and in-vehicle travel time. Additional information like day of week and weather are manually added into AVL data by referring to the historical weather and weekends. Bus scheduled departure interval (5 min) is acquired from the bus company.

3.1.2 Independence test

The premise of the convolution of $f_S(\cdot)$ and $f_V(\cdot)$ is that the two stochastic processes are independent. For $f_S(\cdot)$, it includes other two stochastic processes: the bus headway and the travelers' arrival distribution. It is assumed that the travelers' arrival distribution conforms to either the uniform distribution or the log-normal distribution, which is independent to in-vehicle travel time. If the bus headway is also independent to $f_V(\cdot)$, then $f_S(\cdot)$ is independent to $f_V(\cdot)$. Here, a test of the independence of the No. 63 line's headway series and the in-vehicle travel time series is conducted, which shows that the in-stop waiting processes and the in-vehicle travel processes are approximately independent. The

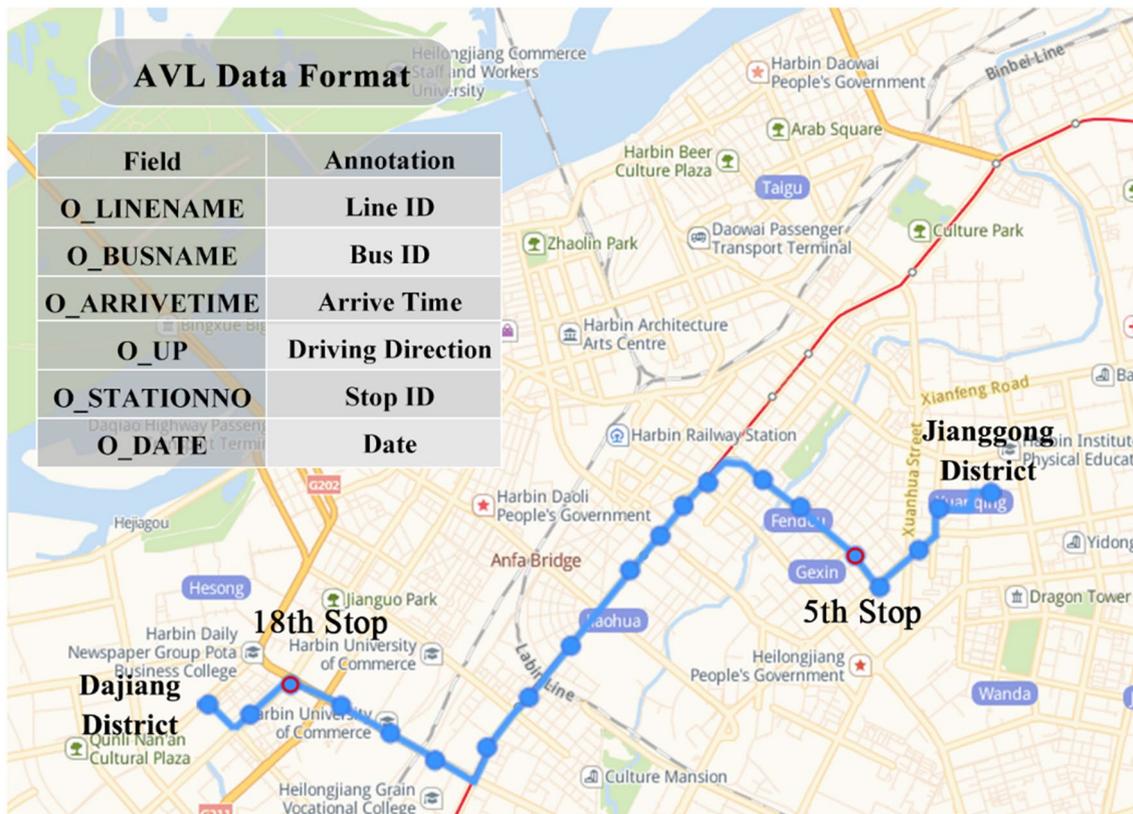


Fig. 1 Route of the No. 63 bus line

correlation coefficient of the two sequences is 0.12. It is usually considered that if the correlation coefficient is between 0 and ± 0.30 , the two processes have negligible correlation (Mukaka 2012). The correlation coefficient is about 0.12, so $f_S(\cdot)$ and $f_V(\cdot)$ can be seen to be independent.

3.1.3 Determine the parameters

To calculate the bus travel time reliability without transfer behavior, the distribution type of the bus headway and the in-vehicle travel time must first be determined. One-hour data is too sparse to accurately fit the distributions. Therefore, one day's data is used to fit the type of distribution.

Take December 3, 2012, for example (Monday). The fitting results of in-vehicle travel time from 5th Stop to 18th Stop of four types of distribution are shown in Table 1. The results show that the normal distribution has the highest fitting degree, followed by the log-normal distribution. Similarly, Table 1 shows the best fit of bus headway is also a normal distribution.

Because the linear combination of normal distributions is still normal distribution, it is reasonable to believe that the hourly in-vehicle travel time and bus headway satisfy Normal distributions. Their parameters can be estimated by the method of moments. Although truncated normal distribution

Table 1 The fitting results of three distributions

| Distribution | SSE | R-square | Adjusted R-square | RMSE |
|---|--------|----------|-------------------|--------|
| <i>Fitting result of in-vehicle travel time</i> | | | | |
| Normal | 0.0079 | 0.7294 | 0.7178 | 0.0130 |
| Log-normal | 0.0086 | 0.7072 | 0.6947 | 0.0135 |
| Exponential | 0.0119 | 0.5963 | 0.5699 | 0.0161 |
| Uniform | 0.0237 | 0.1966 | 0.1966 | 0.0222 |
| <i>Fitting result of bus headway</i> | | | | |
| Normal | 0.0001 | 0.9968 | 0.9966 | 0.0017 |
| Log-normal | 0.0002 | 0.9930 | 0.9927 | 0.0024 |
| Exponential | 0.0146 | 0.6401 | 0.6166 | 0.0178 |
| Uniform | 0.0291 | 0.2841 | 0.2691 | 0.0246 |

is theoretically better; considering the small probability of minus value only causes a tiny difference in the final result, Normal distribution is adopted for simplicity. Then $f_S(\cdot)$ and $f_V(\cdot)$ is determined.

The scheduled bus departure interval of the No. 63 bus line is 5 min; the travelers' arrival distribution is uniform and the minimal in-vehicle travel time between 5th Stop and 18th Stop is 1416.3 s. According to Eq. (3), the traveler's expectation index γ must be determined to obtain the bus travel time threshold T_T .

A proper γ should clearly distinguish different traffic conditions and also passengers' travel experience. Different γ is tested to calculate the corresponding bus travel time reliability. The hourly bus travel time reliabilities on December 3, 2012 under different γ values are shown in Fig. 2. As shown in Fig. 2, too high or too low γ will result in a smaller fluctuation range of bus travel time reliability within a day. The γ applied here is obtained by maximizing the fluctuation of bus travel reliability within a day. The max bus travel time reliability fluctuation range is 0.8406 when $\gamma = 1.4$. This value can sensitively mark the fluctuation of bus operation level and the experience of passengers. The reasonable range of γ given the probability-fixed method is between 1.3 and 1.8 (Wisconsin Department of Transportation 2014), where $\gamma = 1.4$ is within this range. Note that γ calculated by data of different days may be slightly different, but $\gamma = 1.4$ is tested to be suitable for most of the days of that month. γ is set to 1.40 in the following part, and γ can be adjusted under different evaluation purposes or according to travelers' aversion to the travel time unreliability.

In the following part, the value corresponding to time t represents the bus travel time reliability from t to $t + 1$. The relations between bus travel time reliability and the following factors are analyzed: (1) weather, weekday, and time periods within a day; (2) travel distance; (3) distance from the origin terminal to the traveler's origin stop.

3.1.4 The influence of weather, day of week and time periods within a day

For the O–D pair from 5th stop to 18th stop, the bus travel time reliability in different time period is shown in Fig. 3.

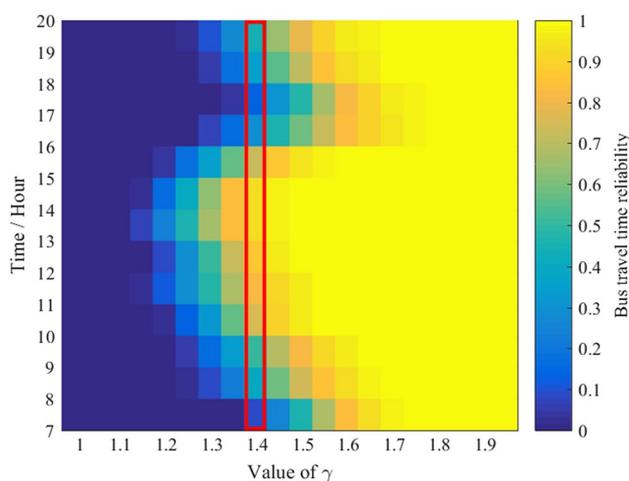


Fig. 2 The hourly bus travel time reliabilities in December 3, 2012 under different γ

Figure 3 shows that the bus travel time reliability is low in peak hours (7:00–9:00, 16:00–20:00), especially in evening peak hours. It indicates that the traffic condition is bad in the two periods.

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. 4. It is shown in Fig. 4 that the median of bus travel time reliability in some days are lower than 0.8. It could be caused by the attributes of the day, e.g., weekend/workday, snow/non-snow.

By referring to the historical weather data, the snow days and other information are shown in Table 2. It is found that for most of the snow days, the median of the bus travel time reliability is lower than 0.8, which indicates a relationship between snowfall and the decrease in bus travel time reliability. In addition, most of the extreme bus travel time reliability data points appear on the workday, which are all low outliers. This indicates that snow can lead to great differences in bus travel time reliability, and peak hours may lead to extremely low bus travel time reliability in non-snow workdays.

Figure 5 gives more details about how weather and day of week influence the bus travel time reliability by considering time periods within a day. Figure 5 shows that the snowy weather clearly leads to a reduction of the bus travel time reliability. Under the same weather conditions, it can be found that the bus travel time reliability on weekends is lower than that on workdays except on morning peaks. It can be concluded that the snowy weather can affect the overall daily travel time reliability and the workday/weekend affects the bus travel time reliability in different time periods of a day.

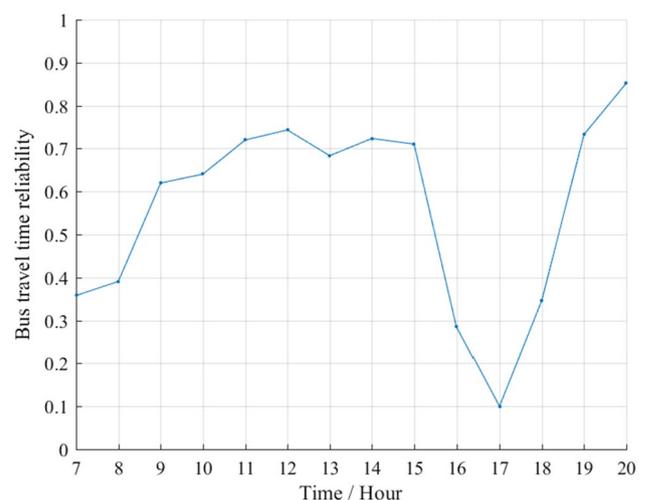


Fig. 3 Bus travel time reliability

Fig. 4 Bus travel time reliability in December 2012

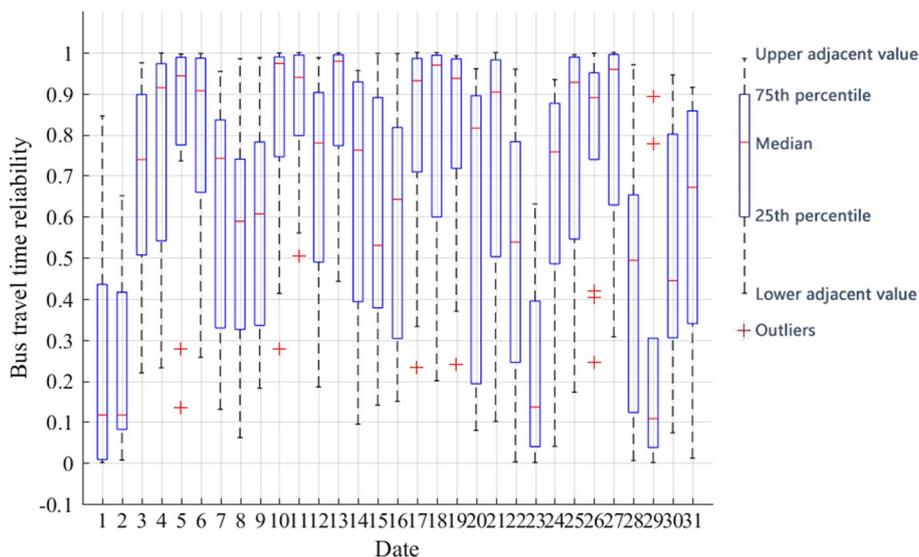


Table 2 Factors in December 2012

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Snow | √ | √ | √ | | | | √ | | | | | √ | | √ | | |
| Workday | | | √ | √ | √ | √ | √ | | | √ | √ | √ | √ | √ | | |
| Mean | 0.26 | 0.24 | 0.68 | 0.78 | 0.82 | 0.78 | 0.65 | 0.55 | 0.59 | 0.84 | 0.87 | 0.68 | 0.86 | 0.68 | 0.60 | 0.60 |
| Std | 0.30 | 0.23 | 0.26 | 0.26 | 0.26 | 0.27 | 0.27 | 0.29 | 0.28 | 0.24 | 0.17 | 0.26 | 0.21 | 0.29 | 0.29 | 0.28 |
| Day | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | |
| Snow | | | | √ | | | √ | √ | | | | √ | √ | | √ | |
| Workday | √ | √ | √ | √ | √ | | | √ | √ | √ | √ | √ | | | √ | |
| Mean | 0.80 | 0.81 | 0.80 | 0.62 | 0.76 | 0.52 | 0.22 | 0.64 | 0.77 | 0.79 | 0.82 | 0.45 | 0.24 | 0.50 | 0.58 | |
| Std | 0.27 | 0.26 | 0.27 | 0.36 | 0.30 | 0.31 | 0.23 | 0.28 | 0.28 | 0.25 | 0.24 | 0.33 | 0.34 | 0.30 | 0.31 | |

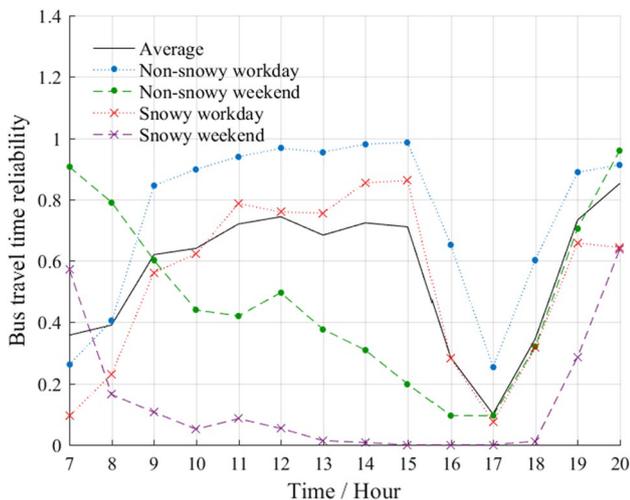


Fig. 5 Bus travel time reliability in different weather and day of week

3.1.5 The influence of travel distance

Usually, for different in-vehicle travel distances, the effect of in-stop waiting time and in-vehicle travel time on bus travel time reliability is also different. In order to explore how the bus travel time reliability can be affected by the in-vehicle travel time, the bus transit travel from 5th stop to different stops is tested. The in-stop waiting time reliability is defined as the bus travel time reliability when all the in-vehicle travel times approach zero. Similarly, the in-vehicle travel time reliability is defined as the bus travel time reliability when all the in-stop waiting times approach zero.

In addition, in order to demonstrate the impact of travel distance and time periods within a day on bus travel time reliability, peak and off-peak hour will be separately discussed. Referring to Fig. 3, we define the peak hour to be

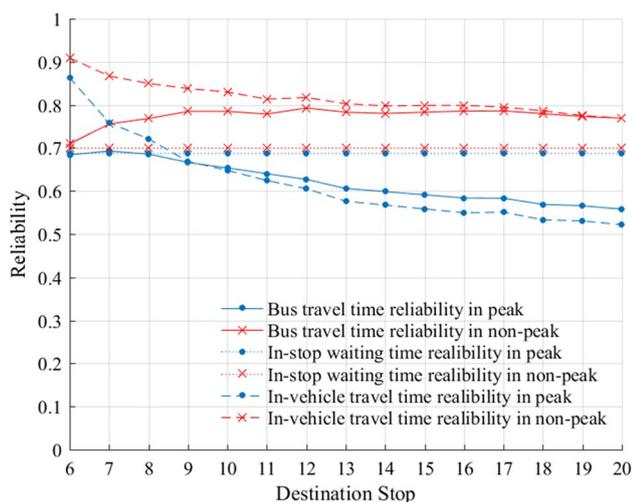


Fig. 6 Bus travel time reliability from 5th Stop to different other stops

the time period where the average bus travel time reliability is lower than 0.8, otherwise, it is the off-peak hour. And all these reliabilities are calculated as monthly average values. The results are shown in Fig. 6.

It can be seen from Fig. 6 that most of the in-vehicle travel time reliability has a small decline with the travel distance increasing. But not all the bus travel time reliability is decline with the in-vehicle travel time reliability, it is always between the in-stop waiting time reliability and the in-vehicle travel time reliability. In the short bus trip, such as the 6th stop to is 10th stop when non-peak, the bus travel time reliability is increasing when the in-stop waiting time is solid and the in-vehicle travel time reliability is decline.

The influence of in-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 in-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. With the increase of travel distance, the in-vehicle travel time takes a higher proportion in the bus travel time. At this time, the in-vehicle travel time reliability tends to have a larger influence on the bus travel time reliability. It consists with the fact that when the bus departure frequency is high, in short-distance travel, people pay more attention to the in-stop waiting time; conversely, in long-distance travel, people pay more attention to in-vehicle travel time. As the bus travel distance increases, the bus travel time reliability curve gradually changes from the in-stop waiting time reliability curve to the in-vehicle travel time curve, shown in Fig. 6.

3.1.6 The influence of the distance between the boarding stop and the bus 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 conditions. 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 analysis. The lengths of the three O–D pairs are 2094 m, 2160 m, and 2010 m respectively. The fluctuations of bus travel time reliability caused by the distance between the boarding stop and the bus 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. 7, it is clear that the O–D 1’s bus travel time reliability is the highest, and O–D 2’s and O–D 3’s is very close. There are two possible influencing factors: the distance between the boarding stop and the bus departure station, which mainly affects the in-stop waiting time reliability; the traffic condition in different areas, which mainly affects the in-vehicle travel time reliability. Figure 8 gives a further analysis.

It is conspicuous that there is an opposite discrepancy between the in-stop waiting time reliabilities and the in-vehicle travel time reliability of the two O–D pairs; the O–D 3’s boarding stop is farther from the departure station, it has smaller waiting time reliability. The O–D 2’s in-vehicle travel time reliability is smaller than O–D 3’s because of the higher road congestion level in O–D 2. Thus, the O–D 2’s and O–D 3’s bus travel time reliabilities become similar.

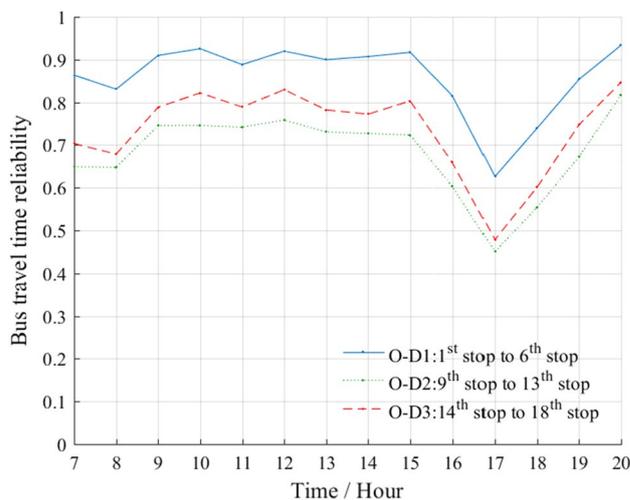


Fig. 7 Bus travel time reliability of different O–D pairs

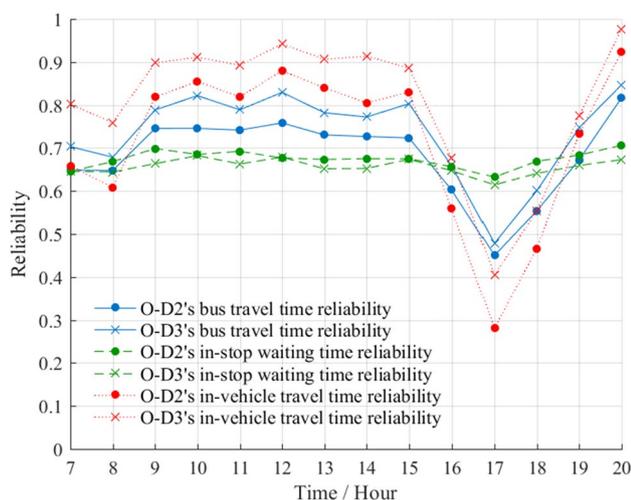


Fig. 8 Reliability in different areas

3.2 The bus travel time reliability with low bus departure frequency

3.2.1 Introduction

In low-frequency bus lines, the impact of in-stop waiting time is more significant. The departure frequency of the No. 40 line (shown in Fig. 9) in Harbin is 20 min, which provides a test example to evaluate our model in low-frequency situations. Due to the long bus departure interval, it is assumed that the travelers' arrival distribution at each stop is log-normal distribution: many travelers arrive at the stop when approximating the bus arrival schedule, thus the mean of in-stop waiting time \bar{T}_S will be less than that in uniform distribution (Barabino et al. 2017; Chen et al. 2010).

3.2.2 Different travelers' arrival distribution

The influence of the bus departure frequency on the bus travel time reliability is mainly reflected in different kinds of travelers' arrival distributions—namely the in-stop waiting time. Figure 10 shows the effect on the PDF of in-stop waiting time under the same headway parameter. The impact of ITS on bus trips is also considered—the travelers' arrival distribution under ITS is considered as the lognormal distribution without late arrival (passengers can always catch the bus).

The travelers' arrival distribution is different due to the bus departure frequency. Here, the data of bus departure frequency, headway, and travelers' arrival distribution is from the No. 63 bus line and the No. 40 bus line (Table 3):

When travelers arrive as uniform distribution, the travelers' arriving function is a constant function, and the PDF of the in-stop waiting time is a decreasing function. In addition,

the mean of the in-stop waiting time is slightly larger than half of the headway.

Unlike the case where travelers' arrival distribution is uniformly distributed, when the travelers' arrival distribution fits log-normally distribution, travelers have a perception of the buses' arrival time, they will arrive intensively before the time when the bus's entry probability is highest. For those who arrive just after the time of bus arrival, they will need to wait for an extended time until the next bus. Therefore, there is a small peak with a long waiting time in the distribution of in-stop waiting time given the log-normal travelers' arrival distribution.

The main contribution of ITS to bus travelers is to reduce the in-stop waiting time and avoid missing buses. All passengers will not miss the bus, so they wait no longer than the headway, and the second peak in log-normal distribution disappears in ITS condition. In the above three kinds of travelers' arrival distributions, it is obvious that ITS has the lowest in-stop waiting time under the same headway, and the magnitude relationship between the log-normal distribution and the uniform distribution depends on the size of the second peak of the lognormal distribution.

3.2.3 The influence of travel distance

In order to show the influence of distance from departure station to boarding stops on the in-stop waiting time reliability, and how the in-stop waiting time influence bus travel time reliability under low bus departure frequency, all the O–D pairs' bus travel time reliabilities in the No. 40 line are calculated. The results are shown in Fig. 11:

The bus travel time reliability in Fig. 11 shows a descending trend from left to right, and the bus travel time reliability of the same boarding stop shows an ascending trend from the bottom to the top. This shows that the traveler with long travel distances and his/her boarding stop near the departure stop can get higher bus travel time reliability. The situation may be caused by the difference in in-stop waiting time. By calculating the data from different boarding stops to the terminal station (to 16th stop), the result in Fig. 12 shows more details.

The horizontal axis in Fig. 12 represents the boarding stops, so the travel distance becomes shorter along the horizontal axis. As the distance from the boarding stop to the bus departure station increases, the in-stop waiting time reliability decreases. Due to the large proportion of in-stop waiting time in the bus travel time, when the bus passes as low frequency, the fluctuation of headway will significantly reduce the bus travel time reliability. At the same time, as the No. 40-line bus travels from the urban area to the suburbs, the in-vehicle travel time reliability almost increases but the proportion of the bus travel time is always declining, so the downward trend of bus travel time reliability has not been curbed.

Fig. 9 Route of the No. 40 bus line

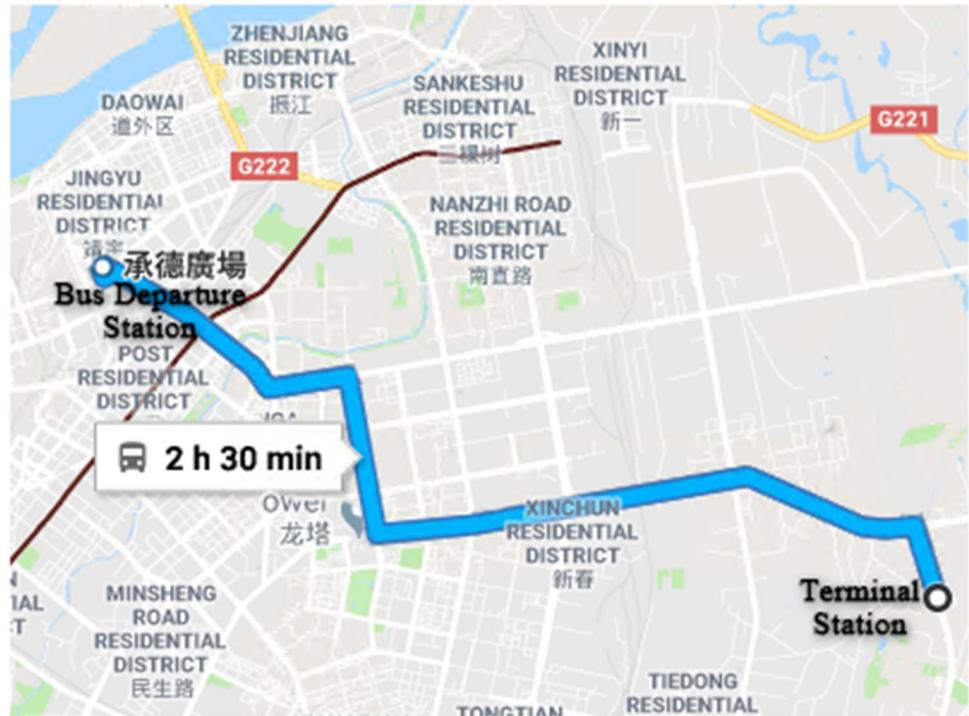
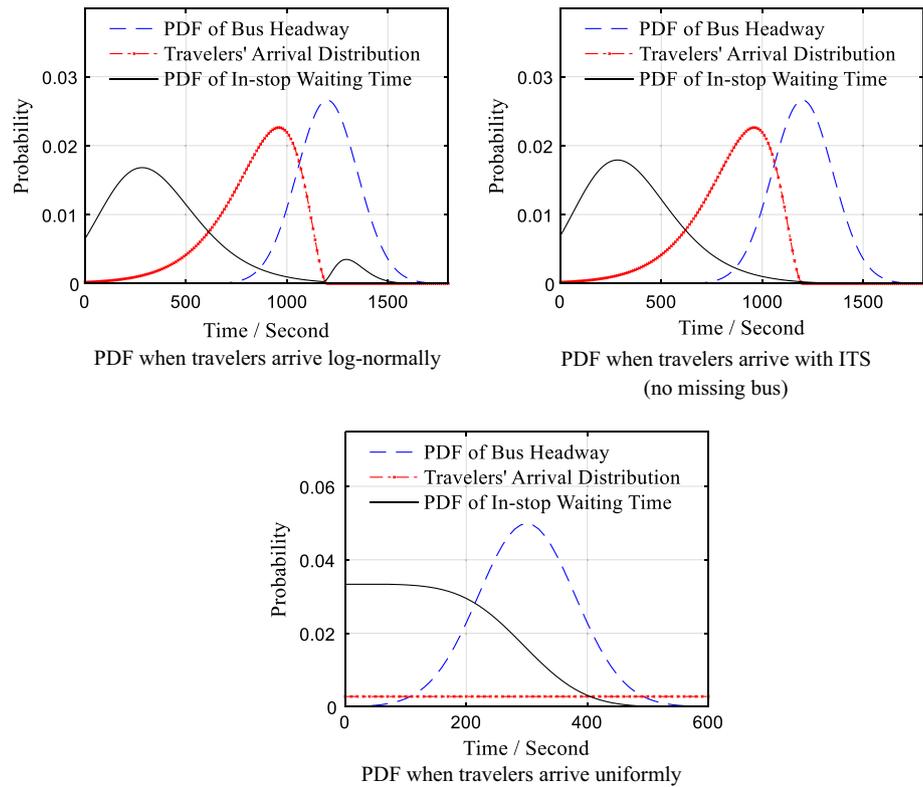


Fig. 10 In-stop waiting time under different travelers' arrival distribution



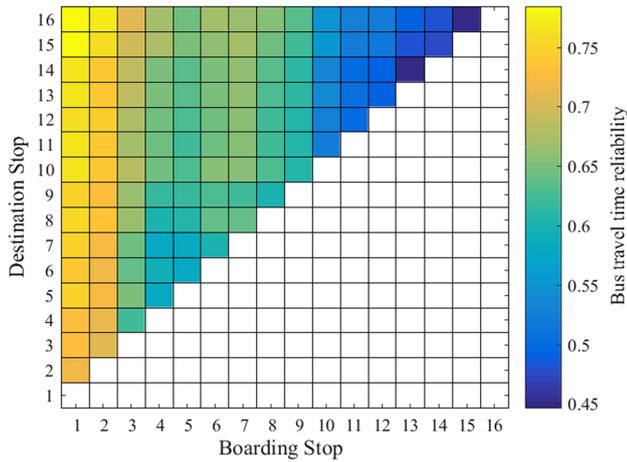


Fig. 11 Bus travel time reliability in different O–D pairs

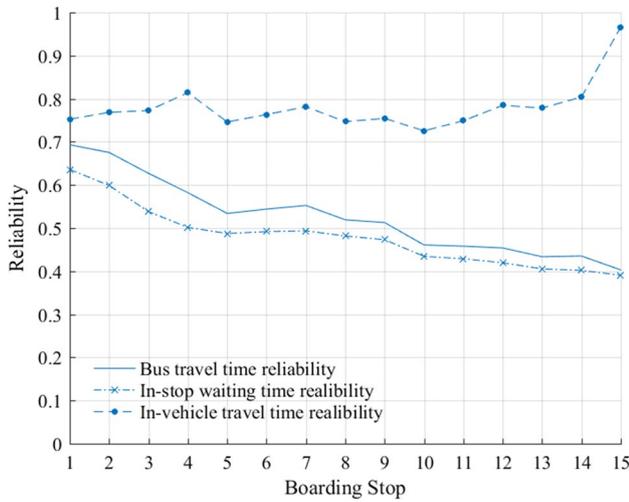


Fig. 12 Bus travel time reliability from different boarding stops to the terminal station

Fig. 13 Bus travel time reliability in different travelers’ arrival distribution

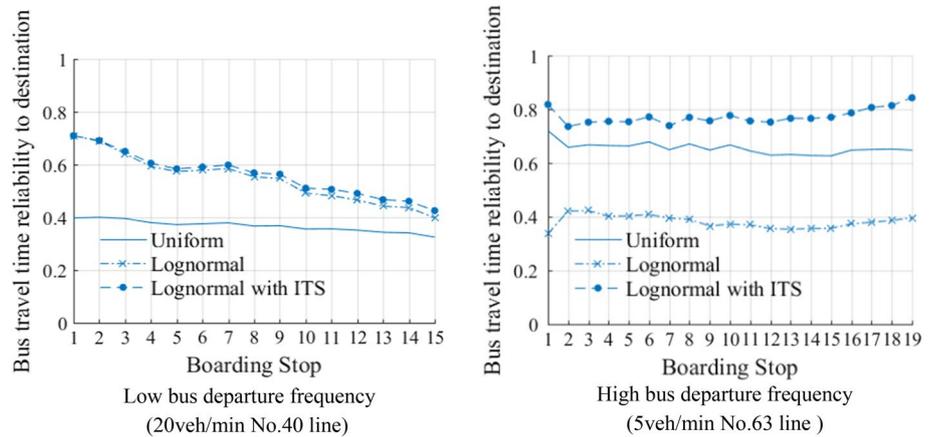


Table 3 Parameters of Fig. 13

| Travelers' arrival distribution | Bus departure frequency | Headway mean (s) | Headway standard deviation (s) | The most traveler arrival time (s) |
|---------------------------------|-------------------------|------------------|--------------------------------|------------------------------------|
| Uniform | High | 300 | 80 | NaN |
| Log-normal | Low | 1200 | 150 | 960 |
| ITS | Low | 1200 | 150 | 960 |

3.2.4 The influence of different travelers’ arrival distribution

Here, the bus travel time reliability model is used to calculate the effect of the three travelers’ arrival distribution. In order to have a uniform evaluation standard, the travel time thresholds of the three is from the result calculated in the log-normal case. And Fig. 13 shows the difference in bus travel time reliability between low and high bus departure frequency.

Obviously, the ITS-guided travelers get the highest bus travel time reliability in both low bus departure frequency and high bus departure frequency conditions. In the case of low bus departure frequency, compared to travelers with log-normal arrival distribution, ITS-guided travelers avoid extra travel time because of not missing buses; In the case of high bus departure frequency, compared to travelers with uniform arrival distribution, ITS-guided travelers have less mean of in-stop waiting time.

In addition, under high-frequency conditions the bus travel time reliability of uniform arrival distribution is higher than that of the lognormal arrival distribution, and opposite under low-frequency conditions. This indicates that as the bus departure frequency decreases, the bus travel time reliability of uniform distribution is gradually lower than that of the lognormal distribution, and about

10 min should be the threshold for the change. This result is in line with the relevant research mentioned earlier. (Yao et al. 2014; Barabino et al. 2017; Eboli et al. 2011).

3.3 The bus travel time reliability considering transfer behavior

Bus travel time reliability is an important reference when comparing bus transfer schemes with close average bus travel time; travelers are inclined to choose the bus route with higher bus travel time reliability. In this section, two bus transfer schemes with close average travel time will be compared in terms of bus travel time reliability. Results show that the proposed metric can be used to recommend more reliable bus route for passengers.

3.3.1 Introduction

The O–D pair from Qunli Road Stop to Ganshui Road Stop in Harbin City are chosen to demonstrate the bus travel time reliability with transfer behavior. Only the cases that transfer once are discussed as transferring twice or more is less common. As shown in Fig. 14, route 1 is marked in solid blue line with Bus Line No. 133 and Bus Line No. 86; route 2 is marked in red dash line with Bus Line No. 209 and No. 90. The two lines are close in travel lengths, and the reference bus travel time given by Google Maps is similar (2 h 23 min for route 1 and 2 h 26 min for route 2, given the congestion

level at 21:00). So Route 1's travel time threshold is set for both routes. In addition, the bus scheduled departure interval (all of them are 10 min) is acquired from the bus company.

3.3.2 Determine the parameters

The different values of γ will lead to different bus travel time reliability results, which may affect the choice of bus routes. Therefore, the influence of the value of γ on the bus travel time reliability of the two routes is analyzed first. We still take the data on December 3, 2012 as an example (the first non-snowy weekday).

It can be seen from Fig. 15 that the bus travel time reliability of the two routes has different trends with the change of γ value and time. For comparison, we take the data that $\gamma = 1.2, 1.4$ and 1.6 in Fig. 15, draw a line chart as Fig. 16.

As can be seen from Fig. 16, different travel time thresholds lead to great relative differences between the two bus routes. When $\gamma = 1.2$, the bus travel time reliability of route 1 is higher than that of route 2 in all hours (although the bus travel time reliabilities of the two routes are low). When $\gamma = 1.4$, the bus travel time reliability of route 2 is higher than route 1 only in 7:00–8:00 and 14:00–15:00, and the difference between the two routes' reliabilities has narrowed down in most hours. When $\gamma = 1.4$, the bus travel time reliability of route 2 is higher than that of route 1 in off-peak hours. Here we simply adopt $\gamma = 1.4$ to conduct subsequent

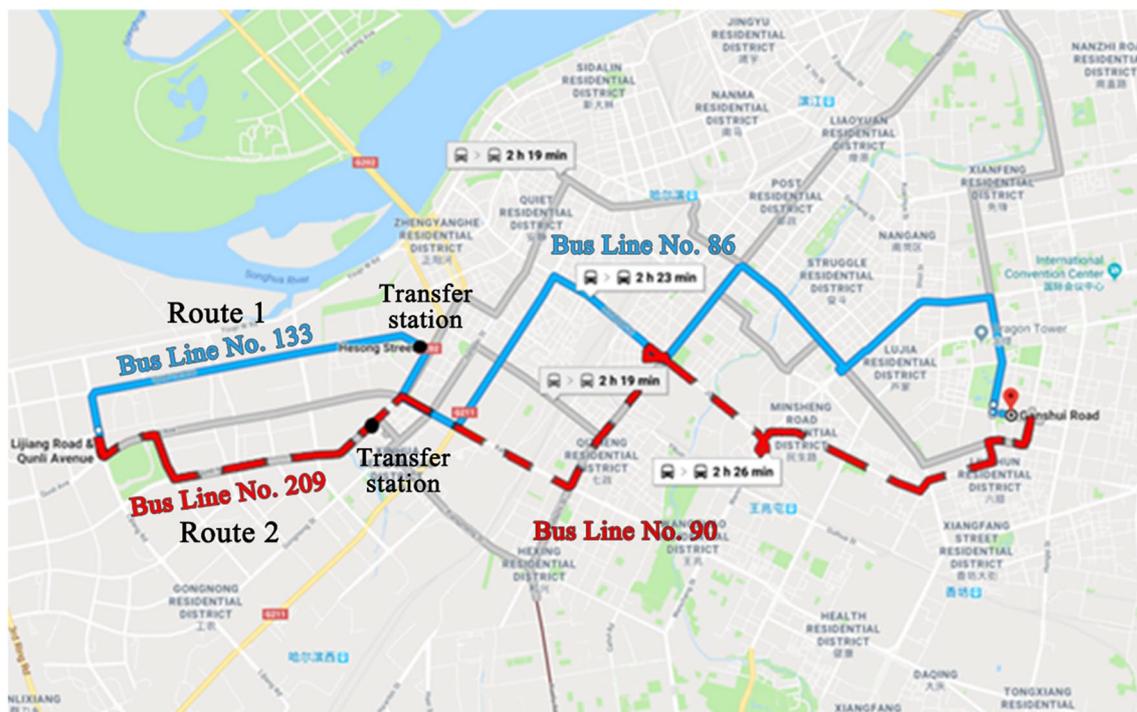


Fig. 14 Two routes from Qunli Road Stop to Ganshui Road Stop

Fig. 15 Two routes' bus travel time reliability under different γ

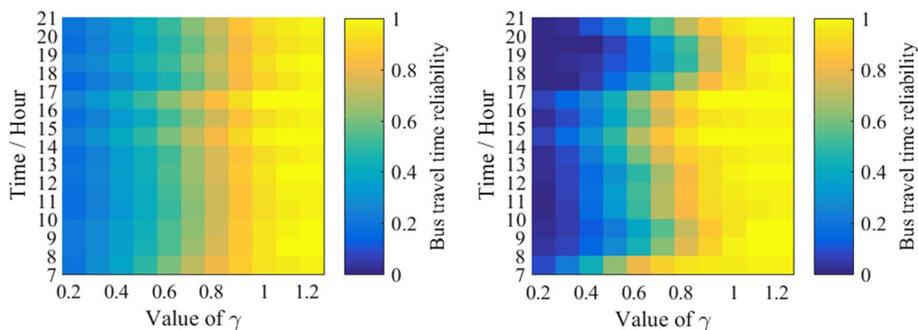
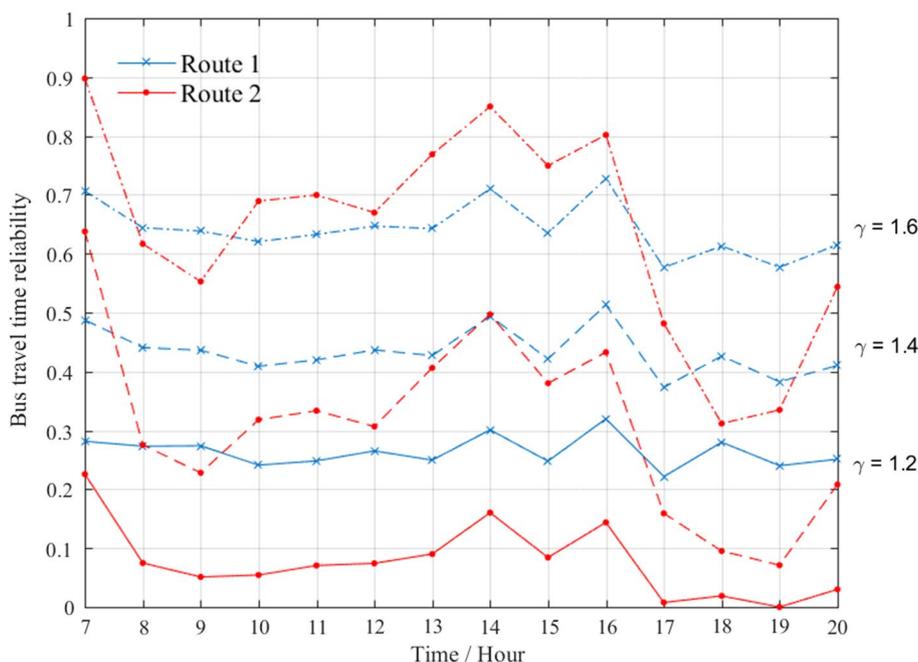


Fig. 16 Bus travel time reliability in different travel time threshold



analysis; when used in a practical context, γ can be adjusted according to users' aversion to travel time unreliability.

3.3.3 The influence of weather, day of week and time periods within a day

In previous examples, we analyzed that weather and week-day/weekend have a significant impact on bus travel time reliability; similar analyses are conducted here. Using one month's data, the means and standard deviations of the bus travel time reliability of the two routes at different conditions are calculated, the results are shown below in Fig. 17.

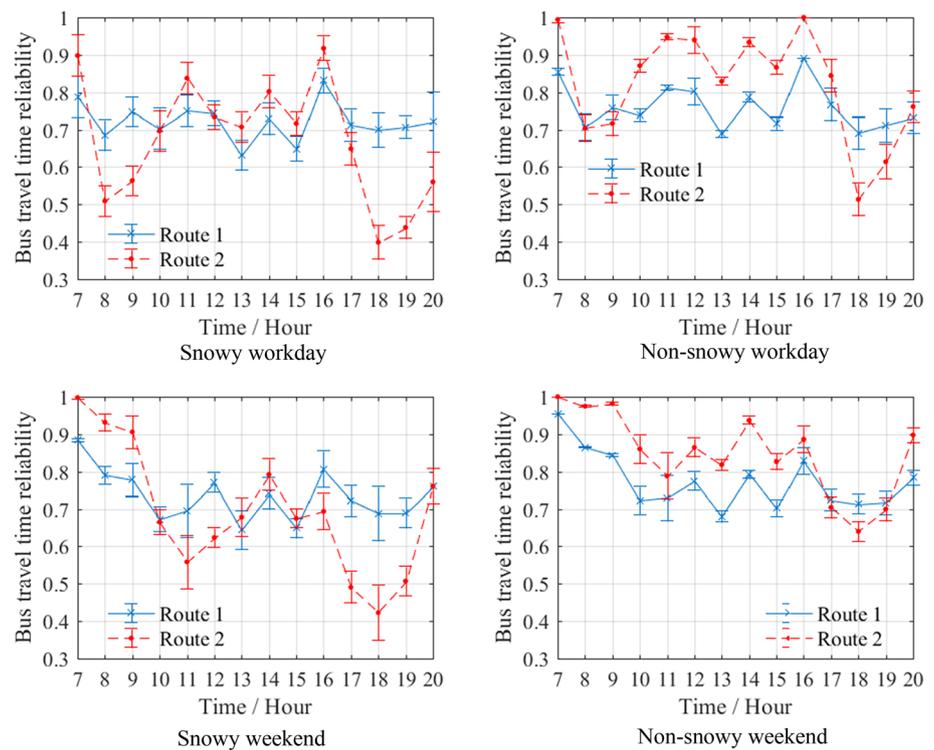
Figure 17 indicates that the fluctuation of bus travel time reliability on a snowy day is higher than the non-snowy days (look at the standard deviation bars). On the other hand, the mean value of bus travel time reliability is higher on

non-snowy days than that on snowy days. These observations are consistent with the non-transfer case in Sect. 3.1.

Comparing the bus travel time reliability of the two routes in all four sub-figures, it can be seen that the overall bus travel time reliability of route 1 is more stable than route 2. Although route 2 often has higher reliability in off-peak hours, it often suffers a dramatic decrease in reliability during peak hours. The time periods in which the bus travel time reliability of route 2 is higher than route 1 basically coincide with the off-peak hours. This is because some roads in route 2 have fewer lanes and larger traffic volumes, which are more vulnerable in peak hours. For weekends, the reliability drops of route 2 in the morning peak and shifts to the midday periods, which reflects the difference in the peak hours of weekdays and weekends.

To summarize, route 1 and route 2 have different reliability patterns. Although bus route 2 often has higher travel

Fig. 17 Bus travel time reliability in different conditions



time reliability under fine traffic conditions (good weather, low traffic volume), it is—on the other hand—often less reliable in poor traffic conditions. Thus, the proposed bus travel time reliability metric can be integrated into a bus route recommendation system, calculate the historical reliability of each bus route under different conditions and give real-time suggestions. Moreover, passengers with different unreliability aversions could have different preferences in balancing travel time and reliability; the proposed method can also set a customized expectation index to cater the needs of passenger groups.

4 Conclusions

This paper proposes a new method to evaluate the bus travel time reliability by considering two stochastic processes: the in-stop waiting process and in-vehicle travel process, then calculate the probability when the bus travel time is less than a certain threshold. It is formulated by the convolution of in-stop waiting time and in-vehicle travel time's PDFs and calculated by AVL data. The proposed reliability metric can be applied to both bus trips with and without transfer behavior. Real AVL data is used to quantitatively evaluate the bus travel time reliabilities with and without transfer behavior of selected bus lines in Harbin under different conditions; observations are summarized as follows:

- (1) Bus travel time reliability is closely related to weekends/weekdays, 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 on weekdays and weekends have different temporal patterns.
- (2) The effect of the in-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 in-stop waiting time, while longer trips are more susceptible to in-vehicle travel time.
- (3) Under similar bus travel conditions, the bus travel time reliability gets worse with the increase of the distance from the boarding stop to the departure station.
- (4) Different bus departure frequencies will result in different travelers' arrival distributions. When the bus departure frequency is high, travelers arrive uniformly and can get better bus travel time reliability than arriving as log-normal distribution; in the case of low frequency, the opposite is true.
- (5) ITS can be applied to the public transport system to reduce travelers' in-stop waiting time, and it also can make travelers avoid missing the target buses, and ultimately improve bus travel time reliability.
- (6) Among several bus transfer schemes of the same O–D pair, the most reliable route often varies under different conditions. The proposed reliability metric can be used

to provide customized bus route suggestions under different conditions.

The proposed reliability metric is tested to be sensitive to various factors and has wide adaptability. The merit of our method is that it provides a single straightforward value qualifying the time reliability of the entire bus trip. And the expectation index can be flexibly adjusted for specific purposes or passengers with different unreliability aversions. Moreover, the reliability has practical significance, and it can cooperate with relevant data to predict the bus travel time probability under a given travel time. Therefore, the proposed reliability metric can be applied in bus route recommendation and bus service evaluation/optimization. However, there is still much further work to carry out. Such as comparing the proposed metric with other metrics, considering not only the upper limit but also the lower limit for bus travel time, and extending the point-to-point reliability model to evaluate the performance of a bus line/network.

Acknowledgements This research was partially supported by the National Natural Science Foundation of China (71871075, 91846301, 71501053), China Postdoctoral Science Foundation (2015M570297), International Postdoctoral Exchange Fellowship (20160076) of China Postdoctoral Council, and CCF-DiDi Big Data Joint Lab.

Author contributions The authors confirm contribution to the paper as follows: project initiator: JY; model design: JY; data collection: ZZ, JW and ZC; data processing: ZZ; analysis and interpretation of results: JY, ZC; JW, SA; draft manuscript preparation: ZC, ZZ and JY. All authors reviewed the results and approved the final version of the manuscript.

Declarations

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

Ethics 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.

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