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A Real-time Bus Traveling Speed Optimization Model for Reducing bus delay and CO2 Emission in Connected Vehicle Environment

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Public transportation plays an important part in sustainable motorization and urbanization. This research presents a novel bus speed operation strategy to reduce bus delay and CO_2 emission within connected vehicle environment. Most previous work merely focuses on optimization of signal timings to decrease bus signal delay by assuming that the speed of buses is given as a constant input and the acceleration and deceleration processes of buses can be neglected. This paper explores the benefits of bus speed control strategy to minimize the total cost that includes bus signal delay and bus travel delay caused by adjusting speed due to frequent stops and intense driving. A set of formulations are developed to capture the benefits of bus speed control. Experimental analyses have shown that the proposed model outperforms the traditional control strategy in terms of reducing average bus delay and CO_2 emission.

1. Introduction

In 2010, congestion caused urban Americans to travel 4.8 billion hours more and to purchase an extra 1.9 billion gallons of fuel for a congestion cost of $101 billion. Vehicles are responsible for almost all of the Carbon Monoxide emissions, for about the 75% of the Hydrocarbon emissions and volatile organic compounds, and for about the 65% of the Nitrogen Oxide emissions (Tzirakis et al., 2006). Traffic congestion and vehicle emissions have emerged as a pressing issue during the process of motorization and urbanization. An increasing number of researchers have recognized that developing public transportation and improving the level of service of buses are potentially sustainable strategies to relieve traffic-related problems (Khandker et al., 2011; Bigerna and Polinori, 2015; Chen et al., 2014; Shi et al., 2011).

In order to improve the level of service of buses, Transit signal priority (TSP) is a promising option (Hickman, 2001, Zhao et al., 2006, Xuan et al., 2011; Daganzo, 2009). However, most existing models for transit signal priority are developed on the basis of the assumption that the travel speed of buses is constant and given as exogenous input, the acceleration and deceleration processes of buses can be neglected (Koehler and Kraus, 2010; Ma et al., 2013; Liu et al., 2011). Based on these assumptions, signal settings are determined to minimize the delay (Zeeshan and Bruce, 2011; Xu et al., 2010). Moreover, most of TSP methods only try to minimize the delay, but the fuel consumptions, pollution emissions are also the critical parameters to measure the level of service of transit system. These parameters are affected by the driving patterns which mainly depend on accelerations and decelerations of buses.

Technical difficulties in reliable bus location, speed, acceleration detection and real time communications between buses and intersection controllers may have been obstacles to use holding and speed control in transit system. But with the development of the wireless communication technology, vehicle infrastructure integration environment have progressed significantly and changed the way we operate the transit systems (Abu-Lebdeh and Chen, 2010).

Under connected vehicle environment, buses and the intersection controller can communicate with each other through wireless communication technology like Dedicated Short Range Communication (DSRC). Buses

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automatically send the real time information like bus location, speed and acceleration to the controller. Then the intersection controller will issue driving order to buses such as when and where to accelerate, decelerate, start to move, begin to stop and so on, based on the signal timing and traffic conditions.
In response to aforementioned concern, this research focuses on developing a bus speed control strategy to improve the level of service of transit systems within connected vehicle environment.

2. General notations

The notations used hereafter are summarized in Table 1.

Table 1: List of key variables used in the formulations

Notations	Explanation
a_{min}, a_{max}	The maximum and minimum accelerations for the bus (m/s2)
a_t	Acceleration/ deceleration of buses(m/s2)
C_a	Acceleration cost
C_0	The cycle length of the signal timing (s)
D_{bus}	Bus delay cost
d_s	Bus signal delay(s)
d_t	Bus travel delay(s)
L	The distance from bus stop to the intersection (m)
l_v	The average vehicle length (m)
q	The constant arrival flow rate (#. of vehs/s)
s	Saturation flow rate (#. of vehs/s)
T_c	Time for bus to close the door at the bus stop and ready to move(s)
T_g	Time for green light starts (s)
T_j	Time for buses stopped by red (s)
T_s	Time for bus to clear the intersection(s)
T_{AB}, T_{BC}, T_{CA}	The boundary point for scenario A, B, and C (s)
t_g	Green time duration (s)
t_{0_v}	Time duration for a bus accelerates from zero to bus traveling speed(s)
V_{bus}	Bus traveling speed (m/s)
V_{min}, V_{max}	The maximum and minimum bus speed limits (m/s)

3. Problem description

The fundamental idea for bus speed control can be illustrated in Figure 1. When the red light begins, a queue will be formed and accumulated until the green light is turned on. Trajectory 1 represents the common bus operation strategy without speed control. In this case, the bus departs from the bus stop at the time T_c, accelerates to average bus speed V_a, then joins in the queue formed by red. Trajectory 2 stands for the bus operation strategy with speed control. In this case, the bus also departs from the bus stop immediately at T_c, but it will accelerate to a relatively lower speed V_l, then it can clear the intersection without stopping again.

4. Objective function

The objective function in this study is to minimize the total cost of the buses, including both delay cost and acceleration cost. It can be specified as

$$\min(C_a + \beta D_{bus}) \tag{1}$$

Where C_a is the acceleration cost caused by frequent stops and vigorous accelerations/ decelerations; D_{bus} is the cost caused by bus delay; β is the weighting factor. In this paper, C_a can be specified as

$$C_a = \sum_{t=T_c}^{T_s} \sqrt{a_t^2} \tag{2}$$

Where a_t is the second by second acceleration or deceleration; T_c is the time for bus to close the door at the bus stop and ready to move; T_s is the time for bus to clear the intersection.
Bus delay is consisted of three parts and can be calculated by the following equation:

$$D_{bus} = d_t + d_s \tag{3}$$

Where d_t is the bus travel delay caused by travelling with a lower speed; d_s is the signal delay caused by red light.

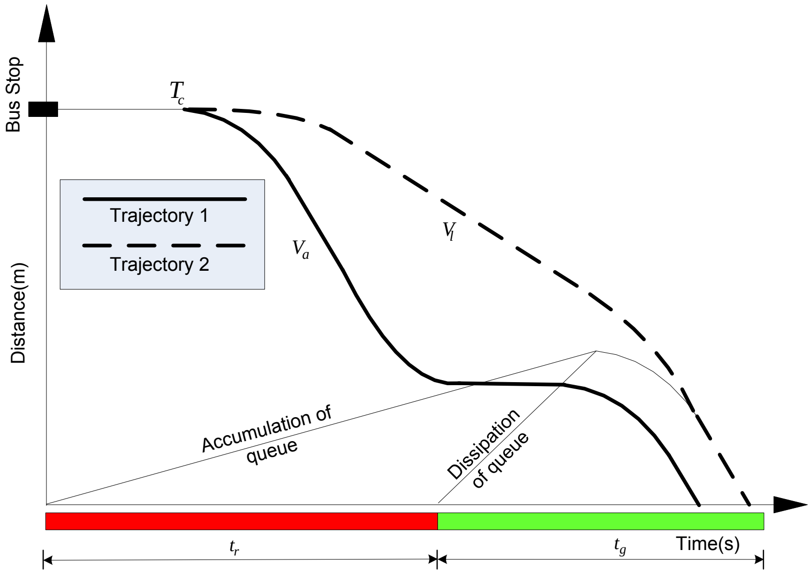

Figure 1. Space-time diagram of two different bus operations

5. Constraints

The operation of the system begins with the bus closing the door and ready to depart from the stop at the current time T_c which is measured relative to the start of the cycle. As shown in Figure 2, bus departure time is divided into five parts, A_1, B, C and A_2. We generated three separate scenarios depending on T_c:

- Scenario *A*, when $0 < T_c < T_{AB}$ or $T_{CA} < T_c < C_0$ (including A_1 and A_2);
- Scenario *B*, when $T_{AB} \leq T_c < T_{BC}$;
- Scenario *C*, when $T_{BC} < T_c < T_{CA}$;

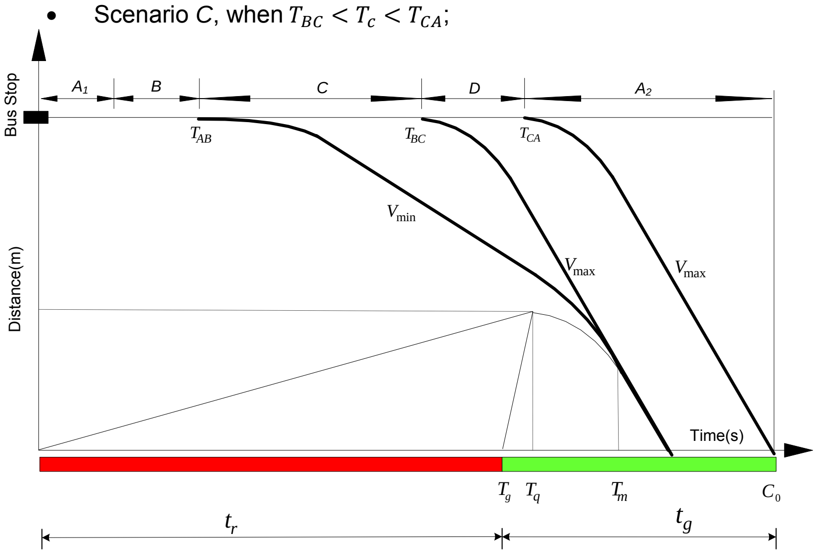

Figure 2: Scenarios for the buses depart from the bus stop

5.1 Scenario *A*

In this scenario, buses could not clear the intersection without stopping by speeding up. This indicates that the bus will experience a stop due to the red light. Buses will depart immediately and then accelerate to V_{bus} . The time duration for the bus accelerating from zero to V_{bus} can be computed as:

$$t_{0\_v} = V_{bus}/a_{bus} \tag{4}$$

The boundary of V_{bus} and a_{bus} can be specified as:

$$V_{min} \leq V_{bus} \leq V_{min} \tag{5}$$

$$a_{min} \leq a_{bus} \leq a_{max} \tag{6}$$

Then the signal delay caused by red light d_s can be computed as:

$$d_s = T_s - T_j \tag{7}$$

With respect to bus travel delayd_t , it is caused by travelling with a lower speed, which can be computed as:

$$d_t = \frac{3V_{bus}}{2a_{bus}} + \frac{L}{V_{bus}} - \frac{L}{V_{max}} \tag{8}$$

With regard to C_a, In scenario A, the travel speed for the bus will accelerate from zero to V_{bus} after the departure from the bus stop. Then the bus will decelerate from V_{bus} to zero due to the red light. After the green light is turned on, the speed of the bus will accelerate from zero to V_{bus} again to clear the intersection. In this scenario, the cost C_a , which is the cost caused by frequent stops and vigorous accelerations and decelerations, can be specified as:

$$C_a = \sum_{t=T_c}^{T_s} \sqrt{a_t^2} = 3V_{bus} \tag{9}$$

5.2 Scenario *B*

In scenario B, buses can clear the intersection without stopping if speed control is implemented. In this scenario, the movements of buses are consisted of three steps. The first step is that buses depart immediately and accelerate to a lower speed. The second step is that buses proceed with a constant velocity. Accelerating to a higher speed and following the last vehicle in the queue to clear the intersection is the last step. To this end, the constant velocity follows that:

$$V_{bus} = ((s-q)L - T_g s q l_v)/(T_g s - T_c(s-q)) \tag{10}$$

Then the bus travel delay in this scenario can be specified as

$$d_t = \frac{V_{bus}}{2a_{bus}} + \frac{L}{V_{bus}} - \frac{L}{V_{max}} \tag{11}$$

There is no signal delay in this scenario, With regard to C_a , there is only a complete acceleration process, thus can be specified as:

$$C_a = \sum_{t=T_c}^{T_s} \sqrt{a_t^2} = V_{bus} \tag{12}$$

5.3 Scenario *C*

In scenario C, buses can clear the intersection without stopping. The time of the boundary point T_{BC} and T_{CA} can be computed as

$$T_{BC} = \frac{T_g s}{s-q} - (L - \frac{T_g s q l_v}{s-q})/V_{max} \tag{13}$$

$$T_{CA} = C_0 - \frac{L}{V_{max}} - \frac{V_{max}}{2a_{max}} \tag{14}$$

In this scenario, the bus delay only contains travel delay, which can specified as

$$d_t = \frac{V_{bus}}{2a_{bus}} + \frac{L}{V_{bus}} - \frac{L}{V_{max}} \tag{15}$$

C_a can be specified as

$$C_a = \sum_{t=T_c}^{T_s} \sqrt{a_t^2} = V_{bus} \tag{16}$$

6. Performance analysis

In order to illustrate the applicability of the proposed model, this study employs an example intersection for numerical tests. The following parameters are assumed: $C_0 = 70s$, $s = 0.5\ veh/s$, $t_g = 35s$, $q = 0.15\ veh/s$, $l_v = 6m$, $L = 200m$, $\beta = 1$, $t_g = 35s$, $V_{min} = 5.6\ m/s$, $V_{max} = 11.1 m/s$, $a_{min} = -3\ m/s$, $a_{max} = 3\ m/s$.

With the above parameters, the boundary for each scenario can be specified as $T_{AB} = 22.3s$, $T_{BC} = 36.0$, $T_{CA} = 50.1s$.
Considering four buses with their door closing time located in each of four time span defined by T_c , Table 2 shows the optimization and comparison results from the proposed model for the four buses.

Table 2: Results for buses to depart at different time

T_c(s)	Scenario	D_{bus}(s)	C_a	$V_{\max}$(m/s)	CO_2 emission(g)	Stopped by red light
3.0	$A(A_1)$	24.5	33.3	11.1	66	Yes
60.0	$A(A_2)$	33.0	33.3	11.1	72	Yes
28.0	B	11.5	11.1	7.1	45	No
45.0	C	1.85	11.1	11.1	36	No

We can reach the following findings from Table 2:

- After buses depart from the bus stop, they will be stopped by red light again only in scenario *A*. In other scenario, buses will clear the intersection without stopping.
- The acceleration cost $C_a$in scenario *A* is three times bigger compared with scenario *B* and *C*. It is because in scenario *B* and *C*, it only contains one full acceleration process after buses depart from the bus stop. But in scenario *A*, the bus will experience one more acceleration process and one more deceleration process because of the stop caused by red light. This result validates that the proposed parameter C_a can be employed to represent the cost caused by frequent stops and vigorous accelerations and decelerations.
- By speed control, buses can avoid unnecessary stops thus reduce CO_2 emission.

Let t_w denotes the time interval in which buses close the door, and then they can clear the intersection without stopping. t_l represents the interval length of t_w; t_s represents the service rate for bus in the whole cycle. Then,

$$t_s = t_l / C_0 \tag{17}$$

Table 3 presents the results of bus service rate in different cases. The results clearly show that proposed method can provide 41.6% service rate for bus clearing the intersection without stopping and higher than the service rate under traditional control method.

Table 3: Results of the bus service rate for different cases

Cases	t_w	t_l	t_s
traditional control method	[36.0,50.1]	14.1	20.1%
proposed method	[21.0,50.1]	29.1	41.6%

7. Conclusion

This paper presents a novel approach for optimization of bus travelling speed to reduce bus delay and CO_2 emission. The objective of the proposed model is to minimize the total cost that includes bus signal delay and bus travel delay caused by adjusting speed and acceleration cost due to frequent stops and intense driving. A set of formulations are developed to capture explicitly the interaction between bus speed and signal timing. Experimental analyses have shown that the proposed integrated operational model outperforms the traditional control in terms of reducing average bus delay and CO_2 emission.
Note that this paper has presented preliminary theoretical analysis and evaluation results for the proposed model. More extensive numerical experiments or field tests will be conducted to assess the effectiveness of the proposed model under various traffic and transit demand patterns. Another possible extension of this study is to optimize signal timings, holding time duration and recommended bus speed together to further improve the level of service of buses.

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