Transport
Volume 167 Issue TR3

Bus travel time reliability analysis: a case study
Qu, Oh, Weng and Jin

ice | proceedings

Proceedings of the Institution of Civil Engineers
Transport 167 June 2014 Issue TR3
Pages 178–184 http://dx.doi.org/10.1680/tran.13.00009
Paper 1300009
Received 21/01/2013 Accepted 28/01/2014
Keywords: mathematical modelling/public policy/transport planning

ice
Institution of Civil Engineers
publishing

Bus travel time reliability analysis: a case study

Xiaobo Qu PhD
Lecturer, Griffith School of Engineering, Griffith University, Gold Coast, Australia

Erwin Oh PhD
Senior Lecturer, Griffith School of Engineering, Griffith University, Gold Coast, Australia

Jinxian Weng PhD
Associate Professor, MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing, China

Sheng Jin PhD
Assistant Professor, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China

The travel time reliability of buses has become increasingly important for public transit companies. In this study, a novel approach is proposed to evaluate and analyse the travel time reliability of bus services provided by TransLink in Queensland, Australia. In view of their stochastic features, the two components of travel time – dwell time and driving time – are represented by discrete distributed and normally distributed random variables respectively. Accordingly, the travel time could be described by Gaussian mixture models. Based on the proposed model, impact analysis shows that bus line reliability would increase by around 15% if onboard top-up for 'go cards' (electronic tickets) was not offered by TransLink. It was found that not providing this top-up method would not significantly harm the benefit of go card users, but it would substantially increase the total social benefit thanks to improved bus line reliability.

Notation

A_i	arrival time at stop i
a_i	scheduled time in the timetable
b	time for doors opening and closing
D_k	dwell time at bus stop k
$f_s(x\|\mu_s, \sigma_s^2)$	component density function of Gaussian mixture model
m_k	number of alighting passengers
$N_{a,i}$	number of alighting passengers at stop i
$N_{b,i}$	number of boarding passengers at stop i
$N(\mu_i, \sigma_i^2)$	normal distribution with a mean μ_i and a variance σ_i^2
n_k	number of boarding passengers
p_s	weight coefficient of Gaussian mixture model
q	punctuality of bus at bus stop i
r	reliability for bus line
T_a	time spent on alighting per passenger
T_b	time spent on boarding per passenger
T_i	driving time from stop $i-1$ to stop i
T_j	driving time at interval j
t_i	expected value of driving time from stop $i-1$ to stop i (as shown in the timetable)
ε_i	random term that depends on traffic state, traffic signals and so on
μ_i	mean value of T_i
σ_i^2	variance of T_i

1. Introduction

Public transport provides a basic mobility service to various types of activities including employment, education, recreation and medical care. It also helps to reduce road congestion, vehicle emissions and oil consumption – all of which benefit both riders and non-riders (Rojo *et al.*, 2011; Yan *et al.*, 2013; Yu *et al.*, 2010). Public transport has thus become an increasingly cost-effective solution to overcome the challenges associated with land availability, economics, energy and the environment (Liu *et al.*, 2013; Szeto and Wu, 2011; Yan *et al.*, 2012). In this regard, land transport authorities have been trying to promote and encourage public transport, especially in compact urban cities with limited land availability. It is well recognised that the attractiveness of public transport services would be seriously undermined by system unreliability (Chen *et al.*, 2009; Mazloumi *et al.*, 2011a, 2011b; Meng and Qu, 2012a; Orth *et al.*, 2011; Vu and Khan, 2010). Consequently, improving the reliability of public transit services is a key priority and primary focus for the TransLink Transit Authority (Queensland), as stated in the 2010–2011 annual report (TransLink, 2010).

Bus schedule reliability is an essential attribute of a bus system, and is consistently ranked as one of the major concerns of passengers (Ng *et al.*, 2011; Orth *et al.*, 2012; Sorratini *et al.*, 2008; Xuan *et al.*, 2011). Therefore, in order to encourage the use of public transit systems, it is of utmost significance to enhance the reliability of bus services. Bus travel time is naturally unstable since a small disturbance, such as a delay in boarding or alighting, can start a vicious cycle that results in bus unpunctuality. The bus travel time on a route can be divided into dwell time and driving time (Dorbritz *et al.*, 2009; Meng and Qu, 2013). The former is the time for passengers boarding and alighting at bus stops, including doors opening and closing, and the latter is the time when buses are actually moving from one stop to another. Both components possess variability. The driving time usually fluctuates at an expected time given in the timetable. Mathematically this is expressed as

$$1.\quad T_i = t_i + \varepsilon_i$$

where T_i is the driving time from stop $i-1$ to stop i, t_i is the expected value of driving time from stop $i-1$ to stop i (as shown in the timetable) and ε_i is a random term that depends on the state of traffic state, traffic signals and so on. Taylor (1982) showed that driving time follows a symmetrical distribution (i.e. normal) distribution. Jordan and Turnquist (1979) showed that driving time at rush hours had a skewed distribution and a gamma distribution provided the best fit. Mazloumi *et al.* (2009) analysed factors that contribute to driving time variability.

Bus dwell time is considered to be a function of the number of alighting and boarding passengers and the amount of time required for opening and closing of bus doors (Levinson, 1983). Since the 1980s, a few regression models have been developed to estimate the bus dwell time in a deterministic manner (Guenthner and Hamat, 1988; Jaiswal *et al.*, 2010; Tirachini, 2013). The basic assumption in these regression models is that the boarding and alighting times for different passengers are similar. However, different passengers may have significantly different boarding times.

Dorbritz *et al.* (2009) discussed the impact of onboard ticket sales on bus dwell time variance. In Queensland, more than 80% of passengers use a 'go card' (an electronic ticket) to tap in and out of the bus (TransLink, 2010). The average boarding time for this category of passenger is around 3 s. By contrast, paper ticket buyers take at least 10 s per passenger for boarding. In Queensland, passengers can also top up their go cards on TransLink buses, and this takes at least 30 s per passenger. The other top-up alternatives are on line, by phone, at most convenience stores and/or supermarkets, on any ferry, at any train station and at some big bus stops. Therefore, random variables are more correct alternatives due to the intrinsic stochastic nature of these parameters.

In this study, a model was developed to evaluate the punctuality of the bus service in Queensland, Australia, by taking into account the stochasticity of both driving time and dwell time. A new index is proposed to evaluate the reliability of a bus line. This is followed by a case study to analyse the impact of onboard travel card top-up on travel time reliability. The impact analysis shows that bus line reliability would increase by around 15% if onboard top-up were completely replaced by the other six top-up alternatives. Removal of the onboard top-up facility would thus, in fact, increase the total social benefit.

2. Data description

2.1 Bus line 709

As shown in Figure 1, bus line 709 in Queensland connects Helensvale train station to Pacific Fair by way of Broad Beach, Surfers Paradise, Australia Fair and Griffith University and Harbour Town. The bus line links Gold Coast central business district to the train station (leading to Brisbane), which is one of the busiest bus lines in Gold Coast. Several minutes' delay results in passengers not being able to catch the subsequent train service and having to wait for another 30 min for the next train.

Figure 1. Route of bus line 709

2.2 Dwell time

Bus dwell time is defined as the time spent by a bus at a bus stop for passenger alighting and boarding, including the time for opening and closing of bus doors (Jaiswal *et al.*, 2010). As mentioned in Section 1, onboard top-up is offered by TransLink. Passengers could thus be categorised into four types in terms of their distinct boarding times for the bus

- travel card users (tapping in)
- travel card users (topping up onboard)
- passengers with disabilities
- single paper ticket users.

The boarding times for 150 boarding passengers were collected. The average boarding times per passenger and the proportion of users in the four categories are presented in Table 1.

2.3 Driving time

The driving time from one stop to another usually fluctuates with a given time. Without loss of generality, it was assumed that the driving times of various intervals follow a normal distribution (Table 2). The mean values are the given times from the timetable of bus line 709 and the variances are assumed to be a proportion of mean values.

The reliability of a bus service will also be affected by the number of boarding and alighting passengers. In this study,

	Number of users	Proportion of users: %	Average boarding time per passenger: s
Disabled passengers	3	2	45
Travel card users (tap in)	123	82	3
Travel card users (onboard top-up)	15	10	30
Single paper ticket users	9	6	15

Table 1. Boarding times and proportion of different types of users

Interval	Mean: s	Variance: s
1	211	21
2	433	43
3	97	10
4	211	21
5	314	31
6	154	15
7	542	54
8	325	32
9	319	32
10	376	38
11	103	10
12	205	21
13	205	21
14	91	9

Table 2. Driving time distribution

passengers' arrival and departure patterns are represented by Table 3. It should be noted that many passengers alight at the destination stop (Helensvale train station) and these passengers do not affect dwell time.

3. Reliability analysis

3.1 Punctuality analysis

If a bus arrives at a bus stop within 3 min of the scheduled time, it is considered punctual at this stop. The arrival time A_i at stop i can be calculated using

$$A_i = \sum_{j=1}^{i} T_j + \sum_{k=1}^{i-1} D_k \tag{2}$$

where T_j is the driving time at interval j (Table 2) and D_k is the dwell time at bus stop k, represented by

$$D_k = \max(n_k T_\mathrm{b} + b,\ m_k T_\mathrm{a} + b) \tag{3}$$

Bus stop	Number of passengers	
	Boarding	Alighting
1	4	2
2	6	4
3	2	2
4	6	2
5	4	8
6	3	3
7	14	8
8	6	2
9	8	4
10	10	4
11	2	2
12	6	2
13	2	4
14	2	3

Table 3. Number of boarding and alighting passengers for the Helensvale train station to Pacific Fair line

where n_k and m_k are the numbers of boarding and alighting passengers respectively, T_b and T_a represent the time spent on boarding and alighting per passenger and b is the time for doors opening and closing. The time for doors opening and closing is taken as 2 s from the survey. Variability in dwell time can also be a result of variations in the number of passengers. In order to evaluate the impact of onboard travel card top-up, in this study it is assumed that the number of passengers is known and remains unchanged. However, the boarding time per passenger is represented by random variables

$$T_\mathrm{b} = \begin{cases} 45\,\mathrm{s}, & p_1 = 0{\cdot}02 \\ 3\,\mathrm{s}, & p_2 = 0{\cdot}82 \\ 30\,\mathrm{s}, & p_3 = 0{\cdot}10 \\ 20\,\mathrm{s}, & p_4 = 0{\cdot}06 \end{cases} \tag{4}$$

where p_1, p_2, p_3 and p_4 refer to the proportions of different users as detailed in Table 1.

From Table 3, we can see that D_k is determined by the boarding times at all bus stops. Therefore, $\sum_{k=1}^{i-1} D_k$ are also discrete distributed random variables

$$\sum_{k=1}^{i-1} D_k = (i-1)b + \sum_{k=1}^{i-1} n_k T_{\mathrm{b}} \tag{5}$$

As T_j follows a normal distribution, $\sum_{j=1}^{i} T_j$ are also normally distributed random variables. The mean value and variance can be calculated as

$$\mu_i = \mu\left(\sum_{j=1}^{i} T_j\right) = \sum_{j=1}^{i} \mu(T_j) \tag{6}$$

$$\sigma_i^2 = \sigma^2\left(\sum_{j=1}^{i} T_j\right) = \sum_{j=1}^{i} \sigma^2(T_j) \tag{7}$$

Accordingly

$$\begin{aligned} A_i = (i-1)b &+ p_1 \sum_{k=1}^{i-1} (45\,\mathrm{s} \times n_k) \\ &+ N(\mu_i, \sigma_i^2) + p_2 \sum_{k=1}^{i-1} (3\,\mathrm{s} \times n_k) + N(\mu_i, \sigma_i^2) \\ &+ p_3 \sum_{k=1}^{i-1} (30\,\mathrm{s} \times n_k) + N(\mu_i, \sigma_i^2) \\ &+ p_4 \sum_{k=1}^{i-1} (15\,\mathrm{s} \times n_k) + N(\mu_i, \sigma_i^2) \end{aligned} \tag{8}$$

where $\sum_{k=1}^{i-1}(45\ \mathrm{s} \times n_k)$, $\sum_{k=1}^{i-1}(3\ \mathrm{s} \times n_k)$, $\sum_{k=1}^{i-1}(30\ \mathrm{s} \times n_k)$ and $\sum_{k=1}^{i-1}(15\ \mathrm{s} \times n_k)$ are deterministic values.

$$\begin{aligned} A_i = (i-1)b &+ p_1 N\left(\mu_i + \sum_{k=1}^{i-1} (45\,\mathrm{s} \times n_k),\ \sigma_i^2\right) \\ &+ p_2 N\left(\mu_i + \sum_{k=1}^{i-1} (3\,\mathrm{s} \times n_k),\ \sigma_i^2\right) \\ &+ p_3 N\left(\mu_i + \sum_{k=1}^{i-1} (30\,\mathrm{s} \times n_k),\ \sigma_i^2\right) \\ &+ p_4 N\left(\mu_i + \sum_{k=1}^{i-1} (15\,\mathrm{s} \times n_k),\ \sigma_i^2\right) \end{aligned} \tag{9}$$

Accordingly, A_i follows a Gaussian mixture distribution, which is a weighted sum of four component normally distributed random variables. The Gaussian mixture model and its derivatives have been widely used in transportation analysis (Jin *et al.*, 2011; Meng and Qu, 2012b; Qu and Meng, 2012). Its probability density function is

$$f(a_i) = \sum_{s=1}^{4} p_s f_s(x \mid \mu_s, \sigma_s^2) \tag{10}$$

where p_s is the weight and $f_s(x \mid \mu_s, \sigma_s^2)$ is the component density function with mean μ_s and variance σ_s^2.

If the bus arrives a stop within 3 min after the scheduled time, the bus is considered punctual at this stop. Therefore, the punctuality of the bus line at bus stop i could be calculated by

$$q = P(A_i \leqslant a_i + 3) \tag{11}$$

where a_i is the scheduled time in the timetable. The calculated punctualities at various bus stops are presented in Table 4.

3.2 Bus line reliability

As can be seen in Table 4, the punctualities at various stops are not the same. In this regard, a proper weighting system needs to be proposed in order to evaluate the reliability for a particular bus line. In this study, a higher weight is given for bus stops with more boarding and alighting passengers. Mathematically, this is represented by

$$r = \sum_{i=1}^{I} (N_{\mathrm{b},i} + N_{\mathrm{a},i}) q_i \tag{12}$$

where $N_{\mathrm{b},i}$ and $N_{\mathrm{a},i}$ are the number of boarding and alighting passengers at stop i respectively and q_i is the punctuality of the bus at stop i. According to Equation 12, the reliability of the bus line is 0·6533.

3.3 Impact analysis of travel card onboard top-up

As already mentioned, there are seven options for travel card top-up – onboard a bus, on line, by phone, at convenience stores and/or supermarkets, on vessels linking cities to recreational islands, at any train station and at some big bus stops. Onboard top-up causes significant delays and reduces the calculated punctuality and reliability, which will consequently discourage use of bus services. An impact analysis was carried out to assess the effect on calculated punctuality and reliability if TransLink were to cease provision for onboard top-up, leaving users with the option of topping up through the other six alternatives. The calculated punctualities at various stops are presented in Table 5 and Figure

Bus stop	Punctuality
1	0·994
2	0·969
3	0·952
4	0·869
5	0·802
6	0·771
7	0·599
8	0·571
9	0·531
10	0·484
11	0·461
12	0·446
13	0·429
14	0·425

Table 4. Calculated punctualities at various bus stops

2. According to Equation 12, bus line reliability without onboard top-up is 0·8052. With the withdrawal of onboard top-up, the overall improvement in terms of bus line reliability is 15·18%. As can be seen in Figure 2, there is no change in punctuality at bus stop 1 when changing the boarding options. This is because the accumulated delay caused by onboard top-up for the first several stops is still generally less than 3 min (see Equation 11). However, as the delay accumulates, the bus line will become more and more unpunctual for both cases (with and without onboard top-up).

3.4 Sensitivity analysis for driving time variability

The impact of driving time variability on bus line reliability was evaluated. The variance in driving time was assumed to be 5%, 10% and 15% of the mean driving time. Table 6 shows that bus line variability is mainly caused by the dwell time variability (5% against 25·18% for 5% variance in driving time, 10% versus 24·67% for the 10% scenario and 15% against 23·97% for the 15% scenario 15%). As shown in Table 6, the removal of the onboard top-up option would result in increases in bus line reliability of 22·21%, 15·19%, and 15·02% for the three scenarios.

4. Discussion, lessons learnt and conclusion

A model was developed to evaluate the calculated punctualities and reliability of bus services in Queensland, Australia by taking into account variability in dwell time and driving time. In view of their characteristics, discrete distributed and normally distributed random variables were used to represent dwell time and driving time respectively. Accordingly, the total travel time could be described by Gaussian mixture models. Based on the model, reliability indices were proposed to assess punctuality/reliability of bus stops and bus lines. An impact analysis was carried out to examine the effects of

Bus stop	Punctuality	
	With onboard top-up	Without onboard top-up
1	0·994	0·999
2	0·969	0·989
3	0·952	0·982
4	0·869	0·946
5	0·802	0·905
6	0·771	0·889
7	0·599	0·785
8	0·571	0·764
9	0·531	0·729
10	0·484	0·698
11	0·461	0·683
12	0·446	0·666
13	0·429	0·652
14	0·425	0·641

Table 5. Result of impact analysis

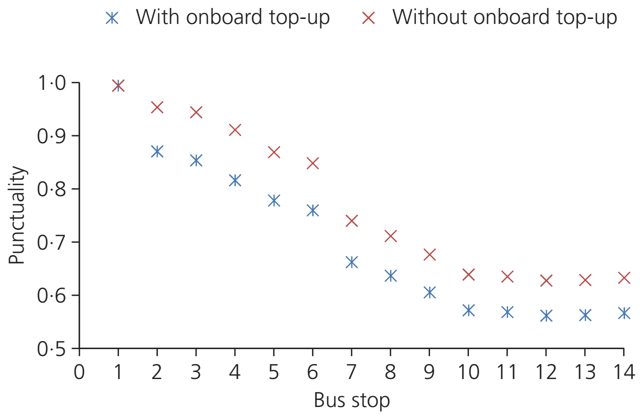

Figure 2. Punctualities at various bus stops

Variance in driving time: %	Bus line reliability	
	With onboard top-up	Without onboard top-up
5	0·6982	0·9203
10	0·6533	0·8052
15	0. 6108	0·7610

Table 6. Sensitivity analysis for driving time variability

passengers topping up their electronic tickets on board the bus.

According to sensitivity analysis, low bus line reliability is mainly caused by dwell time uncertainty, especially with regard to onboard card top-up, single paper ticket holders and passengers with disabilities. Boarding assistance for disabled passengers must be guaranteed to ensure equity and access to public transport services and it is desirable to offer single paper tickets for those who do not have a 'go card' (e.g. tourists). However, onboard top-up appears to disadvantage all passengers as it significantly reduces bus line punctuality and reliability. Six convenient alternatives for top-up are already provided to go card users and it is therefore suggested that, for overall total social benefit, onboard travel card top-up should not be offered by TransLink.

Acknowledgements

This research was supported by the Griffith NRG scheme and the National Science Foundation of China (grant 51208462). The corresponding author for this paper is Dr Sheng Jin.

REFERENCES

Chen X, Yu L, Zhang Y and Guo J (2009) Analyzing urban bus service reliability at the stop, route, and network levels. *Transportation Research Part A* **43(8)**: 722–734.

Dorbritz R, Luthi M, Weidmann UA and Nash A (2009) Effects of onboard ticket sales on public transport reliability. *Transportation Research Record* **2110**: 112–119.

Guenthner R and Hamat K (1988) Transit dwell time under complex fare structure. *Journal of Transportation Engineering ASCE* **114(3)**: 367–379.

Jaiswal S, Bunker J and Ferreira L (2010) Influence of platform walking on BRT station bus dwell time estimation: Australian analysis. *Journal of Transportation Engineering, ASCE* **136(12)**: 1173–1179.

Jin S, Qu X and Wang D (2011) Assessment of expressway traffic safety using Gaussian mixture model based on time to collision. *International Journal of Computational Intelligence Systems* **4(6)**: 1122–1130.

Jordan WC and Turnquist MA (1979) Zone scheduling of bus routes to improve service reliability. *Transportation Science* **13(3)**: 242–268.

Levinson H (1983) Transit travel time performance. *Transportation Research Record* **915**: 1–6.

Liu Z, Yan Y, Qu X and Zhang Y (2013) Bus stop-skipping scheme with random travel time. *Transportation Research Part C: Emerging Technologies* **35**: 46–56.

Mazloumi E, Currie G and Rose G (2009) Using GPS data to gain insight into public transport travel time reliability. *Journal of Transportation Engineering* **136(7)**: 623–631.

Mazloumi E, Rose G, Currie G and Sarvi M (2011a) An integrated framework to predict bus travel time and its variability using traffic flow data. *Journal of Intelligent Transportation Systems* **15(2)**: 75–90.

Mazloumi E, Moridpour S, Currie G and Rose G (2011b) Exploring the value of traffic flow data in bus travel time prediction. *Journal of Transportation Engineering* **138(4)**: 436–446.

Meng Q and Qu X (2012a) Uncertainty propagation in quantitative risk assessment modelling for fire in road tunnels. *IEEE Transactions on Systems, Man, and Cybernetics Part C: Applications and Reviews* **42(6)**: 1454–1464.

Meng Q and Qu X (2012b) Estimation of rear-end vehicle crash frequencies in urban road tunnels. *Accident Analysis and Prevention* **48**: 254–263.

Meng Q and Qu X (2013) Bus dwell time estimation at a bus bay: a probabilistic approach. *Transportation Research Part C: Emerging Technologies* **36**: 61–71.

Ng M, Szeto WY and Waller ST (2011) Distribution-free travel time reliability assessment with probability inequalities. *Transportation Research Part B: Methodological* **45(6)**: 852–866.

Orth H, Dorbritz R and Weidmann U (2011) Public transport capacity and quality – development of an LOS-based evaluation scheme. *Proceedings of 11th Swiss Transport Research Conference, Ascona, Switzerland*.

Orth H, Weidmann U and Dorbritz R (2012) Development of a public transport performance measurement system. Presented at the *91st Transportation Research Board Annual Meeting, Washington, DC, USA*.

Qu X and Meng Q (2012) The economic importance of the straits of Malacca and Singapore: an extreme-scenario analysis. *Transportation Research Part E* **48(1)**: 258–265.

Rojo M, Gonzalo-Orden H, Dell'Olio L and Ibeas A (2011) Modeling gender perception of quality in interurban bus services. *Proceedings of the Institution of Civil Engineers – Transport* **164(1)**: 43–53, http://dx.doi.org/10.1680/tran.9.00031.

Sorratini JA, Liu R and Sinha S (2008) Assessing bus transport reliability using micro-simulation. *Transportation Planning and Technology* **31(2)**: 303–324.

Szeto WY and Wu Y (2011) A simultaneous bus route design and frequency setting problem for Tin Shui Wai, Hong Kong. *European Journal of Operational Research* **209(2)**: 141–155.

Taylor M (1982) Travel time variability – the case of two public models. *Transportation Science* **16(4)**: 507–521.

Tirachini A (2013) Bus dwell time: the effect of different fare collection systems, bus floor level and age of passengers. *Transportmetrica A: Transport Science* **9(1)**: 28–49.

TransLink (TransLink Transit Authority (Queensland)) (2010) *Annual Report 2010–2011*. TransLink, Brisbane, Australia.

Vu NH and Khan AM (2010) Bus running time prediction using a statistical pattern recognition technique. *Transportation Planning and Technology* **33(7)**: 625–642.

Xuan Y, Argote J and Daganzo CF (2011) Dynamic bus holding strategies for schedule reliability: optimal linear control and performance analysis. *Transportation Research Part B* **45(10)**: 1831–1845.

Yan Y, Meng Q, Wang S and Guo X (2012) Robust optimization model of schedule design for a fixed bus route. *Transportation Research Part C* **25**: 113–121.

Yan Y, Liu Z, Meng Q and Yu J (2013) Robust network design for bus transit system with stochastic travel time. *Journal of Transportation Engineering* **139(6)**: 625–634.

Yu B, Yang ZZ and Wang J (2010) Bus travel-time prediction based on bus speed. *Proceedings of the Institution of Civil Engineers – Transport* **163(1)**: 3–7, http://dx.doi.org/10.1680/tran.2010.163.1.3.
