Journal of Southeast University (English Edition) Vol. 29, No. 3, pp. 316 - 321 Sept. 2013 ISSN 1003—7985

Evaluation method on bus arrival headway reliability

Chen Qian[1] Wang Xin[2] Li Wenquan[1]

([1]School of Transportation, Southeast University, Nanjing 210096, China)
([2]Transportation Research Institute, Old Dominion University, Norfolk, VA 23508, USA)

Abstract: To accurately capture the measurement of bus reliability and evaluate whether the transit system is properly operated, an evaluation framework is established to assess the reliability of the transit system from different stratifications, including stops, routes and network levels. The bus operation data of the Hefei city is analyzed as a case study. Comparison is conducted to show the improvement made by using the advanced method, and an example of adding exclusive bus lanes to the existing bus route is provided. The proposed advanced method can avoid the shortcomings of the traditional method. For example, the value of the reliability using the traditional coefficient of variation (CV) is not between 0 and 1, and the value of reliability can decrease with the increase in the transit headway, etc. The case study shows that the advanced method can represent the real operation condition of the transit system and can be used to evaluate the transit headway reliability more reasonably.

Key words: transit operation; reliability of transit; bus arrival headway reliability

doi: 10.3969/j.issn.1003 - 7985.2013.03.016

Improving the reliability of bus service has the potential to increase the attractiveness of public transit to the current and prospective riders. The ability of transport operators to understand and improve reliability relies on their ability to measure it[1]. The transit agencies need to know how efficiently and reliably their transit system operates by using operation data. The data can be obtained by traditional investigation (survey on vehicle, survey at stop) and advanced technologies (automatic vehicle location (AVL) and automatic passenger counters (APC)[2-3]). By analyzing the historical data, trends in service reliability and factors that contribute to service reliability can be obtained, which help a better understanding of the current transit operation system and the implementation of future improvement strategies.

This paper presents an in-depth analysis of bus arrival headway reliability service based on operational characteristics in Hefei, China. First, an improved index on bus arrival headway reliability is proposed. Then, a series of calculating formulae at the stops, routes and network levels are described. Finally, the bus arrival headway reliability is analyzed based on the bus operation data in Hefei. The analysis demonstrates that the new measures provide additional insight to the headway reliability, while the traditional measures of reliability are relatively limited.

1 Overview of Headway Reliability

As far back as the late 1960s some people were devoted to the topic of transit reliability dating and these works have continued until today, not only because the transit agencies place great importance to it, but also because it is a complicated problem that it is still far from being resolved.

1.1 Service reliability

Three types of measures of reliability have been studied in recent research. They are on-time performance (OTP), mean and excess passenger waiting time (EWT) and headway reliability (HR). These measures of reliability are widely used in the evaluation of bus operational reliability[4-5].

On-time performance, the commonly used measure, is used to describe the schedule adherence. It can be denoted as the percentage of vehicle departures that take place in a defined on-time window at a specific location.

Mean passenger waiting time and excess passenger waiting time are measures of estimating the passenger experience indirectly from vehicle location data and measures of operational performance. The excess waiting time is a relative measure that represents the extra amount of time a passenger waiting on average above the scheduled waiting time. It is the waiting time that will result from perfect adherence to schedule, and is noted for being useful[6].

For high-frequency service, often defined as headways of ten minutes or less, variation in vehicle headways becomes a more relevant measure. The headway reliability, defined as the percentage of headways that fall within a specified range from the scheduled headway, is a reliability measure frequently used by transit agencies and research studies.

Received 2013-04-28.

Biography: Chen Qian (1978—), female, doctor, associate professor, seu_chq@163.com.

Foundation items: The National Basic Research Program of China (973 Program) (No. 2012CB725402), the National Natural Science Foundation of China (No. 51208099, 50978057).

Citation: Chen Qian, Wang Xin, Li Wenquan. Evaluation method on bus arrival headway reliability[J]. Journal of Southeast University (English Edition), 2013, 29(3): 316 - 321. [doi: 10.3969/j.issn.1003 - 7985.2013.03.016]

1.2 Headway reliability

There are three types of measures that represent the operational quality of the transit system based on the headway reliability.

One definition is based on the variation method. The headway reliability of a stop is represented by the variation of the headway, and the headway reliability of a route is the average value of all stops on this route[7].

$$P_{Hi} = \frac{h_i}{h_{0i}} - 1 \qquad (1)$$

$$P_H = \frac{\sum_{i=1}^{n} P_{Hi}}{n} \qquad (2)$$

where P_{Hi} is the headway reliability at stop i; P_H is the headway reliability of a route; h_i is the actual headway of stop i; and h_{0i} is the scheduled headway of stop i. This definition is simple to explain and calculate. Nevertheless, the value of P_{Hi} is probably larger than 1 or less than 0, which is not reasonable.

Another definition is based on the probability method. The headways reliability is presented as the probability that the actual headway is less than the defined headway[8].

$$S_t^R = P(S_t < \alpha S_{t0}) \qquad \forall\, l \in L \qquad (3)$$

where S_t^R is the reliability of the headway; S_t is the actual headway in a particular serving period; S_{t0} is the scheduled headway; α is the modification coefficient, $\alpha > l$, and l is the obstruction coefficient, $l \in L$. Based on this definition, three performance parameters were proposed in the case study on transit systems of Beijing in China[9]. However, in this definition, the impact of bunching to the reliability is never considered.

The third definition is based on the statistics method. In the transit capacity and quality of service manual (TCQSM), the coefficient of variation (CV) of the transit headway serving a particular route arriving at a stop is calculated as

$$C_{vh} = \frac{\text{standard deviation of headway deviation}}{\text{mean scheduled headway}} \qquad (4)$$

The headway deviation is measured as the actual headway minus the scheduled headway. From the definition, the coefficient of variation of the headway presents the average variation of the headway, which means unreliability, so 1 minus C_{vh} is suggested as the headway reliability. However when C_{vh} is larger than 1, the headway reliability is smaller than 0.

Transit service reliability has been defined in a variety of ways. In China, almost all of the bus routes have no scheduled arrival time for each stop, and the headway reliability is a proper index with which to evaluate status of the vehicle operation and the reliability of waiting time for passengers. However, the existing studies about this index have some shortcomings, such as the value of reliability is not between 0 and 1; bunching is not considered in the definition; and there is not a series of indices for different levels such as stop, route and network, etc. Few studies notice it and carry on deep research on the definition of headway reliability. The calculation method is required to be modified to fit the evaluations for those routes with high frequency.

2 Methodology

Given the shortcomings of the existing headway reliability measures, a modified measure is proposed here.

2.1 Advanced definition

The headway reliability based on a particular vehicle is formulated in the following equations:

$$H_{ijkm}^{RB} = \begin{cases} 1 - \dfrac{H_{ijkm} - h_{ijkm}}{\varepsilon_{ijkm}^3 - H_{ijkm}} & h_{ijkm} \in [0,\ \varepsilon_{ijkm}^1) \\ 1 & h_{ijkm} \in [\varepsilon_{ijkm}^1,\ \varepsilon_{ijkm}^2) \\ 1 - \dfrac{h_{ijkm} - H_{ijkm}}{\varepsilon_{ijkm}^3 - H_{ijkm}} & h_{ijkm} \in [\varepsilon_{ijkm}^2,\ \varepsilon_{ijkm}^3) \\ 0 & h_{ijkm} \in [\varepsilon_{ijkm}^3,\ \infty) \end{cases} \qquad (5)$$

The headway reliability based on a particular stop is defined as

$$H_{ijk}^{RS} = \sum_m \alpha_{ijkm} H_{ijkm}^{RB} = \sum_m \frac{H_{ijkm}}{\sum_m H_{ijkm}} H_{ijkm}^{RB} \qquad (6)$$

The headway reliability based on a particular route is defined as

$$H_{jk}^{RL} = \sum_i \alpha_{ijk} H_{ijk}^{RS} = \sum_i \frac{Q_{ijk}}{Q_{jk}} H_{ijk}^{RS} \qquad (7)$$

The headway reliability based on the studied bus network is defined as

$$H_k^{RN} = \sum_j \alpha_{jk} H_{jk}^{RL} = \sum_j \frac{Q_{jk}}{Q_k} H_{jk}^{RL} \qquad (8)$$

where H_{ijkm}^{RB} is the headway reliability based on a particular vehicle; H_{ijk}^{RS} is the headway reliability based on a particular stop; H_{jk}^{RL} is the headway reliability based on a particular route; H_k^{RN} is the headway reliability based on the studied bus network; i is the stop index, $i \in I$, and I is the set of evaluation stops; j is the route index, $j \in J$, and J is the set of evaluation routes; k is the interval index, $k \in K$, and K is the set of evaluation intervals; m is the vehicle index, $m \in M$, and M is the set of evaluation vehicles; h_{ijkm} is the actual arrival headway of vehicles; H_{ijkm} is the scheduled arrival headway of vehicles; ε_{ijkm}^1 is the lower bound of headway under normal operation; ε^2_{ijkm} is the upper bound of headway under normal operation; ε^3_{ijkm} is the acceptable maximum headway when the vehicle is late under an abnormal operation; generally, $\varepsilon^1_{ijkm} < H_{ijkm} < \varepsilon^2_{ijkm} < \varepsilon^3_{ijkm}$; α_{ijkm} is the passenger flow weight for vehicle m; α_{ijk} is the passenger flow-based weight for stop i; α_{jk} is the passenger flow-based weight for route j; q_{ijkm} is the boarding passengers at the vehicle m of stop i, route j in a given time period k; Q_{ijk} is the total sum of boardings at stop i of route j in a given time period k, $Q_{ijk} = \sum_m q_{ijkm}$; Q_{jk} is the total sum of boarding passengers along route j in a given time period k, $Q_{jk} = \sum_i Q_{ijk}$; Q_k is the total sum of boardings of all the routes in a given time period k, $Q_k = \sum_j Q_{jk}$.

2.2 Discussion of performance parameters

2.2.1 Threshold value

ε^1_{ijkm}, ε^2_{ijkm} and ε^3_{ijkm} are used to define the lower and upper bounds of passengers and/or operators acceptance level of headway. For instance, In England, the percentage of vehicles arriving earlier within 2 to 8 min than scheduled arrival time, and that of vehicles arriving later within 8 to 15 min than scheduled arrival time are used in evaluating the bus operation in the route with a high frequency service (headway < 10 min). In Queensland of Australia, those vehicles arriving up to 1 min early and 5 min late from the schedule, are regarded as reliable[10]. Since passengers' tolerable degree about waiting time and operators' acceptable level about on-time operation are different. These three parameters are usually determined by a questionnaire survey or the operator's experience.

2.2.2 Definition of H^{RB}_{ijkm}

There are four different situations describing whether the transit vehicle arrives accordant with the satisfaction level.

1) When $h_{ijkm} \in [\varepsilon^1_{ijkm}, \varepsilon^2_{ijkm})$, the vehicle is regarded as arriving under normal operation and the reliability is 1; that is, $H^{\mathrm{RB}}_{ijkm} = 1$.

2) When $h_{ijkm} \in [\varepsilon^3_{ijkm}, \infty)$, the vehicle is regarded as arriving too late to endure and the reliability is 0; that is, $H^{\mathrm{RB}}_{ijkm} = 0$.

3) When $h_{ijkm} \in [\varepsilon^2_{ijkm}, \varepsilon^3_{ijkm})$, the vehicle is regarded as arriving late but tolerable, and the reliability varies with the length of late time, which is expressed as $H^{\mathrm{RB}}_{ijkm} = 1 - \dfrac{h_{ijkm} - H_{ijkm}}{\varepsilon^3_{ijkm} - H_{ijkm}}$.

4) When $h_{ijkm} \in [0, \varepsilon^1_{ijkm})$, the vehicle is regarded as arriving early, and the reliability varies with the length of late time, which is expressed as $H^{\mathrm{RB}}_{ijkm} = 1 - \dfrac{H_{ijkm} - h_{ijkm}}{\varepsilon^3_{ijkm} - H_{ijkm}}$.

In order to ensure consistency between early arrival vehicles and late arrival vehicles, passengers' delay is analyzed to evaluate the reliability of early arrival vehicles.

If the vehicle arrives early, that is, when $h_{ijkm} < H_{ijkm}$, those passengers arriving in the period of time $(h_{ijkm}, H_{ijkm}]$ cannot take the bus on a regular timetable. The scheduled waiting time of these passengers is $\dfrac{H_{ijkm} - h_{ijkm}}{H_{ijkm}} \cdot \bar{q}_{ijkm} \dfrac{H_{ijkm} - h_{ijkm}}{2}$, where $\bar{q}_{ijkm}$ is the theoretical boarding passengers of vehicle m at stop i, route j in a given time period k as scheduled, $\bar{q}_{ijkm} = \dfrac{H_{ijkm}}{\sum_m H_{ijkm}} Q_{ijk}$. The actual waiting time caused by the early arriving vehicle is $\dfrac{H_{ijkm} - h_{ijkm}}{H_{ijkm}} \bar{q}_{ijkm} \left(\dfrac{H_{ijkm} - h_{ijkm}}{2} + H_{ijkm} \right)$, and then the delay time of those passengers is $(H_{ijkm} - h_{ijkm})\bar{q}_{ijkm}$.

If this delay is caused by late arriving vehicle, the headway is supposed to be h'_{ijkm}, $h'_{ijkm} > H_{ijkm}$, and then the delay is $(h'_{ijkm} - H_{ijkm})\bar{q}_{ijkm}$. Command that $(H_{ijkm} - h_{ijkm}) \cdot \bar{q}_{ijkm} = (h'_{ijkm} - H_{ijkm})\bar{q}_{ijkm}$, then $h'_{ijkm} = 2H_{ijkm} - h_{ijkm}$.

Based on the above analysis, when vehicle arrives early ($h_{ijkm} \in [0, \varepsilon^1_{ijkm})$), the reliability can be calculated as $H^{\mathrm{RB}}_{ijkm} = 1 - \dfrac{h'_{ijkm} - H_{ijkm}}{\varepsilon^3_{ijkm} - H_{ijkm}} = 1 - \dfrac{H_{ijkm} - h_{ijkm}}{\varepsilon^3_{ijkm} - H_{ijkm}}$.

3 Case Study

3.1 Data used

Hefei is the capital and the largest city of Anhui Province in China. The operational data used in this paper cover almost all the vehicles of 97 routes of Hefei in a normal weekday, including detailed data on arrival time, passenger flow of boarding and alighting at each stop, during AM peak, PM peak, and off-peak periods. By analyzing the data, we compare the headway reliability using existing measures along with those using the definition presented in this paper.

3.2 Comparison between existing methods and advanced method

3.2.1 CV method vs. advanced method

According to the level of service grades based on the coefficient of variation of the headway established by TCQSM as shown in Tab. 1, we analyze the transit survey data using the CV method.

Fig. 1 demonstrates how the CV calculation and scheduled headway correlated with LOS evaluation. To be noted is that based on field data, C_{vh} drops with the increase of the scheduled headway, which means that the level of service improves with the larger scheduled headway. The growth in the standard deviation of the headway deviation is less than that of the mean scheduled headway. The inconsistency of the growth of numerator and denominator leads to the fact that the value of the fraction C_{vh} is doomed to get smaller along with the increase of headway.

Tab. 1 Transit level of service by headway regularity

Level of service	Coefficient of variation of headway
A	0 to 0. 21
B	0. 22 to 0. 30
C	0. 31 to 0. 39
D	0. 40 to 0. 52
E	0. 53 to 0. 74
F	≥0. 74

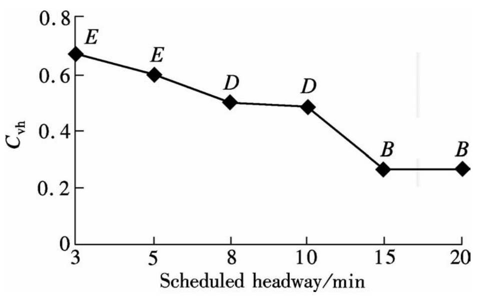

Fig. 1 Distribution of C_{vh} and LOS of bus operation in Hefei

We can conclude that it is not reasonable to evaluate the reliability level of service by C_{vh} only. By the method proposed in this paper, the statistical average headway reliability of bus routes corresponding to different scheduled headways is shown in Fig. 2. We obtain a relatively flat curve of the headway reliability. This overcomes the shortcoming of the CV method.

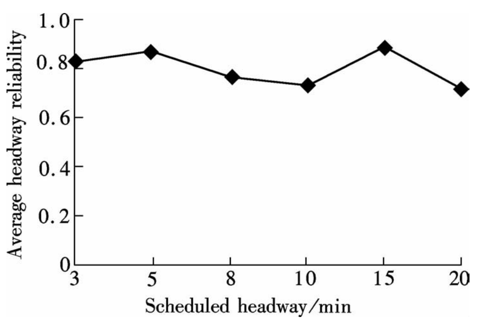

Fig. 2 Average headway reliability of bus routes using advanced method in Hefei

3. 2. 2 Probability method vs. advanced method

Bus Line 1 is selected to compare the differences between the probability method and the advanced method. It has a 5-min interval headway at AM peak with 18 stops. Fig. 3 shows the arrival time of vehicles at each stop on this route.

For the probability method, $\alpha = 2.4$ is required, which means that the reliability of the bus with a headway greater than 12 min is considered as 0 (unreliable). For the advanced method, parameters are selected as follows: $\varepsilon_{ijkm}^{1} = 3$ min, $\varepsilon_{ijkm}^{2} = 8$ min, $\varepsilon_{ijkm}^{3} = 12$ min, which means that the reliability of the bus with the headway smaller than 8 min and larger than 3 min is considered as 1 (reliable), and those with the headway larger than 12 min are considered as 0 (unreliable), which coincides with the probability method.

Fig. 3 shows that in some segments of the line, vehicle 3 and vehicle 4 arrive at the stop as a bunch between stop 1 and stop 11. Using the probability method, the average reliability value of vehicle 4 is 1. Differently, that of vehicle 4 is 0. 50 using the advanced method. Fig. 4 shows the value of the headway reliability of vehicle 4 at each bus stop. From which we find that the values of headway reliability vary from 0. 14 to 0. 28 between bus stop 1 and stop 11 using the advanced method, while those values are 1 at each stop by the probability method. This makes more sense since the advanced method can accurately capture a less reliable situation when buses arrive like a bunch, while this situation is completely ignored by the probability method.

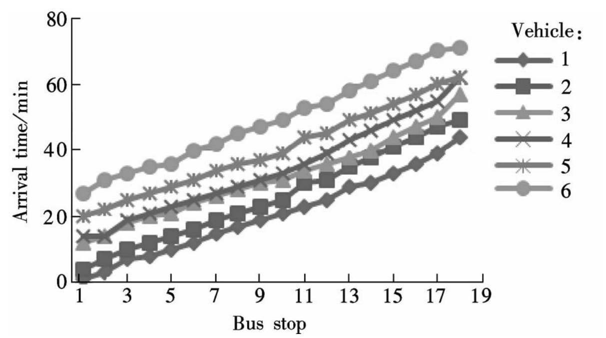

Fig. 3 Arrival time of each bus at AM peak hour on Line 1

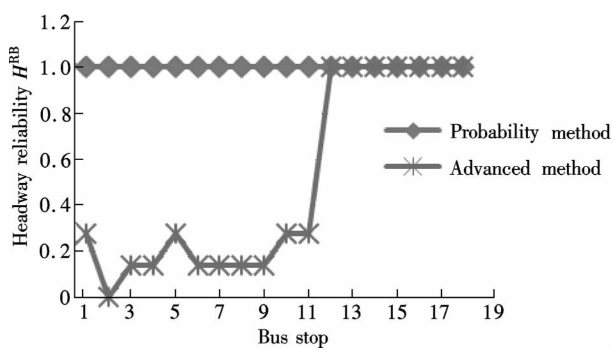

Fig. 4 Headway reliability of vehicle 4 at each stop at AM peak hour on Line 1

3. 3 Application of advanced method

3. 3. 1 Evaluating the transit reliability

Using the advanced method, we calculate the headway reliability values for vehicle, stop, route and network levels in Hefei. For the network level, the average values of the headway reliability of all the survey routes are 0. 87 for the whole day and 0. 81 for peak hours (including morning and evening peaks), which implies that the transit system is well operated at a relatively high reliability level. For the route level, Fig. 5 shows the headway reliability for several routes during a whole travel day and during peak hours. It shows that the value of the headway reliability during peak hours is lower than the average value during the whole day. For the stop level, the average values of the headway reliability of each bus stop varies from 0.56 to 0.91 in peak hours, which are not related to the location of the bus stops. For the vehicle level, the average values of the headway reliability of each vehicle varies from 0.21 to 1.0 in peak hours. These values provide a general picture of the operational reliability of the transit network. For the transit management agencies, it is the basis of establishing measures to improve the operational level.

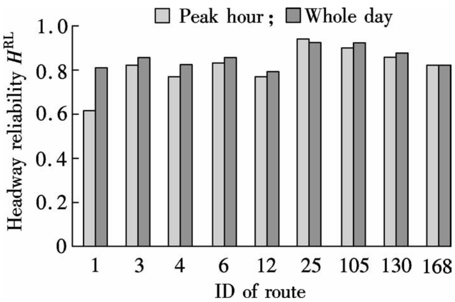

Fig. 5 Headway reliability of some routes in Hefei

3.3.2 Evaluating the effect of exclusive bus lane (XBL)

Here we show a case of using the advanced method presented in this paper to evaluate the effect of adding the XBL to one route. Bus Line 4 is selected in this case study, which has a length of 12.8 km and 20 stops. Some segments on this route (Link between stop 5 and stop 10 is about 3 km) have been upgraded into an XBL since June, 2010. With the before and after survey data, we can evaluate whether adding the XBL improves the reliability of this route or not.

The scheduled headway of Line 4 is 8 min during peak hours. Considering the passengers' acceptable level on waiting time, we define that $\varepsilon_{ijkm}^{1}=6$ min, $\varepsilon_{ijkm}^{2}=12$ min, $\varepsilon_{ijkm}^{3}=16$ min. As shown in Fig. 6, the headway is more equally distributed after the XBL is implemented. Also the headway reliability is increased after providing the XBL. As shown in Fig. 7, the headway reliability level is improved not only for those segments which are upgraded into an XBL but also the overall bus line. More specifically, the headway reliability of Line 4 is 0.768 (peak hour) and 0.807 (whole day) before adding the XBL, while after adding the XBL, these values increase to a high level of 0.953 (peak hour) and 0.967 (whole day). This indicates that adding the XBL is very effective on the transit reliability improvement.

4 Conclusion

This study provides a comprehensively advanced method to evaluate transit headway reliability which overcomes the shortcomings of the existing methods such as the CV method and the probability method. More specifically, the advanced method presented in this study has the following advantages: 1) The value of reliability is between 0 and 1, which facilitates a better explanation of the transit

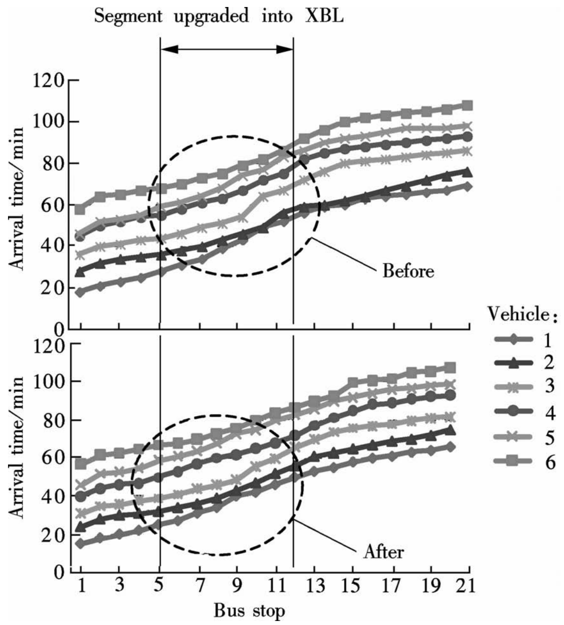

Fig. 6 Arrival time of each bus at AM peak hour of Line 4 before and after adding XBL

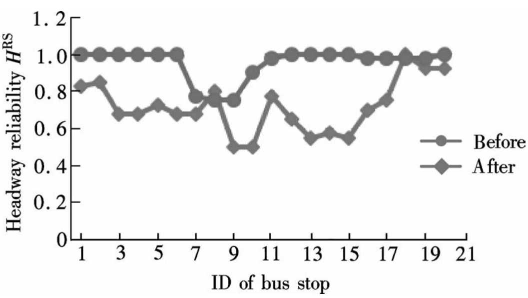

Fig. 7 Headway reliability for each stop at AM peak hour of Line 4 before and after adding XBL

headway reliability. 2) The value of headway no longer depends on scheduled headway. 3) The advanced method takes into account the situation that vehicles arrive as a bunch. Arriving as a bunch can bring uncertainty to transit operations. Ignoring this phenomenon can provide misleading information about transit reliability. This advanced method is more reasonable and practical in evaluating the transit operation. It is useful for the transit management agencies to thoroughly determine the weak points of the transit network.

The limitations of the definition on the headway reliability proposed here is how to determine the value of the threshold, which is the embodiment of passengers' acceptable level of waiting time. It is difficult to measure the acceptance level for different people accurately, because this is affected by many factors, such as family income, car ownership, trip purpose and distance, traveler's ages and gender, etc, which are well worth studying deeply.

References

[1] Uniman D L. Service reliability measurement framework

using smart card data: application to the London underground [D]. Boston: Department of Civil and Environmental Engineering and Department of Urban Studies and Planning, Massachusetts Institute of Technology, 2009.

[2] Tétreault P R, El-Geneidy A M. Estimating bus run times for new limited-stop service using archived AVL and APC data [J]. *Transportation Research Part A: Policy and Practice*, 2010, **44**(6):390 −402

[3] El-Geneidy A, Horning J, Krizek K. Analyzing transit service reliability using detailed data from automatic vehicular locator systems [J]. *Journal of Advanced Transportation*, 2011, **45**(1):66 −79.

[4] 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.

[5] Chen Xumei, Yu Lei, Song Guohua, et al. Comparative study of emissions from bus rapid transit and conventional bus systems[J]. *Transportation Research Board*, 2012, **2277**:11 −20.

[6] Lin J, Ruan M. Probability-based bus headway regularity measure [J]. *Intelligent Transport Systems*, 2009, **3**(4):400 −408.

[7] Oort N V, Nes R V. Improving reliability in urban public transport in strategic and tactical design [C]//*Transportation Research Board Annual Meeting* 2008 *Paper*. Washington, DC, USA, 2008:0581.

[8] Gao Guifen, Wei Hua, Yan Baoji. Study on reliability evaluation of urban public transit service quality [J]. *Journal of Wuhan University of technology: Transportation Science &Engineering*, 2007, **31**(1):140 −143. (in Chinese)

[9] Chen Xumei, Yu Lei, Zhang Yushi, et al. Analyzing urban bus service reliability at the stop, route, and network levels [J]. *Transportation Research Part A: Policy and Practice*, 2009, **43**(8):722 −734.

[10] Song Xiaomei. Multi-level models and algorithms for evaluating operational reliability of bus networks [D]. Beijing: School of Traffic and Transportation, Beijing University of Technology, 2010. (in Chinese)

公交车辆行车间隔可靠性评价方法

陈　茜[1]　王　辛[2]　李文权[1]

([1] 东南大学交通学院, 南京 210096)

([2]Transportation Research Institute, Old Dominion University, Norfolk, VA 23508, USA)

摘要:为了准确描述公交车辆运行可靠性、合理评价公共交通系统运营状况,提出了一种针对站点、线路、路网不同层面的公交可靠性改进计算方法. 结合合肥市的公交实际运营数据,验证了所提出的可靠性定义对于传统方法的改进效果,并应用该方法分析了设置公交专用道后公交车辆运营可靠性的提升效果. 研究表明,所提出的改进方法,可以克服传统可靠性评价方法的不足之处,例如间隔可靠性评价值会出现小于0和大于1的情况,且随着发车间隔的增大,计算的可靠性指标值呈现减小的趋势等. 该方法可以更真实地反映公交系统运营状态,提高了公交车辆运行可靠性评价的合理性.

关键词:公交运营;公交可靠性;车辆行车间隔可靠性

中图分类号:TP491