Analytical and Empirical Investigations of the Effect of Bus Drivers' Reactions to Schedules on Transit Operations Reliability

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Abstract

This paper presents an investigation and quantification of the effect of bus drivers' reactions to schedules on transit operations reliability following both analytical and empirical treatments. Understanding drivers' behavior would be useful for developing simulation tools, designing bus schedules, evaluating transit operations reliability, and developing real-time control strategies. Two hypotheses are investigated: (i) drivers may lengthen (shorten) the dwell times at stops (including time-points and other stops) if buses arrive early (late), and (ii) drivers may slow down (speed up) along the roadways between consecutive stops if buses are ahead of (behind) the schedule with the intent of maintaining the schedule.

The investigation begins with the development of an analytical model followed by an empirical study. In the developed analytical model, the effect of drivers' reactions to the schedule at bus stops is represented by the covariance between the arrival time deviation from the schedule and dwell time with respect to the same stop. The ability of drivers to lengthen (shorten) the dwell times when buses arrive early (late) is reflected in a negative magnitude of this covariance. Similarly, the effect of drivers' reactions along the roadways between consecutive stops is represented by the covariance between the departure time deviation from a schedule with respect to a stop and the bus travel time between that stop and the next downstream stop. The ability of drivers to adjust speeds according to the schedule is reflected in a negative magnitude of this covariance. However, it is also recognized that drivers' reactions to the schedule may be constrained by factors such as heavy passenger demand at stops, traffic congestion, limited bus parking space at stops, and roadway geometry constraints.

The effect of drivers' reactions to the schedule is investigated and quantified in an empirical study using Automatic Vehicle Location (AVL) data. The empirical study focuses on the Campus Loop South (CLS) route serving The Ohio State University campus in the morning peak period (7am-9am) and in the late morning period (9am-11am) over 50 days where 238 and 260 bus trips are available for the two periods, respectively. This route is 8.29 kilometers in length and serves 19 bus stops. The hypotheses aforementioned are confirmed by the empirical data in both periods. It is found that drivers are able to adjust the dwell times based on the arrival time deviation from the schedule at most of the time-points plus some additional stops, and also adjust the bus speeds based on the current bus location and it's standing with respect to the schedule. It is also found that drivers have more freedom to adjust the bus speeds in the late morning period presumably due to the lower vehicular and pedestrian traffic. Finally, it is revealed that drivers' reactions to the schedule are helpful in improving transit reliability. More specifically, on average, 43% of the improvement is due to drivers' reactions to the schedule at time points (by holding), 17% is due to drivers' reactions to the schedule at other stops (by lengthening or shortening the dwell time), and another 40% is due to driver's reactions to the schedule by adjusting speeds along roadways between consecutive stops.

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1. Introduction

Unreliable transit service results in increased passenger waiting times and route transfer delays. Waiting time and transfer delays are important factors affecting the mode choice of travelers (Prioni & Hensher, 2000). For transit providers, unreliable service also leads to additional cost. For example, if bus bunching occurs frequently, transit providers have to provide additional vehicles and operators to restore reliable service. The cost caused by unreliable service was conservatively estimated to contribute to 3-5% of operating and capital costs (Hickman, 2001).

When service becomes too unreliable, transit operators will adopt certain control actions to restore reliability. Holding a bus at a stop is one of the most common control methods because it is relatively easy to implement and is less frustrating to passengers than many of the other methods (Eberlein, Nigel, & Bernstein, 2001)). Holding could be defined as the process of intentionally delaying the departure of a bus from a bus stop for some additional time after passengers alight and board. Holding strategies include headway-based and schedule-based holding. A headway-based holding strategy holds the bus until the scheduled headway if the headway between the current bus and the previous bus is less than the scheduled headway. Otherwise, the bus departs from the stop after passengers alight and board. A schedule-based holding strategy holds the bus until the scheduled departure time if the bus arrives earlier than the scheduled time. Otherwise, the bus departs from the stop after passengers alight and board.

Transit reliability and the effect of holding on transit reliability have been widely studied. In the literature, there are three general approaches: analytical models (Osuna & Newwell, 1972; Turnquist, 1978; Adedisi, 1984; Hickman, 2001), simulation models (Senenirante, 1990; Adamski & Turnau, 1998), and empirical studies (Strathman et al., 1999; Bertini & EI-Geneidy, 2004). For example, Adedisi (1984) developed an analytical model to analyze the variance of bus headways using basic probability concepts. The results indicated that the bus loading and traffic conditions along the route are the major factors affecting the headway variability. Senenirante (1990) studied the effect of holding on the variation of headways using simulation. It was found that holding has a positive impact on reducing the variation of headways. Strathman, et al. (1999, 2003) presented a baseline analysis of transit reliability using empirical Automate Vehicle Location (AVL) data. It was found that control actions, such as holding, swapping and short-turning, are helpful in reducing the variance of headways.

The process of holding could be viewed as the drivers' reaction to the schedule at time-points. Time-points are pre-determined locations along the route (usually stops) where buses have scheduled times to arrive or depart at and, naturally, they are the locations where holding takes place. In addition to these adjustments at time-points, it should be recognized that drivers may also adjust the dwell times at other stops and regulate the roadway speed while traveling between stops based on the current bus location, the schedule, and traffic conditions. For example, at bus stops not designated as time-points, drivers may dwell slightly longer (shorter) when they are running ahead of (behind) the schedule. Similarly, in between stops, bus drivers may slow down (speed up) when they realize that they are ahead of (behind) the schedule. Simulation and empirical studies have shown that holding at time-points decreases the variation of headways from the holding time-point to the next downstream stop (Senenirante, 1990; Strathman, et al., 1999). However, the effect of drivers' reactions to the schedule as reflected in their behavior at other stops and while traveling between stops has drawn little attention in the literature.

Mishalani et al. (2008) modelled the upcoming bus running time as a function of the most recent schedule deviation at the terminus. It was found that, while driver behavior is heterogenious, in general, drivers of late buses atempt to shorten the upcoming running time to maintain the schedule, and vice versa. The investigation was carried out at the resolution of the running time. While this study is also concerned with driver behavior in reaction to the schedule, the focus is on inverstigating the behavior at the resolution of individual bus stops and stop-to-stop roadway segments and the subsequent effect the identified driver behavior has on transit reliability.

The investigation is first conducted analytically and then empirically. An analytical model is developed to investigate the progression of transit reliability along a bus route. This model explains how the reactions of drivers to the schedule in conjunction with other exogenous factors affect the progression of transit reliability. Following the development of the analytical model, an empirical study is carried out using AVL data on an actual bus route to quantify the effect of drivers' reactions to the schedule on reliability.

This paper is organized as follows. The notation and some basic relations used as building blocks are presented in section 2. Measures of transit reliability are discussed in section 3. The analytical model is introduced in section 4, and the empirical study is presented in section 5. Concluding remarks are made and possible future research directions are discussed in section 6.

2. Notation and Basic Relations

Suppose the arrival time of the j^{th} bus trip at stop *k* is $t_{a,k}^{j}$, the dwell time at stop *k* is dt_k^j, the departure time at stop *k* is $t_{d,k}^{j}$, and the travel time from bus stop *k* to the next downstream stop *k* + 1 is tt_k^j. Similarly, suppose the scheduled arrival time of the j^{th} bus trip at stop *k* is $t_{a,k}^{j,sch}$, the scheduled dwell time at stop *k* is $dt_k^{j,sch}$, the scheduled departure time at stop *k* is $t_{d,k}^{j,sch}$, and the scheduled travel time from stop *k* to the next downstream bus stop *k* + 1 is $tt_k^{j,sch}$.

The arrival time deviation AD_k^j, that is the difference between the actual arrival time $t_{a,k}^{j}$ and the scheduled arrival time $t_{a,k}^{j,sch}$, is given by:

$$AD_k^j = t_{a,k}^{j} - t_{a,k}^{j,sch} \tag{1}$$

The departure time deviation DD_k^j, that is the difference between the actual departure time $t_{d,k}^{j}$ and the scheduled departure time $t_{d,k}^{j,sch}$, is given by:

$$DD_k^j = t_{d,k}^{j} - t_{d,k}^{j,sch} \tag{2}$$

Mathematically, the departure time at stop *k* can be written as the sum of the arrival time and dwell time at stop *k*. Similarly, the scheduled departure time at stop *k* can be written as the sum of the scheduled arrival time and scheduled dwell time at stop *k*. Therefore, the departure time deviation at stop *k* can also be written as:

$$\begin{aligned} DD_k^j &= t_{d,k}^{j} - t_{d,k}^{j,sch} = (t_{a,k}^{j} + dt_k^j) - (t_{a,k}^{j,sch} + dt_k^{j,sch}) \\ &= (t_{a,k}^{j} - t_{a,k}^{j,sch}) + (dt_k^j - dt_k^{j,sch}) = AD_k^j + (dt_k^j - dt_k^{j,sch}) \end{aligned} \tag{3}$$

Mathematically, the arrival time at stop *k* can be written as the sum of the departure time at upstream stop *k* – 1 and the travel time from stop *k* – 1 to downstream stop *k*. Similarly, the scheduled arrival time at stop *k* can be written as the sum of the scheduled departure time at upstream stop *k* – 1 and the scheduled travel time from stop *k* – 1 to downstream stop *k*. Therefore, the arrival time deviation at stop *k* can also be written as:

$$\begin{aligned} AD_k^j &= t_{a,k}^j - t_{a,k}^{j,sch} = (t_{d,k-1}^j + tt_{k-1}^j) - (t_{d,k-1}^{j,sch} + tt_{k-1}^{j,sch}) \\ &= (t_{d,k-1}^j - t_{d,k-1}^{j,sch}) + (tt_{k-1}^j - tt_{k-1}^{j,sch}) = DD_{k-1}^j + (tt_{k-1}^j - tt_{k-1}^{j,sch}) \end{aligned} \tag{4}$$

The headway between the j^{th} bus trip and $(j+1)^{th}$ bus trip at stop *k* is the difference between the departure times of these two consecutive bus trips at stop *k* as given by:

$$H_k^j = t_{d,k}^{j+1} - t_{d,k}^j \tag{5}$$

Similarly, the scheduled headway between the j^{th} bus trip and $(j+1)^{th}$ bus trip at stop *k* is the difference between the scheduled departure times of these two consecutive bus trips at stop *k* as given by:

$$H_k^{j,sch} = t_{d,k}^{j+1,sch} - t_{d,k}^{j,sch} \tag{6}$$

All the above relations are used as building blocks in the subsequent model development.

3. Measures of Transit Reliability

In the case of long headways where passengers are likely to consult the schedule in planning their arrival to a stop, reducing the variation of deviations from the schedule results in an improvement of transit service. Consider the extreme case where a bus is consistently some constant period behind the schedule, the passengers who use the bus route often will eventually perceive this deterministic deviation from the schedule and plan their arrivals at the bus stop according to their “perceived” schedule times. Under this situation, transit operators can also revise the timetable to correct for this bias in the operation. That is, even though there is a non-zero schedule deviation, given that the variation in schedule deviation is zero, the service is completely correctable by either the passengers adjusting their arrival behavior or by the operators adjusting the schedule in a manner that totally corrects for the deterministic bias in the service. On the other hand, if the variation of schedule deviations is large, passengers need to arrive at the bus stop early enough to avoid missing the bus with a high probability. In such cases their wait time will also be highly varied. The variation of schedule deviations can be assessed using the standard deviation or variance of departure time deviations.

In the case of short headways where passengers are likely to arrive at bus stops in a totally random manner, better headway adherence results in improved transit service. Headway adherence is defined as the regularity of headways and can be assessed using the standard deviation or variance of headway. The average waiting time of passengers is minimized when the variation of headways is zero (Welding, 1957).

While the variance in departure time deviation and variance of headway are thought of as measures of transit reliability of relevance under different passenger arrival behaviors, the two measures are related to one another. Based on Equations 2, 5, and 6 and under the assumption that the scheduled headway is constant, the variance of headway at stop k $\mathrm{var}(H_k)$ is given by (the superscript j representing bus trip is omitted in what follows when the notation is not specific to a certain bus trip):

$$\begin{aligned}\mathrm{var}(H_k) &= \mathrm{var}(t_{d,k}^{j+1} - t_{d,k}^{j}) = \mathrm{var}((t_{d,k}^{j+1} - t_{d,k}^{j+1,sch}) - (t_{d,k}^{j} - t_{d,k}^{j,sch}) + H_k^{j,sch}) \\ &= \mathrm{var}(DD_k^{j+1} - DD_k^{j} + H_k^{j,sch}) = 2\times\mathrm{var}(DD_k) + 2\times\mathrm{cov}(DD_k^{j+1}, DD_k^{j})\end{aligned} \tag{7}$$

The covariance of the departure time deviations between consecutive bus trips at the same stop $\mathrm{cov}(DD_k^{j+1}, DD_k^j)$ may be positive or negative depending on two different situations. When vehicular traffic is congested, buses may be running consistently late. Under this situation, the covariance term would be positive. On the other hand, when bus bunching occurs frequently in the period of interest (a common phenomenon under extreme high bus transit demand conditions), the late lead bus is likely to be followed by an early bus. Under this situation, the covariance term would be negative.

However, when vehicular traffic is not congested and when the bus transit demand is not particularly high, the deviations of the departure times from the schedule for two consecutive buses are mainly due to the randomness of travel times and dwell times. That is, the departure time of the lead bus would not change the likelihood of whether the following bus would depart early or late. In this case, it would be reasonable to assume that the departure time deviations of two consecutive buses are independent. Consequently, Equation 7 would reduces to:

$$\mathrm{var}(H_k) = 2 \times \mathrm{var}(DD_k) \tag{8}$$

Thus, when independence holds whereby the variance of headway, $\mathrm{var}(H_k)$, is directly proportional to the variance of departure deviation, $\mathrm{var}(DD_k)$, as reflected in Equation (8) or when the absolute magnitude of the covariance term in Equation (7) is relatively small, either the variance of headway or the variance of departure time deviation can be used to assess transit reliability irrespective of whether the focus of assessing reliability is related to the long or short headway cases. When the absolute magnitude of the covariance term in Equation (7) is relatively large, the relationship between the variance of headway and variance of departure time deviation is more complex and is reserved for further investigation as part of future research.

In the cases where the variance of headway and the variance of departure time deviation can substitute for one another in assessing transit reliability, the advantage of one over the other lies in the nature of the data available to the agency. While the installation of bus AVL systems is becoming more widespread, the reliability of such systems is not always high where either some buses may have malfunctioning equipment or the AVL data may be unavailable on certain portions of a route (a common problem with Geographic Positioning System based AVL technologies in the vicinity of tall structures). Since headway observations require a pair of consecutive departure times, under limited AVL reliability conditions, estimating the variance of departure time deviation would be more suitable because much more observations can be used to estimate it than estimating the variance of headway, and doing so avoids the need to confirm that a pair of departure time observations are indeed consecutive. Therefore, the remainder of this paper focuses on the variance of departure time deviation, $\operatorname{var}(DD_k)$.

4. Analytical Model Development

The relationship between the departure and arrival time deviations at stop *k* is described in Equation 3. Based on this relationship, the variance of departure time deviation at stop *k* can be written as:

$$\operatorname{var}(DD_k) = \operatorname{var}(AD_k) + \operatorname{var}(dt_k - dt_k^{sch}) + 2 \times \operatorname{cov}(AD_k, dt_k - dt_k^{sch}) \tag{9}$$

The relationship between the departure time deviation at stop $k-1$ and the arrival time deviation at stop *k* is described in Equation 4. Based on this relationship, the variance of arrival time deviation at stop *k* can be written as:

$$\operatorname{var}(AD_k) = \operatorname{var}(DD_{k-1}) + \operatorname{var}(tt_{k-1} - tt_{k-1}^{sch}) + 2 \times \operatorname{cov}(DD_{k-1}, tt_{k-1} - tt_{k-1}^{sch}) \tag{10}$$

It is reasonable to assume that for a homogenous period the scheduled dwell times at a given bus stop are constant, and the scheduled stop-to-stop travel times between two adjacent stops are constant. Under these assumptions, substituting Equation (10) into Equation (9), the relationship between the variance of departure time deviations at stop $k-1$ and stop k can be written as:

$$\operatorname{var}(DD_k) - \operatorname{var}(DD_{k-1}) = \operatorname{var}(tt_{k-1}) + \operatorname{var}(dt_k) + 2\times\operatorname{cov}(AD_k, dt_k) + 2\times\operatorname{cov}(DD_{k-1}, tt_{k-1}) \qquad (11)$$

Equation (11) describes the progression of reliability (in the form of the variance of departure time deviation) from one stop to the next downstream stop and includes two important factors affecting this process: travel time between the two stops and dwell time at the downstream stop.

Obviously, as captured by the first two variance terms on the right-hand-side of Equation (11), the variations of the travel time and the dwell time at the downstream stop increase the variance of departure time deviation at the downstream stop with respect to the upstream stop. The effect of bus drivers' reactions to the schedule on reducing the magnification of unreliability as it progresses from one stop to the next downstream stop are captured by the third and fourth (covariance) terms in Equation (11) when these terms take negative values. The covariance of arrival time deviation and dwell time at downstream stop k, $\operatorname{cov}(AD_k, dt_k)$, would be negative if drivers lengthen (shorten) the dwell time when buses arrive early (late) at downstream stop k. Similarly, the covariance of departure time deviation at upstream stop $k-1$ and travel time from that stop to downstream stop k, $\operatorname{cov}(DD_{k-1}, tt_{k-1})$, would be negative if drivers slow down (speed up) when buses are ahead of (behind) the schedule at the upstream stop $k-1$.

Naturally though, drivers' reactions may be constrained by exogenous factors outside their control such as heavy passenger demand at stops, vehicular traffic congestion, limited bus stopping space at stops, and roadway geometry constraints. For example, even when drivers intend to shorten the dwell time to the least possible when the bus is running behind schedule (i.e., positive arrival time deviation at the downstream stop), it is not uncommon for the demand in such cases to be relatively higher resulting in more passenger boarding or alighting activity, which constrain the drivers' ability to limit the duration of the dwell time. Under such situations the dwell time could in fact be relatively higher and, therefore, the corresponding covariance between the arrival time deviation and dwell time at the downstream stop would be positive. Similarly, even when drivers intend to speed up between stops when buses depart late (i.e., positive departure time deviation at the upstream stop), it is not uncommon for traffic congestion in such cases to be relatively higher, which constrains the drivers' ability to speed up to reduce the travel time between strops. Under such situations the travel time could in fact be relatively higher and, therefore, the corresponding covariance between the departure time deviation at the upstream stop and travel between that stop and the downstream stop would be positive.

In summary, the variance of departure time deviations increases along the route if drivers do not adjust dwell times and travel times between stops according to the schedule. And, drivers' reactions to the schedule could be helpful in reducing the variance of departure time deviations going from one stop to the next downstream stop. At stops, drivers could reduce the change in the variation of departure time deviations from stop to stop through lengthening or shortening dwell times according to the bus' arrival time deviation from the schedule. Along the roadways between stops, drivers could speed up or slow down intentionally according to the departure time deviation to reduce the change in the variation of departure time deviations from stop to stop. However, it should be recognized that drivers' reactions to the schedule may be constrained by certain exogenous conditions at bus stops and along the roadways between stops as discussed in detail above. In the following empirical study, AVL data are used to assess bus transit reliability and quantify the effect of drivers' reactions to the schedule on bus transit reliability.

5. Empirical Study

5.1. Data

The AVL data used in this application were collected through The Ohio State University's first generation Campus Transit Lab (CTL), which consists of the Campus Area Bus Service (CABS), a transit service owned and run by The Ohio State University (OSU) serving approximately four million passengers annually on and in the vicinity of the OSU campus, and includes an GPS-based AVL monitoring system (BLIS 2006). The AVL signals in that first generation implementation of CTL were transmitted every 100 meters or 3 minutes to a central server, depending on which occurs first. The signals are stored in a file for each day, which is archived on the central server.

Bus arrival times at a bus stop are estimated by extrapolating the most recent AVL signal before that bus stop toward that bus stop. Bus departure times at a bus stop are estimated by extrapolating the first AVL signal after that bus stop backward to that bus stop. Extrapolation of the arrival and departure times may produce negative dwell times. These extrapolated arrival and departure times are discarded for the purpose of this analysis.

The CABS transit network consists of several routes. This study focuses on the Campus Loop South (CLS) route in the morning peak period (7am-9am) and the late morning period (9am-11am) for Spring quarter (April-June) 2004 (50 days) where 238 and 260 bus trips are available for the two periods, respectively. The CLS route is 8.29 kilometers in length and served 19 bus stops at that time. There are four bus stops that serve as time-points along the route: stops

3, 4, 8, and 15. While drivers are expected to observe the scheduled departure times at these times points when the bus arrives earlier than scheduled, based on their experience, they also have a sense of whether they are running late or early based on the arrival times at the other stops and, consequently, may also react to the early or late status of the bus at those stops as well. Therefore, scheduled times at these non-time-point stops are calculated based on the scheduled times at the time-points and the sample mean travel times between stops. These calculated scheduled times are used as proxies for the times bus drivers may anticipate when running on schedule. Detailed information about the bus route structure and schedule can be found in Ji (2006).

Finally, calculating the arrival and departure time deviations involves matching the AVL bus trajectories to the schedule. An assignment-based method (Ji, 2006; Ji et al., 2009) is adopted to achieve this matching. The adopted method minimizes a defined match error and guarantees that one AVL bus trajectory is matched to only one scheduled trip and one scheduled trip is matched to only one AVL bus trajectory.

5.2. Empirical results and interpretations

Given that departure time deviation is the central variable behind the progression of transit reliability from one stop to the next downstream stop as described by Equation (11), this variable is first analyzed directly as it varies across the route. Following that, the variance or standard deviation of departure time deviation is examined setting the stage to investigate the various terms that influence its progression from one stop to the next downstream stop. Finally, the contributions of the various possible reactions drivers' could have to the schedule in attempts to maintain reliable service are quantified.

Figure 1 presents box plots of departure time deviations along the route for the two periods. The asterisk symbol represents the mean values. In addition, a notched-box and whisker plot are shown for each bus stop. The notched-box indicates the lower, median, and upper quartile values. The whiskers are lines extending from each end of the notched-box to show the extent of the distribution of departure time deviation. The length of the whiskers is 1.5 times the inter-quartile range. Data with values beyond the ends of the whiskers are considered to be outliers and are indicated by the plus symbol.

In Figure 1, positive departure time deviations indicate buses departing late, and negative departure time deviations indicate buses departing early. Absolute departure time deviations less than 1 minute could be regarded as “on time”. Departure time deviations in both periods show similar patterns. Namely, most buses depart around the scheduled departure times at time-points 3 and 4 where the average deviations are almost zero, then downstream from there buses start to depart later and later until time-point 15, after which the departure deviations diminish reflecting a catching up trend towards the schedule with average deviations converging back to almost zero at stops 18 and 19. And, while the patterns are similar between the two periods, the positive deviations from stop 4 onward appear to be larger during the morning peak period.

Figure 2 presents the standard deviations of departure time deviation along the route in both the morning peak and late morning periods. Both plots appear to have similar patterns. The standard deviation decreases from stop 1 to stops 4 or 5, and then in general increases going downstream towards stop 19. It appears that time-points 3 and 4 (among all four time-points) are the main holding stops that reduce the variation of departure time deviation. And, while the patterns are similar for the two time periods, the standard deviations in the late morning period are lower than those of the morning peak period, and the rate of increase in the standard deviation from stop 4 onward is flatter in the late morning period.

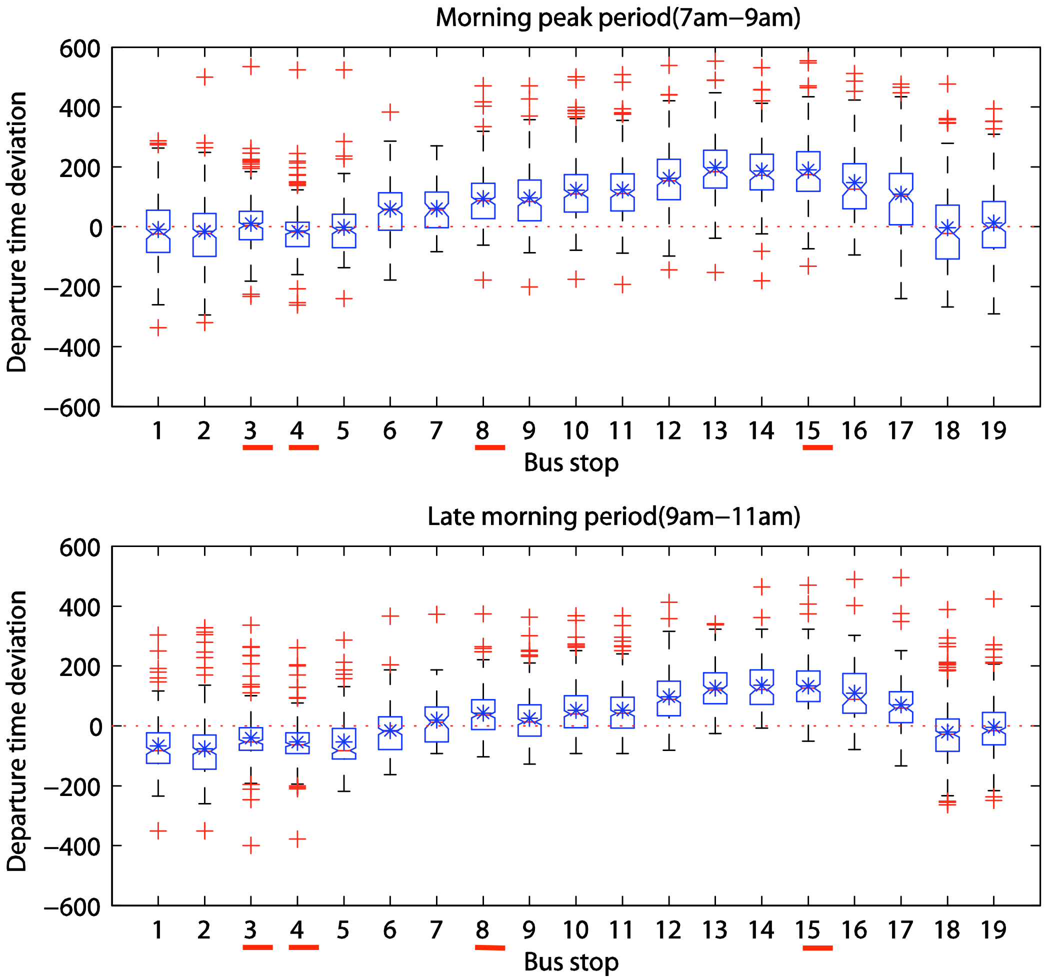


Figure 1: Box plot of departure time deviations along route (unit: second)

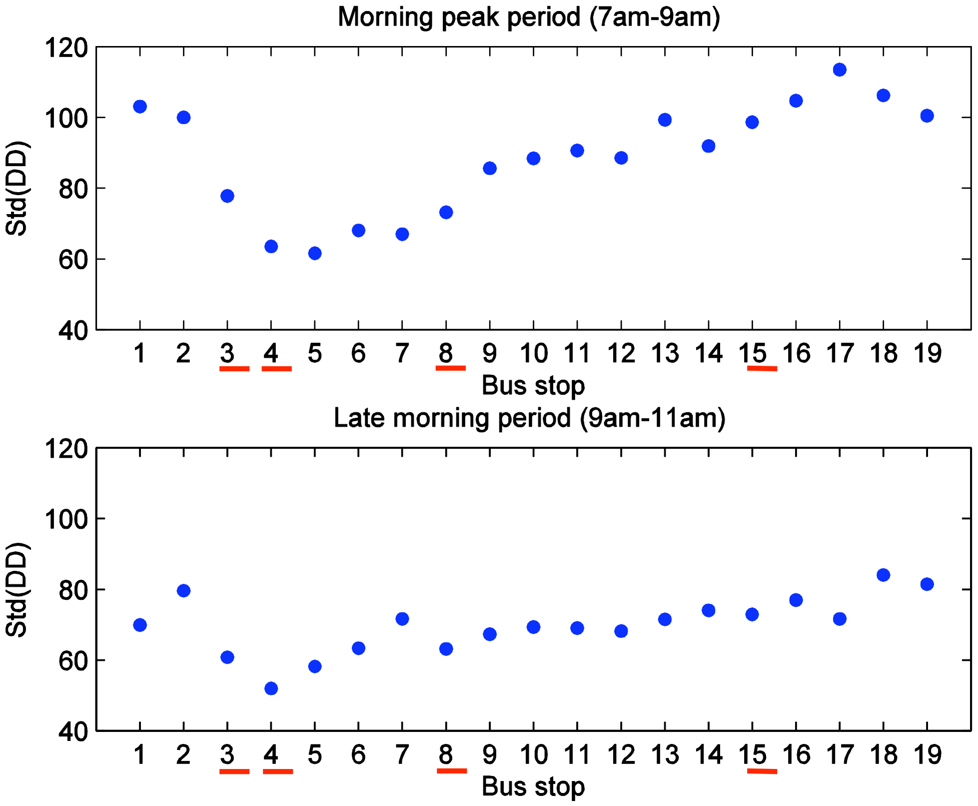


Figure 2 Standard deviation of departure time deviation along route (unit: second)

The results shown in Figures 1 and 2 indicate that time-points 3 and 4 are dominant in improving the reliability of the operation, time-point 15 has some impact on reducing the positive deviations from the schedule, and in the late morning period there are more opportunities to avoid degradation in reliability in comparison to the morning peak period. These findings are investigated in more detail subsequently by examining the terms that contribute to the progression of the variance of departure time deviation from stop to stop as described in Equation (11).

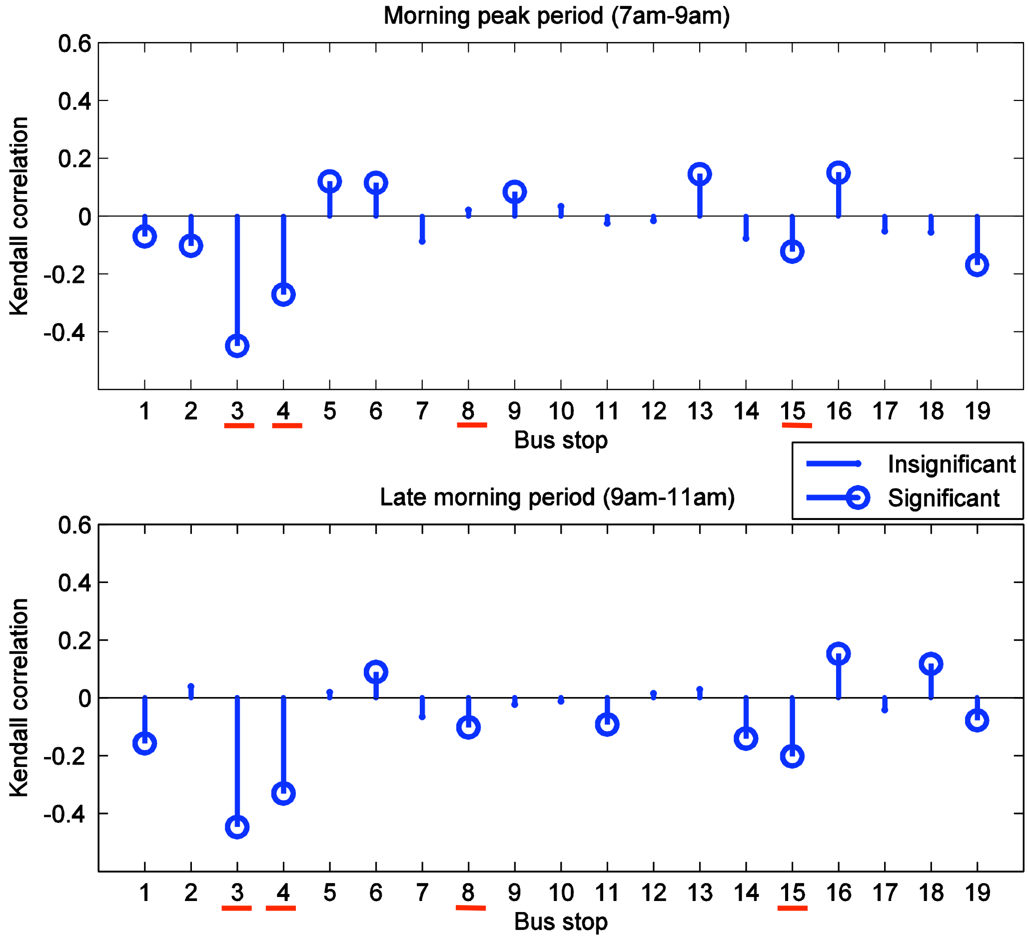
To assess whether drivers are able to react to the schedule or whether the exogenous factors dominate as discussed in section 4, the two covariance terms in Equation (11) are examined by estimating a measure of correlation. In this study, Kendall's tau test based on the Kendall correlation coefficient is adopted. Kendall's tau test is a distribution-free test for independence between two random variables (Hollander & Wolfe, 1999). The null hypothesis is that the pairs of random variables or interest (i.e., the arrival time deviation and dwell time at a bus stop, and the departure time deviation at a stop and the travel time from that stop to the next downstream stop) are independent, and the alternative hypothesis is that the two variables are negatively or positively correlated.

Kendall's tau test and correlation coefficient are used instead of the *t*-test and Pearson correlation coefficient in this application for two reasons. Firstly, the *t*-test is based on the assumption that the variables in question are Normally distributed. These assumptions were in general found not to hold empirically. Therefore, the non-parametric nature of Kendall's tau test makes it more appropriate to use in this case. Secondly, the *t*-test and Pearson correlation coefficient only capture the linear relationship between two variables while Kendall's tau test and correlation coefficient are not restricted to capturing linear relationships and there is no reason to believe that a linear restriction applies to the relationships between the variables of interest.

Regarding the two covariance terms in Equation (11), the one between arrival time deviation and dwell time is investigated first. Figure 3 shows the Kendall correlation coefficent of these variables for the two periods. A significance level of 0.1 is adopted in assessing whether the correlation coefficient is significantly negative or positive. Significant cases are indicated by a circle in Figure 3. As discussed in section 4, a significantly negative correlation coefficient means that drivers adjust the dwell times according to the arrival time deviations. Such cases can be seen at time-points 3, 4 and 15 in both periods, while at time-point 8 the test does not reject the null hypothesis that the correlation is zero in the morning peak period whereas the correlation is significantly negative in the late morning period. At time-points 3 and 4 a large proportion of buses depart by the scheduled departure time (see Figure 1). Earlier buses (negative arrival time deviations) dwell longer, which results in the negative correlation between arrival time deviation and dwell time. At time point 15, although most buses arrive late given their late departure times (see Figure 1), drivers tend to dwell for shorter periods when buses arrive later, which also results in the observed negative correlation between arrival time deviation and dwell time. It is not clear why the effect of holding at time-point 8 in the morning peak period is not detected. Explanations will be explored as part of future research.

Significantly negative correlation coefficients are also observed at bus stops 1, 2 and 19 in the morning peak period, and at stops 1, 11, 13 and 19 in the late morning period. At these bus stops, drivers also react to the schedule in attempting to improve the reliability of service by lengthening (shortening) dwell times when buses are early (late). Based on a priori knowledge of the operation of the CLS route, the conditions are suitable for such reactions. For example, in the morning the boarding and alighting demand at stop 19 is usually low. Therefore, drivers have more opportunity to adjust dwell times based on bus arrival time deviations.

As discussed in section 4, significantly positive correlation coefficients in Figure 3 indicate that late buses incur longer dwell times when arriving late most likely due to the relatively larger number of passenger boarding and alighting, a situation sometimes associated with operations running behind schedule. Such correlation coefficients are observed at stops 5, 6, 9, 13, and 16 in the morning peak period and at stops 6, 16, and 18 in the late morning period. This result agrees with a priori expectation regarding the demand patterns on the route. For example, the number of passengers boarding at stop 6 and the number of passengers alighting at stop 16 are relatively large in both morning periods. Consequently, late buses tend to have more passengers boarding at bus stop 6 and alighting at bus stop 16 resulting in longer dwell times at these two stops. Therefore, drivers have limited opportunities to reduce the dwell times at this and other high demand stops when running late.


Morning peak period (7am-9am)

Late morning period (9am-11am)

Figure 3: Correlation of arrival time deviation and dwell time

As for the covariance terms in Equation (11) between the departure time deviation at a given stop and the travel time from that stop to the next downstream stop, the corresponding Kendall correlation coefficients are shown in Figure 4. Significantly negative values are observed for 7 out of the 19 stop-to-stop roadway segment pairs in the morning peak period and in 12 out of 19 pairs in the late morning period. That is, over these roadway segments, drivers adjust the speed based on the bus departure time deviations from the schedule at the upstream stop. The difference in the results between the two periods is consistent with a priori expectations. Specifically, more stop-to-stop segments in the main campus area (stops 6 through 18) have significantly negative correlations in the late morning period than in the morning peak period because there is high vehicle and pedestrian traffic in the main campus area in the morning peak period making it harder for drivers to adjust speeds to maintain the schedule on those segments. Conversely, in the late morning period, there is less vehicle and pedestrian traffic in the main campus area allowing drivers to adjust bus speeds accordingly to maintain the schedule.

Significantly positive correlations are observed for only 2 out of the 19 stop-to-stop roadway segments in the morning peak period and none in the late morning period. The significantly positive correlations between stops 13 and 14 and between stops 14 and 15 in the morning peak period are likely to be due to heavy vehicle and pedestrian traffic resulting in a simultaneous increase in both departure time deviation from the schedule at the upstream stops and travel times from upstream to downstream stops.

Recall, Equation (11) is the analytical relationship describing the change in the variance of departure time deviations from one stop to the next downstream stop. This change consists of four terms: the variance of travel time between the stops, the variance of dwell time at the downstream stop, the covariance between arrival time deviation and dwell time at the downstream stop, and the covariance between departure time deviation at the upstream stop and the travel time between the two stops. Note that the first two terms are always positive and, therefore, contribute to increasing the variance in departure time deviation (i.e., increasing the unreliability) going from one stop to the next downstream stop. The third and fourth terms could either add to this increase in absolute terms if they taken positive values, which result from the cases where the exogenous effects of vehicular congestion and high transit demand are dominant, or counter the increase if they take negative values, which result from cases where drivers are able to react to the schedule in a manner that reduces the variance in schedule deviation going from one stop to the next downstream stop (i.e., either increasing the reliability or at least diminishing the unreliability). Also note that the second and third terms relate to the bus stops while the first and fourth terms relate to the roadway segments between consecutive stops.

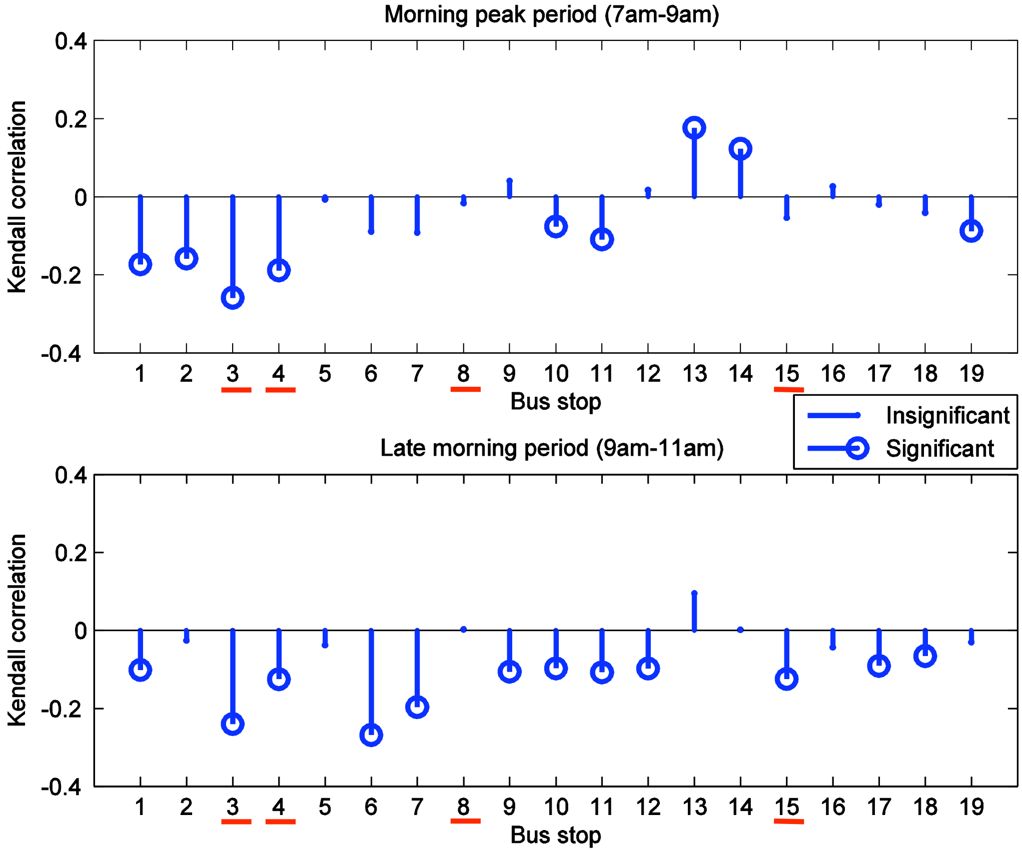


Figure 4: Correlation of departure time deviation and travel time

Therefore, to quantify the contributions to the change in the variance in departure time deviation going from a stop to the next downstream stop for all stops and for all roadway segments between consecutive stops, the positive and negative contributions are plotted separately for each of the two periods as shown in Figure 5. For each stop, each of the variance of dwell time (i.e., the second term) and the covariance between the arrival time deviation and the dwell time (i.e., the third term) are plotted as positive and negative (or zero) values, respectively, if the latter is negative (or zero). And, the two terms are added to one another and plotted as a single positive value if the covariance term is strictly positive. Therefore, in the cases where the drivers are able to react to the schedule by reducing the dwell time at stops, Figure 5 shows two values for those stops, one positive and one negative where the negative values reflect the extent to which the drivers' are able to counter the increase in the variance in departure time deviation (i.e., reduce transit unreliability) from one stop to the next downstream stop.

Similarly, for each stop-to-stop roadway segment, each of the variance of travel time (i.e., the first term) and the covariance between the departure time deviation and the travel time (i.e., the fourth term) are plotted as positive and negative (or zero) values, respectively, if the latter is negative (or zero). And, the two terms are added to one another and plotted as a single positive value if the covariance term is strictly positive. Therefore, in the cases where the drivers are able to react to the schedule by reducing the travel time on the stop-to-stop roadway segments, Figure 5 shows two values for those segments (plotted between the consecutive stops defining each segment), one positive and one negative where the negative values reflect the extent to which the drivers' are able to counter the increase in the variance in departure time deviation (i.e., reduce transit unreliability) from one stop to the next downstream stop.

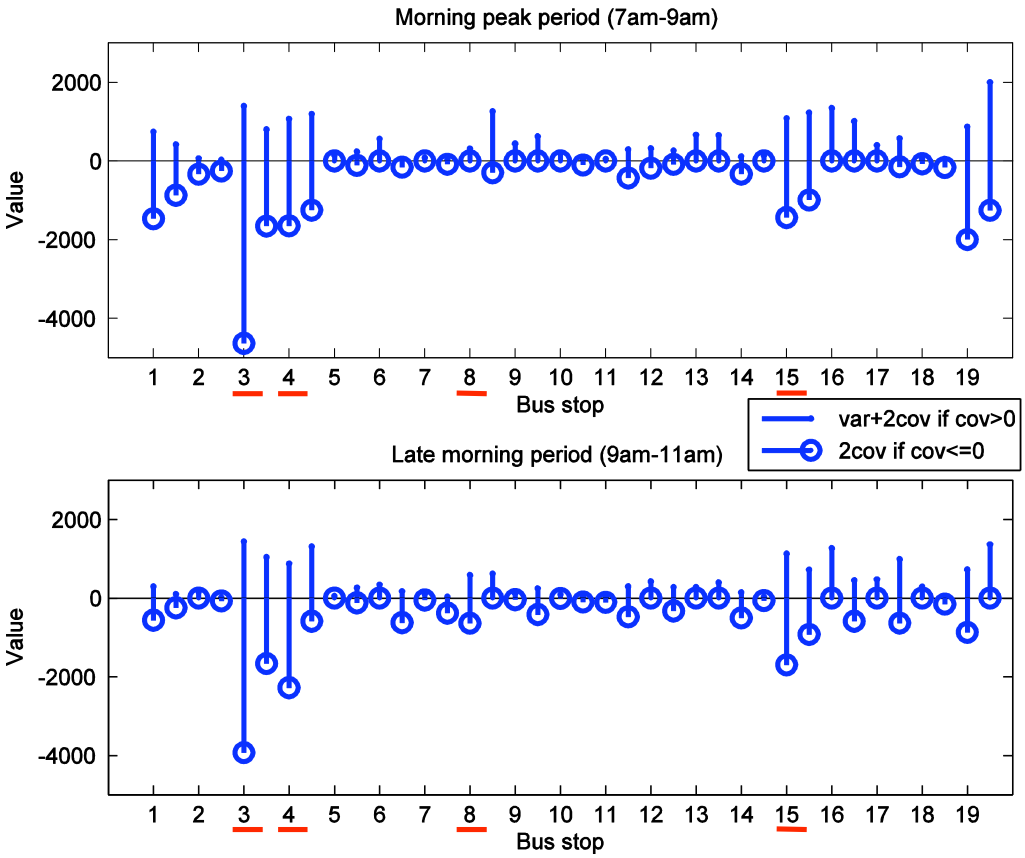


Figure 5 Distribution of positive and negative groups along bus route (unit: second^2)

In Figure 5, large positive values can be seen in the regions between stops 3 through 5, between stops 15 through 17, and between stops 19 through 1 in both periods. Additionally, a large positive value can be seen between stops 8 and 9 in the morning peak period. The deterioration of transit reliability along the route is mainly due to the boarding and alighting activities at stops and the traffic conditions on the roadway segments in these areas along the route.

Moreover, large negative values can be seen at time-points 3, 4, and 15 in Figure 5. Large values at time-points 3 and 4 are due to the effect of holding, while the large value at time-point

15 is not due to holding, but due to the fact that drivers are able to dwell for relatively shorter periods when the buses are late. Additionally, the effects of drivers' reactions to the schedule in reducing unreliability could also be seen at other stops and roadway segments, especially for the stops and roadway segments close to the time-points. For example, relatively high negative values could be seen at stops 1 and 19, roadway segments between stops 3 and 4, and between stops 4 and 5. Again, the above results reflect the ability of drivers to react to the schedule to reduce unreliability at these locations, reinforcing the results surrounding Figures 3 and 4 and, at the same time, quantifying the effects of the drivers' reactions on the improvement in reliability going from one stop to the next downstream stop.

Having separated the positive and negative contributions to reducing the difference in departure time reliability going from one stop to the next downstream stop, the aggregate contributions relating to each of time-points, other stops, and stop-to-stop segments can also be quantified. Table 1 presents the deterioration (i.e., the positive values in Figure 5) and improvement of transit reliability (i.e., the negative values in Figure 5) in proportion to the total deterioration (i.e., the total across all positive values) and total improvement (i.e., the total across all negative values) for each of the three categories of locations. As can be seen in Table 1, exogenous activities at stops (including time-points) and exogenous factors along the stop-to-stop roadway segments contribute almost equally to the deterioration of transit reliability. As for the improvement of transit reliability, on average, 43% is due to the effect of holding at time-points, 17% is due to drivers' reactions to the schedule at other stops in the form of lengethening or shortening dwell times at stops, and 40% is due to drivers' reactions to the schedule in the form of increased or reduced travel times on stop-to-stop roadway segments.

Table 1: Deterioration and improvement of transit reliability by time points, other stops and road segments

Deterioration of transit reliability		
Segment	Morning peak (7am-9am)	Late Morning (9am-11am)
Time-points	19%	24%
Other stops	29%	28%
Stop-to-stop segments	52%	49%
Total	100%	100%
Improvement of transit reliability		
Segment	Morning peak (7am-9am)	Late Morning (9am-11am)
Time points	39%	47%
Other stops	22%	12%
Road segments	39%	41%
Total	100%	100%

6. Concluding Remarks and Future Research

In this paper, the effect of drivers' reactions to the schedule on transit reliability is investigated analytically and empirically. The study reveals that drivers' reactions to the schedule are helpful in improving transit reliability. At time-points, drivers intentionally hold buses when they arrive early. At other stops, drivers may lengthen or shorten dwell times when buses arrive early or late, respectively. Similarly, along the roadways between consecutive stops, drivers may speed up or slow down when buses are behind or ahead of the schedule, respectively.

The arrival time deviations are correlated with the dwell times not only at time points, but also at other stops. Moreover, the departure time deviations at a stop are correlated with the travel times from that stop to the next downstream stop. Recognizing these two correlations are important in developing simulation tools to mimic bus operations, and analyze and design holding strategies. For example, in simulations, the bus dwell time should be a function not only of the number of passengers boarding and alighting, but also of the arrival time deviations. Also, the bus travel time between two consecutive stops should be drawn from a distribution conditional on the departure time deviation of the upstream stop.

Understanding how drivers react to the schedule is also informative for real-time bus arrival time forecasts. Conditional on the current time and location of a bus, the arrival time of this bus at a subsequent bus stop is the sum of travel times from the location of this bus to the location of the bus stop and dwell times at bus stops between the bus and the stop of interest. According to the findings of this study, bus deviation from the schedule should be an important factor in forecasting the travel times and dwell times and, consequently, the forecasted bus arrival time at the bus stop of interest.

In this study it has been shown that drivers may speed up or slow down based on the schedule at time-points and their experience with the bus route as reflected in their anticipated location when running according to the schedule. This result is informative with regard to designing good schedules. Loose schedules encourage drivers to slow down resulting in longer than necessary travel times along with corresponding inefficiencies, and tight schedules tempt drivers to speed up causing safety concerns. Therefore, a well-designed schedule coupled with reasonable pressure to maintain the schedule have the potential to improve transit reliability. Reasonable pressure could take the form of better information to drivers. For example, real-time on-board information systems could provide drivers with scheduled and estimated arrival times at the next downstream bus stop. Under such a system, drivers do not have to anticipate arrival times based on their own experience and, thus, react more effectively to the schedule and potentially achieve improved reliability. Investigating such possibilities would be worthwhile.

Another valuable future research activity is to apply the developed empirical analysis methodology to other time periods and other bus routes. The factors that constrain drivers' response to the schedule vary from time period to time period and vary from route to route. For example, drivers may pay more attention to the schedule when the scheduled headway is long given the impact of unreliability on passengers' waiting times. On the other hand, drivers may ignore the schedule when the scheduled headway is short. Therefore, understanding such effects along with the effects of driving adjustment constraints discussed in this paper through a more comprehensive empirical analysis would be very useful for both off-line planning and real-time control.

In addition, introducing drivers' heterogeneity into the model is another possible future research direction worth pursuing. Mishalani et al. (2008) showed that driver-bus heterogeneity is a significant factor affecting the relatonship between the schedule deviation at the terminal and the running time. Different drivers may have different reactions to the schedule when considering behavior at stops and between stops. For example, some drivers may have a good sense of anticipated traffic condition and number of passengers at downstream stops and are able to adjust bus dwell times and speeds appropriately and more aggressively conditional on the bus location and the schedule. Others may be insensitive to the schedule or less aggressive about making adjustments in which case their driving behavior would be independent from the bus deviations from the schedule.

Finally, it would be worthwhile to empirically study the more general relationship between the variance of headway and the variance of departure deviation described by Equation (7). With the advent of higher resolution and more reliable AVL data it would be possible to empirically estimate the variance of the headway and the covariance between the departure deviation at two consecutive bus trips to conduct such an investigation.

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