Investigating the Effect of Traffic Signals on Transit Reliability

Paper Submitted for Presentation at the 95th Transportation Research Board Annual Meeting
(2016)

by

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Nov. 13, 2015

4,168 Words + 1 Table + 3 Figures = 5,168 Words
ABSTRACT

This study investigates the influence of traffic signals and Transit Signal Priority (TSP) on the evolution of transit reliability using stochastic simulations. The analyses reveal that traffic signals tend to deteriorate transit reliability and that TSP could counter the deterioration of transit reliability. The variation of dwell time and the scheduled headway are identified as two major factors that would influence the effects of traffic signals and TSP. Possible explanations are provided. These insights would shed some light on the optimization of transit service.
INTRODUCTION
Transit operations are influenced by various factors, including passenger demand variation, traffic congestion, traffic signals, accidents and weather conditions. As a result, buses would inevitably bunch up without controls (1). Bus bunching reduces transit reliability and increases the waiting times of passengers. Bus bunching also leads to additional costs for transit agencies since they have to provide additional vehicles and operators to restore reliable service.

Ibarra-Rojas et al. classified commonly used control strategies into two categories based on the locations where controls are conducted (2): station control and inter-station control. Station control strategies include holding (3-5), stop-skipping (6, 7) and boarding limits(8, 9). Inter-station control strategies include bus speed regulation (10, 11) and traffic signal priority (12, 13).

Understanding the dynamics of transit operations is important for efficiently deploying control strategies. In the literature, there are three general approaches to investigate transit operations: analytic models, simulation studies, and empirical studies. Analytical models described bus motions using mathematical formulations. Assumptions were made to simplify the analyses. Newell and Potts developed a simple and deterministic model to explain the bus bunching phenomenon (1). The developed model described bus motions by considering bus travel times along the road and dwell times at bus stops. It was assumed that bus travel times are constant and that bus dwell times are linear functions of the number of boarding passengers. Adedisi developed a mathematical model to analyze the variance of headway using basic probability concepts (15). Hickman presented a stochastic transit service model that can be used to determine the optimal holding time (3).

Numerical simulations have been widely used to describe the dynamics of transit operations and evaluate the effects of various control strategies due to their flexibility. For example, Liu and Wirasinghe proposed a simulation model to design schedule for a transit route (17). The model could be used to determine the locations of time points and the amount of slack time for each time point.

The recent development of Automatic Vehicle Location (AVL) and Automatic Passenger Counter (APC) technologies facilitates empirical studies of transit operations. For instance, Strathman and Kimpel compared the effects of various control strategies whose objective was to maintain headways (19). It was found that control actions, such as holding and short turn, are helpful in reducing the variance of headway. Ji, He and Zhang analyzed bus drivers’ reactions to real-time information using empirical AVL data (20). It was demonstrated that bus drivers would adjust bus speeds along the road and dwell times at bus stops based on real-time information and their reactions are helpful in improving transit reliability.

In most of the analytical and simulation models, the instability of transit system is usually reproduced by considering that the dwell time of a given bus at a bus stop would increase with the headway between the given bus and its preceding bus. Although traffic signals have been considered as an important contributor to transit unreliability, their effects are usually implicitly considered in the variation of travel time. Hans, Chiabaut and Leclercq pointed out that the variation of travel time cannot fully account for the effect of non-dynamic signals (21). They showed that a bus system could be self-regulated in the presence of traffic signals.

The main objective of this study is to obtain a good understanding of the influence of traffic signals on the dynamics of transit operations. This study is motivated by a phenomenon observed in several metropolitan cities in China, such as Shanghai and Beijing. That is, the scheduled headways of some bus routes are set very short (e.g., 2-4 minutes) to accommodate
high passenger demand. At the same time, the cycles of traffic signals at intersections along the
bus routes are relatively long (e.g., 3 minutes) to handle large vehicular and pedestrian flows.
Under the influence of traffic signals, bus bunching is very common. Given the long signal
cycles and the short scheduled headways, consecutive buses are very likely to encounter the
same red phase at the same intersection, resulting in bus bunching. The likelihood of bus
bunching may decrease when the scheduled headway is higher. Nevertheless, to the best
knowledge of the authors, few studies have examined the evolutions of transit operations in the
presence of traffic signals when different scheduled headways are adopted.

In this study, we investigate the influence of traffic signals and TSP on transit reliability
on a fixed bus route. The investigations are carried out using stochastic numerical simulations.
Bus trajectories are considered to include dwell times at bus stops for passenger boarding and
alighting, travel times along the roads between bus stops and intersections, and signalized delays
at intersections.

**NUMERICAL EVALUATION**

**Simulation Process**

The simulations update bus trajectories by generating their dwell times at bus stops, travel times
between bus stops and intersections and signalized delays at intersections.

The dwell times reflect the effect of passenger demand on transit operations. It is
assumed that the dwell time is determined by the boarding process. The dwell time, \( d_{i,s} \), of bus
trip \( i \) at bus stop \( s \) is estimated by (17):

\[
d_{i,s} = \alpha + \beta \times b_{i,s}
\]

(1)

where \( \alpha \) represents the time lost in opening and closing doors, \( \beta \) represents the individual
boarding time, and \( b_{i,s} \) represents the number of passengers boarding bus trip \( i \) at stop \( s \). The
boarding count, \( b_{i,s} \), is assumed to follow Poisson distribution (17, 22):

\[
b_{i,s} \sim \text{Poisson}(\lambda_{i,s})
\]

(2)

where \( \lambda_{s} \) represents the passenger demand rate at stop \( s \), \( h_{i,s} \) represents the headway between bus
trip \( i \) and its preceding bus trip at stop \( s \). The alighting count, \( a_{i,s} \), on bus trip \( i \) at stop \( s \) is
assumed to follow binomial(\( l_{i,s}, p_{i,s} \)) distribution (4, 17, 23), where \( l_{i,s} \) represents the number of
passengers onboard bus trip \( i \) immediately upstream of bus stop \( s \), and \( p_{s} \) represents the
probability that an onboard passenger will alight at stop \( s \).

When a bus is travelling along the road, the speed, \( v \), of this bus is generated randomly.
We assume that the speed follows normal distribution. Based on the generated speed, bus arrival
time at intersections or bus stops can be obtained. The arrival time of a given bus at an
intersection is then used to calculate the signalized delay of the given bus, which has been
described in the previous section. The arrival time of a given bus at a given stop is used to
calculate the headway of the given bus, the number of boarding passengers and the dwell time of
the given bus at the given bus stop (see Equations (1) and (2)).

The capacity of a bus is assumed finite. Bus capacity is determined by the scheduled
headway and the maximum bus load (24). Passengers have to wait for the next bus when the bus
is full. In addition, bus overtaking is not allowed in the simulation.

Numerical evaluation also considers the effect of Transit Signal Priority (TSP) on transit
operations. TSP gives a bus priority if its headway with the preceding bus is less than the
scheduled headway. Two types of priority are used: green extension where the green phase is
extended as long as 15 seconds and early green where the red phase is truncated as early as 15
seconds.
Simulation Setup

The parameters of the numerical simulations are summarized in Table 1. The bus route under investigation has 20 bus stops. Buses travel on a closed loop. All buses start from stop 1 evenly according to the scheduled headway. There is a signalized intersection between two consecutive bus stops. It is assumed that the signal settings are fixed and are the same at all intersections. The signal cycles are set to be 3 minutes to represent the relatively long signal cycles in cities such as Shanghai in China. Bus operations in the case of constant and variable dwell times are evaluated separately. Travel speeds are assumed to be stochastic.

<table>
<thead>
<tr>
<th>Parameters (unit)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Bus stops</td>
<td>20</td>
</tr>
<tr>
<td>Distance between a bus stop and the adjacent intersection (m)</td>
<td>500</td>
</tr>
<tr>
<td>Common cycle of all signals (s)</td>
<td>180</td>
</tr>
<tr>
<td>Green time of all signals (s)</td>
<td>90</td>
</tr>
<tr>
<td>Mean of travel speed (km/h)</td>
<td>30</td>
</tr>
<tr>
<td>Standard deviation of travel speed (km/h)</td>
<td>5</td>
</tr>
<tr>
<td>Passenger demand rate at each stop (pass/min)</td>
<td>1</td>
</tr>
<tr>
<td>Time loss in opening and closing doors (s)</td>
<td>10</td>
</tr>
<tr>
<td>Unit passenger boarding time (s/pass)</td>
<td>4</td>
</tr>
<tr>
<td>Dwell time when it is assumed constant (s)</td>
<td>15</td>
</tr>
</tbody>
</table>

Measures of Transit Reliability

We use Expected Waiting Time (EWT) to measure the reliability of transit operations. The EWT is determined by the mean and variance of headway. At a given bus stop, the EWT is given by (25):

\[
EWT = \frac{E(h)}{2} + \frac{Var(h)}{2E(h)}
\]

where \(E(h)\) and \(Var(h)\) represent the mean and variance of the headway at the given bus stop. In the literature, the random arrivals of buses are often modelled by assuming that the headway follows exponential distribution (26-28). As a result, the EWT equals the scheduled headway.

When buses bunch up, they form a bus platoon. A bus platoon is analogous to a bus with larger capacity. Smaller number of bus platoons suggests that more buses bunch up. It can be shown that Equation 3 is also valid when \(h\) represents the headway between consecutive bus platoons.

Analyses of the Numerical Results

We run the simulation for 500 times. In each run, all buses start their trips from Stop 1 according to the scheduled headway. To investigate the evolution of transit reliability over time, each simulation run produces bus trajectories in 9 hours.
Figure 1 presents the headways between consecutive buses at each bus stop when buses travel along the route for one simulation run. The two rows of Figure 1 represent the cases where the dwell times are constant and variable, respectively. The three columns of Figure 1 present the results in the absence of signals, in the presence of signals and in the presence of TSP, respectively.

When the dwell times are constant, the effect of traffic signals on bus headways is noticeable even though travel speeds are stochastic. As shown in Figure (1a), without signals, buses will not bunch when the scheduled headway is relatively large. Only a few buses bunch up when the scheduled headway is close to the signal cycle. In either case, the headways are relatively stable over time. Figure (1b) reveals that the headway is more variable under the influence of traffic signals. It is interesting to observe that most of the headways equal integer multiples of the signal cycle, reflecting the regulation effect of traffic signals. Figure (1c) demonstrates that TSP could efficiently maintain the regularity of transit service. When the scheduled headway equals 10 minutes, the headways are maintained between 9 and 12 minutes. When scheduled headway equals 2 minutes, the headways are under 3 minutes. Note that the bounds also equal integer multiples of the signal cycle.

Figures (1d)-(1f) clearly show that the dependence of dwell times on passenger demand is the major contributor to bus bunching. The results are consistent with the findings in (I). As can be seen in Figure (1d), when the dwell times are variable, buses tend to bunch up without signals. Bus bunching is also observed in Figure (1e) when traffic signals are present. Nevertheless, it seems that traffic signals could lower the upper bound of the headways. Lastly, Figure (1f) reveals that TSP is not able to maintain the regularity of transit service when the dwell times are variable.
FIGURE 1: Evolutions of the Headways over Time: (a) Constant Dwell Times and No Signals; (b) Constant Dwell Times and with Signals; (c) Constant Dwell Times and with TSP; (d) Variable Dwell Times and No Signals; (e) Variable Dwell Times and with Signals; (f) Variable Dwell Times and with TSP.

Figure 2 presents the evolution of the mean number of bus platoons over time. The mean value is calculated based on the results of 500 simulation runs. The two rows of Figure 2 represent the cases where the dwell times are assumed to be constant and variable, respectively. The two columns of Figure 2 present the results when scheduled headways equal 2 and 10 minutes, respectively.

As shown in Figure (2a), more buses bunch up due to the presence of traffic signals, resulting in lower number of bus platoons. Using TSP could stabilize the regularity of bus service. Nevertheless, some buses still bunch up. Figure (2b) shows that buses will not bunch when the scheduled headway is relatively larger than the signal cycle.

Figure (2c) shows that passenger demand has great impact on transit operations. The number of bus platoons decreases to 6 after 4 hours. Traffic signals tend to expedite the rate of bus bunching and TSP could slow the rate of bus bunching. Figure (2d) shows the results when the scheduled headway is relatively larger than the signal cycle. The numbers of bus platoons in three cases are more variable than in Figure (2b), but they are relatively stable over time.

The rapid decrease of the number of bus platoons when the scheduled headway equals 2 minutes is understandable. Given that the scheduled headway is close to the signal cycle, buses are very likely to encounter the same red phase at the same intersection when the leading bus dwells at a bus stop longer for serving more passengers than the tailing bus, resulting in bus bunching. When buses bunch up, TSP is not able to separate them up. The number of bus
platoons would be stable when the headways between bus platoons become relatively large. That is, the likelihood that two bus platoons join up is low when the headway between them is large.

Figure 2 presents the evolution of the number of bus platoons over time: (a) Constant Dwell Times and Scheduled Headway of 2 Minutes; (b) Constant Dwell Times and Scheduled Headway of 10 Minutes; (c) Variable Dwell Times and Scheduled Headway of 2 Minutes; (d) Variable Dwell Times and Scheduled Headway of 10 Minutes.

FIGURE 2 Evolution of the Number of Bus Platoons over Time: (a) Constant Dwell Times and Scheduled Headway of 2 Minutes; (b) Constant Dwell Times and Scheduled Headway of 10 Minutes; (c) Variable Dwell Times and Scheduled Headway of 2 Minutes; (d) Variable Dwell Times and Scheduled Headway of 10 Minutes.

Figure 3 presents the evolution of the mean of the Expected Waiting Time (EWT) at bus stop 20. The expected waiting time for the $i$th loop is based on the headways of all buses that arrive at bus stop 20 for the $i$th time. The mean value is calculated based on the results of 500 simulation runs. As shown in Figures (3a) and (3b), when the dwell times are constant, the presence of signals increases the EWT. Adopting TSP could decrease the EWT and maintain the stability of the EWT over time.

Figures (3c) and (3d) assume that the dwell times depend on passenger demand. Figure (3c) shows the results when the scheduled headway equals 2 minutes. The EWT increases fast over time, no matter whether traffic signals are present and no matter whether TSP is adopted. For example, in the absence of traffic signals, the EWT increases from 2 minutes to 26 minutes from the first loop to the ninth loop. Traffic signals increase the EWT by about 3 minutes. When TSP is adopted, the EWT is reduced to the level that is close to the results when signals are absent. Figure (3d) shows the results when the scheduled headway equals 10 minutes. Compared with the results in Figure (3c), the effect of traffic signals is much smaller and the effect of TSP is more obvious in Figure (3d).

The results that the impact of traffic signals is greater and TSP is less efficient when the scheduled headway is close to the signal cycle are explainable. At the beginning, buses are
departed based on the scheduled headway. Buses are more likely to bunch up when the
scheduled headway is close to the signal cycle, as discussed in Figure 4, resulting in faster
increase of the EWT. After the 3rd or 4th loops, buses form about 6 bus platoons for the scheduled
headway of 2 minutes. The number of bus platoons is stable and is about 5 for the scheduled
headway of 10 minutes. Although the numbers of bus platoons are close, the headways between
bus platoons are more variable for the scheduled headway of 2 minutes. As a result, the EWT for
the scheduled headway of 10 minutes could be lower than that for the scheduled headway of 2
minutes.

**FIGURE 3 Evolution of the Expected Passenger Waiting Time over Time:** *(a) Constant
Dwell Times and Scheduled Headway of 2 Minutes; (b) Constant Dwell Times and
Scheduled Headway of 10 Minutes; (c) Variable Dwell Times and Scheduled Headway of 2
Minutes; (d) Variable Dwell Times and Scheduled Headway of 10 Minutes.*

**CONCLUSIONS AND FUTURE RESEARCH**

In this study, we investigate the effect of traffic signals and TSP on the evolution of transit
reliability. Bus trajectories are modelled by considering dwell times at bus stops, travel times
between stops and intersections, and signalized delays at intersections. The investigations
particularly focus on the effect of relatively long signal cycles on transit reliability when the
scheduled headway is close to the signal cycle and when the scheduled headway is relatively
larger than the signal cycle.

The analyses result in some interesting findings. It is found that traffic signals tend to
deteriorate transit reliability and TSP could counter the deterioration of transit reliability.
However, the effects of traffic signals and TSP depend on the variation of the dwell time and the
scheduled headway adopted. When the dwell times are constant, traffic signals have clear
regulation effects on bus headways and TSP could efficiently maintain the stability of headway. When the dwell times are variable and depend on passenger demand, the effect of passenger demand dominates the evolution of transit reliability. As a result, the effect of traffic signals diminishes and TSP is not able to maintain the regularity of transit service.

Although our study is based on numerical simulations, it provides interesting insights on bus operations in the presence of long signal cycles. Validating the simulation model with empirical data is the next step we are taking. In addition, incorporating the findings into the optimization of transit service is worth pursuing in the future.

ACKNOWLEDGEMENT

This research was supported by the National Natural Science Foundation of China (51308410) and the Fundamental Research Funds for the Central Universities of China (1600219247). The work was also supported by Program for Changjiang Scholars and Innovative Research Team in University.

REFERENCE


