Journal of Southeast University (English Edition) Vol. 28, No. 1, pp. 100 – 105 Mar. 2012 ISSN 1003—7985

Bus transit travel time reliability evaluation based on automatic vehicle location data

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Abstract: In order to provide important parameters for schedule designing, decision-making bases for transit operation management and references for passengers traveling by bus, bus transit travel time reliability is analyzed and evaluated based on automatic vehicle location (AVL) data. Based on the statistical analysis of the bus transit travel time, six indices including the coefficient of variance, the width of travel time distribution, the mean commercial speed, the congestion frequency, the planning time index and the buffer time index are proposed. Moreover, a framework for evaluating bus transit travel time reliability is constructed. Finally, a case study on a certain bus route in Suzhou is conducted. Results show that the proposed evaluation index system is simple and intuitive, and it can effectively reflect the efficiency and stability of bus operations. And a distinguishing feature of bus transit travel time reliability is the temporal pattern. It varies across different time periods.

Key words: bus transit travel time reliability; evaluation and analysis; automatic vehicle location data; statistical analysis
doi: 10.3969/j.issn.1003 –7985.2012.01.017

Bus transit travel time demonstrates a stochastic nature. Travel time reliability is a major concern when transit passengers make their choices of bus routes and departure time. A reliable service is proven to be of the same importance as a rapid service[1], especially for commuting trips. Travel time reliability analysis is important for planning the scheduled travel time, which not only maximizes on-time performance, but also helps minimize operating costs. The operating condition of buses can also be obtained by investigating travel time reliability. The knowledge is also important for transit operators to highlight routes for improvement measures, such as bus lane, transit signal priority or route design change.

Bus transit travel time reliability is usually evaluated by descriptive statistics[2-3]. However, descriptive statistics cannot reflect the operating condition of buses and the extent to which bus travel time reliability is influenced by external factors. Using the data collected by the automatic vehicle location (AVL) system, this paper aims at proposing a method to evaluate the bus transit travel time reliability. To distinguish it from the segment-based bus transit travel time which studies the in-vehicle travel time between two adjacent stops, the route-based bus transit travel time (bus transit travel time in brief) is selected as the study object. In the coming sections, this paper will describe how the indices of reliability are used in the evaluation process and suggest that the added indices can result in a better understanding of bus transit travel time reliability.

1 Evaluation Methodology

For a concerned bus route, travel time reliability is defined as the consistency or dependability in travel times. It is one of the important determinants of service quality. It serves as an indicator of the stability degree of service that is provided by transit operators.

A wide range of factors may cause variations in bus transit travel time, such as pedestrian or bicycle movements, side parking friction, and traffic signals. Besides the objective effects, it is also affected by passenger demand. Route configurations influence bus transit travel time, including the number of bus stops and the spatial location of a bus route. Weather conditions and driver characteristics can also influence bus transit travel time.

1.1 Evaluation index system

According to the definition, the bus transit travel time reliability of a certain bus route refers to three aspects: variability, difference, and condition. When selecting the indices, the following principles are strictly adhered to: 1) The chosen indices should reveal the overall characteristics of variability; 2) The chosen indices should focus on extreme values rather than only mean values; 3) The chosen indices should uncover the operating conditions of buses on the route; 4) The indices should apply to the evaluation via AVL data. Following these principles, six indices are proposed, namely, the coefficient of variance, the width of travel time distribution, the mean

Received 2011-09-21.
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Foundation item: The Soft Science Research Project of Ministry of Housing and Urban-Rural Development of China (No. 2008-k5-14).
Citation: Yan Yadan, Guo Xiucheng, Li Yan, et al. Bus transit travel time reliability evaluation based on automatic vehicle location data[J]. Journal of Southeast University (English Edition), 2012, 28(1): 100 – 105. [doi: 10.3969/j.issn.1003 –7985.2012.01.017]

commercial speed, the congestion frequency, the planning time index, and the buffer time index. These evaluation indices highlight the differences between average operating conditions and the most extreme delays. These differences may be the most important factors in shaping a passenger's cognitive map.

The indices can be used by transit operators to monitor the reliability of bus transit travel time. The coefficient of variation and the width of travel time distribution are variability-based measures, and higher values indicate that travel times are more variable. The mean commercial speed and the congestion frequency are condition-based measures. The planning time index and the buffer time index are difference-based measures.

The coefficient of variation (CV) is calculated as the standard deviation divided by the mean travel time. It standardizes the variation in travel times, allowing comparison across different days and time periods[4].

$$\mathrm{CV} = \frac{\sigma_{\mathrm{T}}}{\bar{T}} \tag{1}$$

where σ_{T} is the standard deviation; $\bar{T}$ is the mean travel time.

The width of the travel time distribution W_{T} is calculated by

$$W_{\mathrm{T}} = \frac{T_{90} - T_{10}}{T_{50}} \tag{2}$$

where T_{90} is the 90th percentile travel time; T_{10} is the 10th percentile travel time; T_{50} is the 50th percentile travel time, i. e., the median travel time.

The congestion frequency F_{c} is the percent of travel time whose speed drops below threshold. The threshold here is defined as 1.3 times the free-flow travel time[5]. The analysis of the congestion frequency indicates the extent to which external factors influence the bus operating.

$$F_{\mathrm{c}} = \frac{N_{1.3}}{N} \tag{3}$$

where $N_{1.3}$ is the number of travel times that are greater than 1.3 times the free-flow travel time; N is the number of all trips.

The mean commercial speed S_{c} is referred to as the mean speed of buses along a bus route over stretches, including all the operational stops (bus stops, terminals, and traffic lights). It is different from the running speed, which only considers moving buses[6]. It reflects the operating condition of buses from a global picture of the situation and allows the detection of periods with poor operating conditions.

$$S_{\mathrm{c}} = \frac{L}{\bar{T}} \tag{4}$$

where L is the length of the studied bus route.

The planning time index I_{PT} is calculated as the 95th percentile travel time divided by the free-flow travel time. It suggests the total travel time needed to plan for a 95% on time arrival.

$$I_{\mathrm{PT}} = \frac{T_{95}}{T_0} \tag{5}$$

where T_{95} is the 95th percentile travel time; T_0 is the free-flow travel time.

The buffer time index I_{BT} is calculated as the difference between the 95th percentile travel time and the mean travel time divided by the mean travel time. It represents the percentage of extra travel time that most people will need to add on to their route trip in order to ensure on time arrival.

$$I_{\mathrm{BT}} = \frac{T_{95} - \bar{T}}{\bar{T}} \tag{6}$$

1.2 Framework for evaluation

The AVL system collects, processes and communicates location information to other applications that need accurate and timely location data. By associating time and location attributes, it enables the collection of disaggregated data by other on-board systems without the expense of assigning a person to the task[7]. The AVL system is a complement of technologies that track vehicle locations in an accurate and timely manner. It may be narrowly defined as the navigation suite: sensors and tracking software.

The most used sensor technology is the global positioning system (GPS). The AVL data collection process leads to a sample of stop level observations. The stop level data include information related to the bus, the stop, the time when the bus arrives at the stop, and the time when the bus leaves the stop.

The route-based bus transit travel time is defined as the difference between the departure time from the start stop and the arrival time at the end stop. It is the time that a bus needs to finish a complete trip. The bus transit travel time T is

$$T = t_{\mathrm{d}}^{\mathrm{s}} - t_{\mathrm{a}}^{\mathrm{e}}$$

where $t_{\mathrm{d}}^{\mathrm{s}}$ is the departure time from the start stop; $t_{\mathrm{a}}^{\mathrm{e}}$ is the arrival time at the end stop.

The AVL data in this study cover a certain bus route. They are subjected to a detailed observation to remove any abnormal travel time that might have occurred due to the presence of accidents or any other interruptions along the route[8]. Homogeneous time periods are the periods of constant scheduled bus transit travel time. Hence, the study tries to evaluate the bus transit travel time reliability from a temporal scale. The whole framework for evaluating the bus transit travel time reliability of a certain bus route is shown in Fig. 1.

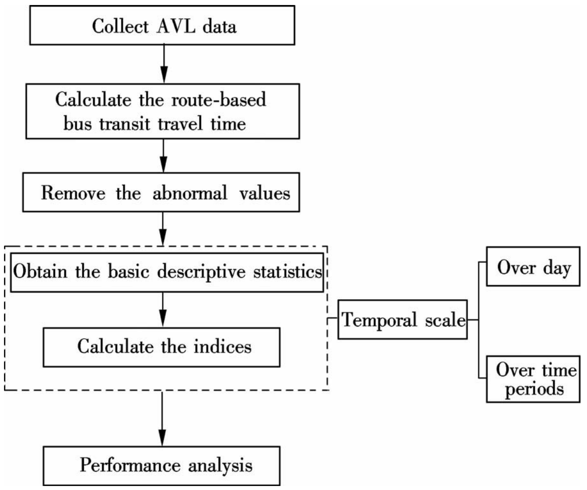

Fig. 1 Framework of evaluating bus transit travel time reliability

2 Case Study

The AVL system in Suzhou is based on the GPS. The selected route contains 36 bus stops, and has a length of 24 km. The fleet allocated on the route is 25 buses. The GPS devices are equipped on the fleet. Only the AVL data for the northbound buses are analyzed. The operating time for the bus route is from 5: 50 to 22: 30. Bus services are planned to operate every 12 min in morning peak (i. e. AM peak) and afternoon peak (i. e. PM peak), while 15 min in other time periods. However, the actual frequency of service varies over the day, ranging from less than 10 min to more than 20 min. In this study, the data set collected covers a five-day period from May 4 to 8, 2011. Six trips with abnormal values are removed. The research data include the travel times of 445 complete trips.

2.1 Reliability indices over day

Daily reports highlighting basic statistics and reliability indices for the entire bus transit system can be the snapshot of the bus service operation condition in the city. The report shows how each index changes from the previous day. It provides useful information for bus transit system planners and operation planning personnel. Bus routes with the worst travel time reliability should be candidates for improvement strategies.

Fig. 2 and Fig. 3 show bus transit travel times on weekdays and weekends, respectively. The notable features are that May 4 − 6 show similar fluctuation patterns and May 7 − 8 show similar fluctuation patterns.

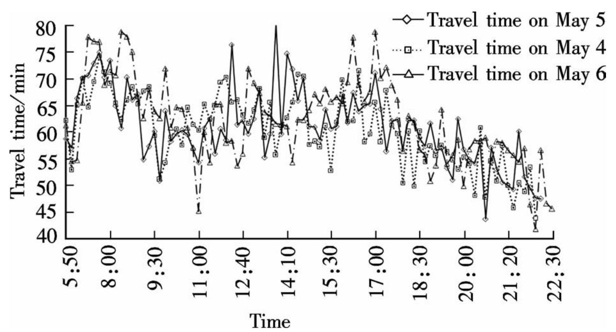

Fig. 2 Travel time observations on May 4 − 6 (weekdays)

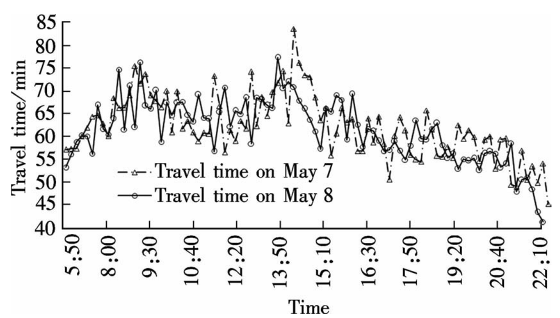

Fig. 3 Travel time observations on May 7 − 8 (weekends)

Compared with weekends, more travel times are greater than 75 min on weekdays. The travel time ranges from less than 45 min to more than 80 min. The plot of travel time also provides a metric for comparing actual conditions with those that a passenger might experience during an off-peak period. Assuming that buses mainly operate at free-flow speed in the evenings, the minimum travel time after 22: 00 is considered as the free-flow travel time. Calculating results are shown in Tab. 1.

Tab. 1 Calculating results of indices for different days

Day	T_0/min	$\bar{T}$/min	T_{95}/min	σ_T/min	CV/%	W_T/%	S_c/(km · h^{-1})	F_c/%	I_{PT}	I_{BT}
May 4	43.8	60.4	70.8	6.8	11	31	24	72	1.62	0.17
May 5	43.7	60.9	74.2	7.1	12	32	24	75	1.70	0.22
May 6	41.7	62.2	77.7	8.1	13	30	23	89	1.86	0.25
May 7	45.2	62.0	73.9	6.8	11	30	23	71	1.63	0.19
May 8	41.4	61.3	71.2	6.8	11	27	23	89	1.72	0.16

Take travel time observations of May 4 for example (see Tab. 1). CV is 11% and W_T is 31%, suggesting the wide spread of travel times. The variability in bus transit travel time is great for northbound buses.

Fig. 4 shows a buffer time of 10. 4 min. Reliability indices shown in Tab. 1 include I_{PT} (1. 62) and I_{BT} (0. 17). For a passenger who wants to ride on this route and expects to be 95% on time, the planning time index suggests that 27. 0 min should be reserved for his or her trip. These two values indicate that the level of service perceived by commuters is much poorer than the average level of service. That is exactly why passengers are very unsatisfied with the bus service.

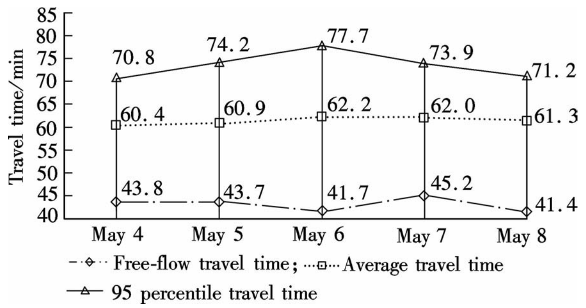

Fig. 4 Travel time distributions for May 4 − 8

S_c is 24 km/h, indicating that buses run fast on average across the day. However, 72% of travel times are larger than 1.3 times the free-flow travel time, as shown by the F_c value. External factors, especially traffic conditions, have an important impact on the travel time.

Indices of May 5 − 8 indicate the same characteristics as those of May 4. The studied bus route is with bad reliability, though it is rapid according to its commercial speed.

2.2 Reliability indices over time period

Travel time and travel time reliability are primary inputs for bus scheduling, helping to determine scheduled travel times. Bus transit travel time varies considerably between trips and between time periods. Hence, schedules are purposely built not only to account for the mean travel time, but also to provide a sufficient buffer[9]. In this way, most delays can be absorbed so the bus will not begin its next trip late. The period-to-period travel time reliability analysis can be examined to decide whether the schedule should be modified.

Fig. 2 and Fig. 3 show the spreads of travel times across the weekdays and weekends. Five distinct periods on weekdays are obtained using the clustering method: 5:50 − 7:00, 7:00 − 9:00, 9:00 − 16:00, 16:00 − 18:00 and 18:00 − 22:30. The number of periods on weekends is the same as that on weekdays. However, the lengths are different: 5:50 − 8:00, 8:00 − 9:30, 9:30 − 13:30, 13:30 − 15:00, and 15:00 − 22:30. Compared with weekdays, morning peaks on weekends start later and have a shorter duration, while afternoon peaks start earlier and also have a shorter duration on weekends.

Tab. 2 and Tab. 3 show reliability measures at five time periods on weekdays and weekends. The mean value of three free-flow travel times on May 4 − 6 is considered as the free-flow travel time on weekdays for analysis. The mean value of two free-flow travel times on May 7 − 8 is considered as the free-flow travel time on weekends for analysis.

Tab. 2 Calculated results of indices for five time periods on weekdays

Time period	Time	$\bar{T}$/min	σ_T/min	CV/%	W_T/%	T_{95}/min	S_c/(km · h^{-1})	F_c/%	I_{PT}	I_{BT}
AM off-peak	5:50 − 7:00	61.5	6.0	10	27	70.2	23	75	1.63(27.1 min)	0.14(8.7 min)
AM peak	7:00 − 9:00	71.0	5.0	7	20	78.5	20	100	1.82(35.5 min)	0.11(7.6 min)
Inter-peak	9:00 − 16:00	62.6	5.5	9	22	71.8	23	88	1.67(28.7 min)	0.15(9.2 min)
PM peak	16:00 − 18:0	65.1	5.7	9	22	78.0	22	97	1.81(34.9 min)	0.20(12.9 min)
PM off-peak	18:00 − 22:30	54.3	5.0	9	24	62.2	26	44	1.44(19.1 min)	0.14(7.9 min)

Tab. 3 Calculated results of indices for five time periods on weekends

Time period	Time	$\bar{T}$/min	σ_T/min	CV%	W_T/%	T_{95}/min	S_c/(km · h^{-1})	F_c/%	I_{PT}	I_{BT}
AM off-peak	5:50 − 8:00	59.7	3.7	6	17	66.6	24	81	1.54(23.3 min)	0.12(7.0 min)
AM peak	8:00 − 9:30	67.5	5.3	8	22	76.0	21	100	1.75(32.7 min)	0.12(8.5 min)
Inter-peak	9:30 − 13:30	64.6	4.2	6	17	72.3	22	100	1.67(29.0 min)	0.12(7.7 min)
PM peak	13:30 − 15:0	71.0	5.3	7	22	83.3	20	100	1.92(40.0 min)	0.17(12.3 min)
PM off-peak	15:00 − 22:30	57.7	5.5	10	25	66.9	25	61	1.54(23.6 min)	0.16(9.2 min)

For the weekdays, the mean travel time varies across the day ranging from 54.3 min in the PM off-peak to 71.0 min in the morning peak. For the weekends, the mean travel time ranges from 57.7 min in the PM off-peak to 71.0 min in the afternoon peak.

AM off-peak has the highest CV and W_T values on the weekdays. PM off-peak has the highest CV and W_T values on the weekends. More variable travel times exist at AM off-peak and PM off-peak periods. It may be due to the fact that some first buses operate at AM off-peak while some last buses operate at PM off-peak.

S_c in the morning peak on weekdays and S_c in the afternoon peak on weekends are lower than the mean value by 20%. These two time periods go through the worst operating conditions. The values of F_c in five time periods on weekends are all greater than those on weekdays. It indicates the change in external factors to some extent.

Passengers will have to pay 35.5 min more in the morning peak than in the free-flow condition on weekdays, and 40.0 min in the afternoon peak on weekends. Besides, passengers will have to pay 12.9 min more in the afternoon peak than in the average conditions on weekdays, and 12.3 min in the afternoon peak on weekends. I_{PT} and I_{BT} can provide departure time references for passengers. Understanding these two indices helps to explain the inconsistency in passengers' cognition of the level of service.

Different timetables should be used on weekdays and weekends and different scheduled travel times should be used in the schedule planning for different time periods. More scheduled travel time is required in the morning peak and afternoon peak periods. Tab. 4 shows scheduled travel times for different time periods that are now used by the transit operator. If the scheduled travel time is based on the 95th percentile criterion, there will be only a 5% chance that a bus will arrive late. The timetable used now needs to be revised by further analysis. Less scheduled travel time makes the bus have to start new trips already being delayed. More scheduled travel time leads to the waste of bus and driver resources. Unreasonable division of time periods will also lead to the temporally inappropriate allocation of bus and driver resources.

Tab. 4 Scheduled travel times for different time periods

Time	5:55 − 6:30	6:30 − 7:20	7:20 − 15:30	15:30 − 18:50	18:50 − 22:30
Scheduled travel time/min	55	68	73	82	68

2.3 Travel time distribution

Travel time distributions describe the nature and pattern of variability. Considering the contradictions in the literature about the use of normal distribution and lognormal distribution in modeling transit systems[10], the normality test of travel time data is conducted by using the Kolmogorov-Smirnov (K-S) test. The results indicate that the p-values of lognormal and normal distributions during all the three time periods on weekdays and weekends are almost the same (see Tab. 5). Both lognormal and normal distributions can be employed as the fitting distributions. The sample in the AM off-peak is small and buses mainly operate with a free-flow speed in the evenings. Inclusion of these travel time observations will result in a bimodal distribution. Hence, the AM off-peak and PM off-peak time periods are not considered for travel time distribution analysis.

Tab. 5 K-S test results for three time periods

Time period	Weekdays		Weekends	
	Z/P value (lognormal)	Z/P value (normal)	Z/P value (lognormal)	Z/P value (normal)
AM peak	0.532/0.940	0.471/0.980	0.579/0.891	0.569/0.903
Inter-peak	0.559/0.914	0.564/0.908	0.467/0.981	0.428/0.993
PM peak	0.517/0.952	0.520/0.950	0.332/1.000	0.370/0.999

3 Conclusion

Indices of travel time reliability are important indicators of the efficiency and stability of bus operation, and can reveal changes in operating conditions. The AVL data are used to calculate the reliability indices, which indicate that the travel time reliability of this bus route is poor. The research also suggests that the most distinguishing feature of bus transit travel time reliability is its temporal pattern, which varies daily across time periods. The analysis of congestion frequency indicates that external factors have an important impact on the bus running. Both lognormal and normal distributions can be used as the fitting distributions for the peak periods and the inter-peak periods. This finding is significant since an appropriate choice of travel time distribution is important in the micro-simulation of transit systems. It can also be used by transit operators to monitor the reliability of a system and to design optimal schedules.

The framework in this study can be applied to an entire bus route or to specific segments of any length, either for an entire day or for certain time periods. It can also be used to perform "before and after" evaluations and to compare routes that use roads with different infrastructure features. The methodology identified in this paper provides a valuable means of analyzing AVL data. The study of causes that lead to bus transit travel time unreliability is considered as future research.

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基于车辆自动定位系统数据的地面公共交通运行时间可靠性分析

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摘要: 为了给公交线路车辆调度提供重要参数及给公交运营管理和居民公交出行提供决策依据,应用车辆自动定位系统数据对公共交通运行时间可靠性进行了分析. 基于对公共交通运行时间的统计分析,提出变异系数、分布宽度、运行速度、堵率、规划时间、预留时间等 6 个指标,构建了公共交通运行时间可靠性评价分析框架. 苏州市某公交线路实例分析结果表明,所提出的评价指标体系简单直观,能有效反映该线路公交车辆运行的效率和稳定性,且公共交通运行时间可靠性具有随不同时段变化的特征.

关键词: 公共交通运行时间可靠性;评价分析;车辆自动定位系统数据;统计分析

中图分类号: U491.17