

Study on Detecting Location for Bus Rapid Transit with Signal Priority

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Key words: Traffic engineering; Bus rapid transit; Signal priority; Detector; VISSIM

Abstract: Three signal priority scenarios were proposed for bus rapid transit(BRT) at isolated intersection based on early green and green extended strategies. The stopping time model of BRT at intersection was built considering signal phase status, detector location and its progression speed. Calculation results were compared with VISSIM simulation results, and the influence of detector location on the stopping time of BRT was analyzed under different progression speeds and cycle time. Results prove the effectiveness of model proposed in this paper. There is critical location for detector to minimize stopping time. When detector is closer to the stopping line than the critical location, stopping time decreases with detector's distance far away from stopping line. When it is beyond the critical location, stopping time is approaching to some stable value. Moreover, higher speed of bus causes longer stopping time and results in further critical location. Critical location almost has nothing to do with signal cycle time.

Introduction

Signal priority system is composed of signal control system and vehicle detecting system[1]. Signal priority strategies are the priority rules[2]. Early green and green extended are two common priority strategies[3]. Vehicle detection technology is the core of detecting system including automatic vehicle location[4], infrared detecting system[5], radio frequency identification devices[6], induction coil, and video[7]. Actually, detecting location has effect on the stopping time of priority vehicle at intersection which also influences priority effect.

Although there are studies on detecting location, some critical problems still have not been solved very well. Jeong[8] developed a method to ensure the optimal location of detector. However, simulation results were not identical with calculation results. Liu[9] holds the view that stopping time of bus has relationship with waiting time for green and queue clearance time. In his research, bus delay connected with detecting location was developed, but the relationship of them was achieved from simulation instead of the proposed model and lack of demonstration. Yan[10] got the conclusion that optimal detecting locations are 75m and 150m for early green and green extended respectively. However, these two priority strategies are conducted in compatible application and use the same detector in general. His research divided them into two scenarios and got two detecting locations which was not proper for the real.

It is necessary to explore the effect from detecting location on bus stopping time at intersection to inform optimal location under given priority strategies. Compared with the existing literatures, this paper put forward three priority scenarios clearly firstly. Calculating model is built then to release how the stopping time of bus changes with detecting location. Critical location for detector is achieved by the model and the results are closer to simulation. At last, influence factors of the relationship between them are analyzed. The results of changing regularity for stopping time with detecting location make sense to detecting system of BRT.

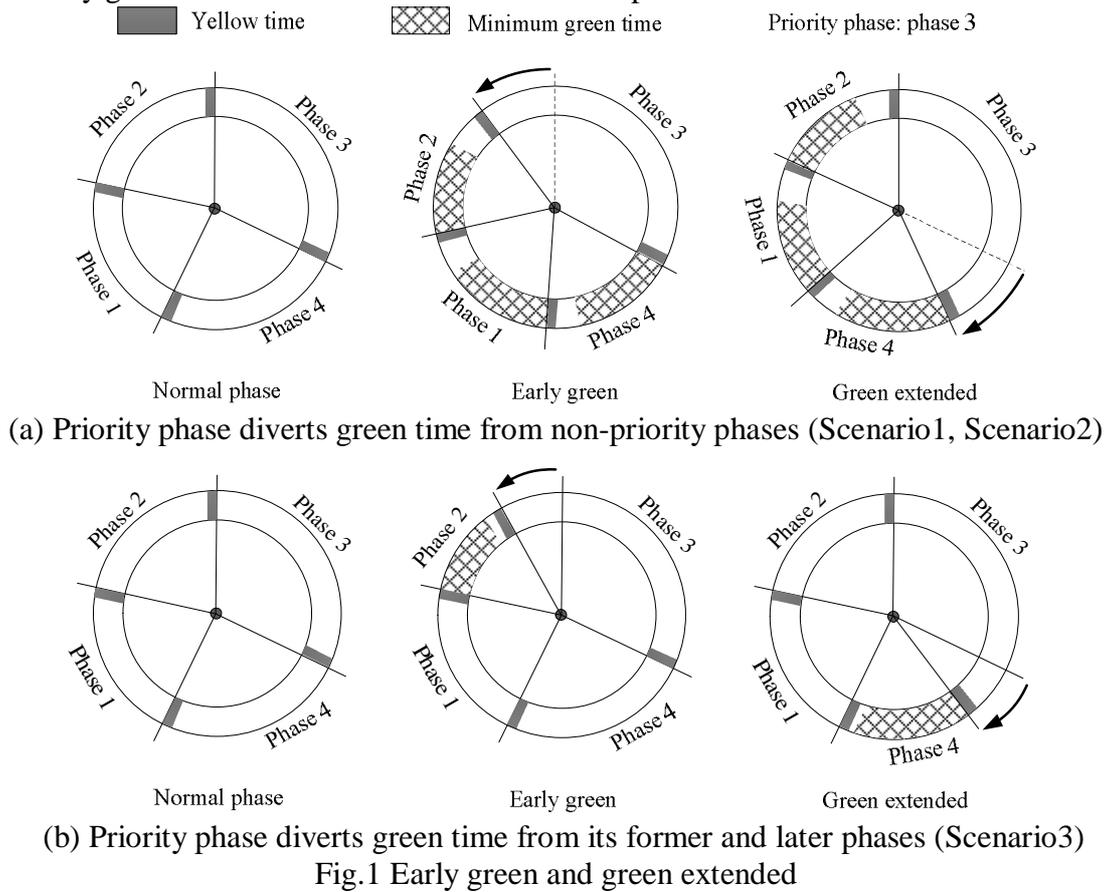
Priority scenarios for BRT

Priority strategies are early green and green extended. Cycle time and minimum green times of non-priority phases are remained. Three specific scenarios are established according to where the extra green time of priority phase is from and whether early green is conducted or not once bus stops at intersection.

Scenario 1: the extra green time of priority phase is from all the other non-priority phases as shown in Fig. 1(a), and early green will not be conducted once bus stops.

Scenario 2: the extra green time of priority phase is from all the other non-priority phases as shown in Fig. 1(a), and early green is still conducted once bus stops.

Scenario 3: the extra green time of priority phase is just from the adjacent phases as shown in Fig. 1(b), and early green will not be conducted once bus stops.



Stopping time of bus at intersection

Assuming there is bus-only lane, detecting location is influenced by signal timing and progression speed of bus and has nothing to do with traffic flow. Moreover, there is no queue vehicle and ignore the station's impact. After detecting a bus in upstream, according to the distance from detector to stopping line and progression speed of bus, signal controller will judge whether conduct priority and the proper strategies considering signal condition at intersection. Based on this, let the signal is conducting at t second of k phase when detecting the bus. Stopping time model of bus is proposed for Scenario1, Scenario2 and Scenario3 by taking k and t as independent variables. Define variables and parameters as following.

- w : stopping time of bus at intersection, (s). w_1 is the stopping time in Scenario1.
- n : sum of phase numbers.
- k : phase number of signal when detecting bus, $k = 1, 2, \dots, n$.
- t : signal is conducting at t second of k phase when detecting bus, (s).

- j : priority phase number, $j = 1, 2, \mathbf{L}, n$.
 i : phase number, $i = 1, 2, \mathbf{L}, n$.
 C : cycle time, (s).
 G_i : normal green time of phase i , (s).
 g_i : minimum green time of phase i , (s).
 A_i : yellow time of phase i , (s).
 l : distance from detector to stopping line, (m).
 v : progression speed of bus between detector and stopping line, (m/s).
 t : deceleration, (m/s²).
 g_{ext} : maximum green extended time for priority, (s).
 g_{ear} : maximum early green time for priority, (s);

For Scenario1, according to the relationship between the phase when detecting bus and the priority phase, there are three situations, $k < j$, $k > j$ and $k = j$, need to be discussed

(1) If $k < j$, there are three stopping times according to the time when bus arrives at the stopping line.

1) Even conducting early green, bus still arrives at the stopping line before green light. It will stop and wait for the green light. So $0 \leq \frac{l}{v} < \sum_{i=k}^{j-1} (g_i + A_i) - t$.

$$w_1(k < j, t) = \sum_{i=k}^{j-1} (G_i + A_i) - t - \frac{l}{v} - \frac{v}{2t} \quad (1)$$

2) Bus can drive through the intersection in green time without stop. So $\sum_{i=k}^{j-1} (g_i + A_i) - t \leq \frac{l}{v} < \sum_{i=k}^{j-1} (G_i + A_i) + G_j + g_{ext} - t$.

$$w_1(k < j, t) = 0 \quad (2)$$

3) Even conducting green extended, bus still cannot go through the stopping line before green time finishes. It has to wait for the next green time. So $\sum_{i=k}^{j-1} (G_i + A_i) + G_j + g_{ext} - t \leq \frac{l}{v} \leq C$.

$$w_1(k < j, t) = C + \sum_{i=k}^{j-1} (G_i + A_i) - t - \frac{l}{v} - \frac{v}{2t} \quad (3)$$

(2) If $k > j$, there are three stopping times as following.

1) Even conducting early green, bus still arrives at the stopping line before green light. So $0 \leq \frac{l}{v} < \sum_{\substack{i=1 \\ (i \neq j, \mathbf{L}, k-1)}}^n (g_i + A_i) - t$.

$$w_1(k > j, t) = \sum_{\substack{i=1 \\ (i \neq j, \mathbf{L}, k-1)}}^n (G_i + A_i) - t - \frac{l}{v} - \frac{v}{2t} \quad (4)$$

2) Bus can drive through the intersection in green time without stop. So $\sum_{\substack{i=1 \\ (i \neq j, \mathbf{L}, k-1)}}^n (g_i + A_i) - t \leq \frac{l}{v} < \sum_{\substack{i=1 \\ (i \neq j, \mathbf{L}, k-1)}}^n (G_i + A_i) + G_j + g_{ext} - t$.

$$w_1(k > j, t) = 0 \quad (5)$$

3) Even conducting green extended, bus still cannot go through the stopping line before green time finishes. So $\sum_{\substack{i=1 \\ (i \neq j, \mathbf{L}, k-1)}}^n (G_i + A_i) + G_j + g_{ext} - t \leq \frac{l}{v} \leq C$.

$$w_1(k > j, t) = C + \sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n (G_j + A_i) - t - \frac{l}{v} - \frac{v}{2t} \quad (6)$$

(3) If $k = j$, there are two stopping times because early green cannot be conducted.

1) Bus can drive through the intersection in green time without stop. So $0 \leq \frac{l}{v} < G_j + g_{ext} - t$.

$$w_1(k = j, t) = 0 \quad (7)$$

2) Even conducting green extended, bus still cannot go through the stopping line before green time finishes. So $\frac{l}{v} \leq G_j + g_{ext} - t \leq C$.

$$w_1(k = j, t) = C - t - \frac{l}{v} - \frac{v}{2t} \quad (8)$$

It is similar for Scenario2 and Scenario3 to get the stopping time of bus. Let a_1 , a_2 and a_3 are 0-1 variables. If they equal zero, bus doesn't stop at the intersection, while equal one, bus stops. Let b_1 and b_2 are 0-1 variables. If they equal zero, green time has not came when bus arrives, while equal one, green time has finished and bus needs to wait for the next green light to pass. a is 0-1 variable. $a=0$ in Scenario1, $a=1$ in Scenario2, and $a=0$ in Scenario3. b is also 0-1 variable. $b=0$ in Scenario1, $b=0$ in Scenario2, and $b=1$ in Scenario3. Stopping time in three scenarios under various situations can be expressed by function (9).

$$w(k, t) = \begin{cases} a_1 \times \left\{ b_1 \times \left[C + a \left(\sum_{i=k}^{j-1} (G_i - g_i) - g_{ear} \right) \right] + \sum_{i=k}^{j-1} [ag_i + (1-a)G_i + A_i] - t - \frac{l}{v} - \frac{v}{2t} \right\} & , k < j \\ a_2 \times \left\{ b_2 \times \left[C + a \left(\sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n (G_i - g_i) - g_{ear} \right) \right] + \sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n [ag_i + (1-a)G_j + A_i] - t - \frac{l}{v} - \frac{v}{2t} \right\} & , k > j \\ a_3 \times \left(C - t - \frac{l}{v} - ag_{ear} - \frac{v}{2t} \right) & , k = j \end{cases} \quad (9)$$

where,

$$a_1 = \begin{cases} 0, & \sum_{i=k}^{j-1} [bG_i + (1-b)g_i + A_i] - bg_{ear} - t \leq \frac{l}{v} < \sum_{i=k}^{j-1} (G_i + A_i) + G_j + g_{ext} - t \\ 1, & \text{else} \end{cases} \quad (10)$$

$$a_2 = \begin{cases} 0, & \sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n [bG_i + (1-b)g_i + A_i] - bg_{ear} - t \leq \frac{l}{v} < \sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n (G_i + A_i) + G_j + g_{ext} - t \\ 1, & \text{else} \end{cases} \quad (11)$$

$$a_3 = \begin{cases} 0, & 0 \leq \frac{l}{v} < G_j + g_{ext} - t \\ 1, & \text{else} \end{cases} \quad (12)$$

$$b_1 = \begin{cases} 0, & 0 \leq \frac{l}{v} < \sum_{i=k}^{j-1} [bG_i + (1-b)g_i + A_i] - bg_{ear} - t \\ 1, & \text{else} \end{cases} \quad (13)$$

$$b_2 = \begin{cases} 0, & 0 \leq \frac{l}{v} < \sum_{\substack{i=1 \\ (i \neq j \mathbf{L} k-1)}}^n [bG_i + (1-b)g_i + A_i] - bg_{ear} - t \\ 1, & \text{else} \end{cases} \quad (14)$$

It is a random probability event to detect bus if ignoring timetable. Let W is the expectation

value of stopping time. So,

$$W = E(w) = \sum_{k,t} \frac{w(k,t)}{C} \quad (15)$$

Case study

Take a four phases intersection as case, shown in Fig. 2. There are bus-only lanes for east-west directions. Signal timing is presented in table 1.

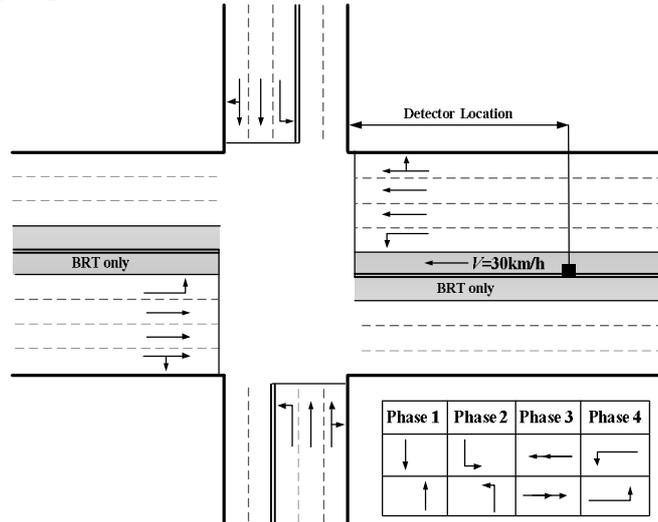


Fig. 2 Phase sequence of the intersection

Table 1 Signal parameters of the intersection (unit: second)

Cycle time	Phase	Minimum green time	Normal green time	Yellow time
120	1	27	32	3
	2	17	22	3
	3(Priority phase)	32	32	3
	4	17	22	3

Results and analysis. Let $l=50,60,\dots,300(m)$, $g_{ext} = 15s$, and $g_{ear} = 15s$. Curves of stopping time changing with detecting location in three scenarios are shown in Fig. 3.

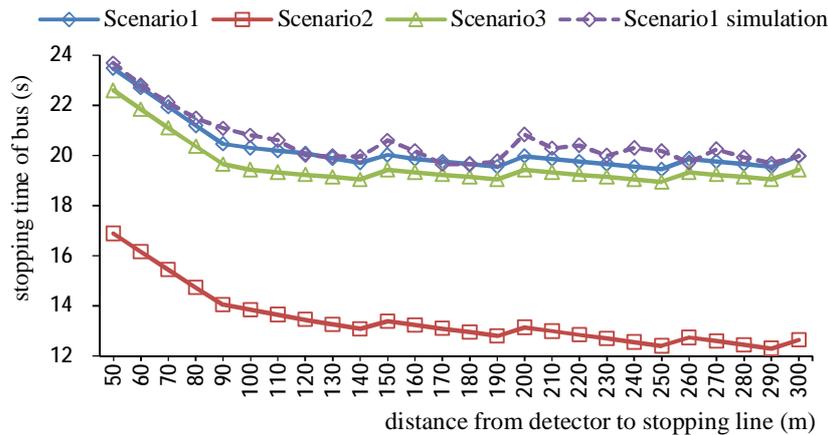


Fig. 3 Stopping time of bus varies from detecting location in three scenarios

It is obvious from Fig. 3 that stopping time of bus decreases firstly along with detector far away from the stopping line, and then tends to be a stable value after the detector is placed beyond some location. Thus stopping time of bus will be relative low when the distance from stopping line to detecting location is more than some value which is called critical location in this paper. In these three scenarios, the decreases of stopping time drop from 3.5% to 0.8%, 4.7% to 1.4%, 3.5% to 1.1% respectively at 90m of detector. Therefore, 90m is the critical detecting location for stopping

time. It is better to settle detection system upstream beyond 90m to get a lower stopping time of bus. Actually, considering the bus stop location, passenger convenience, progression speed volatility, detector is not proper to settle too far away from intersection. With overall consideration, 90m~150m is the suggestive location of detector.

For demonstrating the correctness of model proposed in this paper, simulation is conducted in virtue of VISSIM. The same actuated signal control plan with Scenario1 is designed through VisVAP. Curve is shown as dashed line in Fig. 3. Simulation results are almost the same with calculation results. The average value of their differences is just 0.31s and the variance is $0.8s^2$, which proves the model is effective.

Influence of progression speed of bus. In Scenario1, let the progression speed of bus $v=10, 20, 30, 40, 50$ (km/h). The relationships between stopping time and detecting location in various speeds are calculated and shown in Fig. 4.

When bus is quite slow like $v=10$ km/h, stopping time is about 21s and almost doesn't influenced by detecting location. As the speed developing, the critical location is becoming farther. Critical location is 70m when $v=20$ km/h, 90m when $v=30$ km/h, 130m when $v=40$ km/h, and 160m when $v=50$ km/h, shown as the black marks in figure. The average stopping time is positive correlation with speed as detector is closer to intersection than the critical location. While if the detector is beyond than the critical location, stopping time tends to be a stable value and this value is smaller as speed larger.

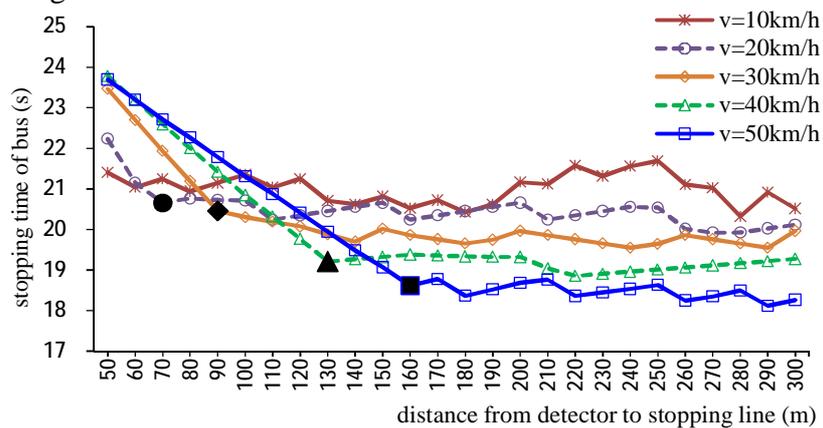


Fig. 4 Stopping time of BRT varies from detecting location under different speed

Influence of cycle time. In Scenario1, let the cycle time $C=80, 100, 120, 140, 160$ (s). Green time of each phase changes with cycle time by an interval of 5s. The priority phase's green time $G_3=22, 27, 32, 37, 42$ (s) accordingly. The relationships between stopping time and detecting location in various cycle times are calculated and shown in Fig. 5.

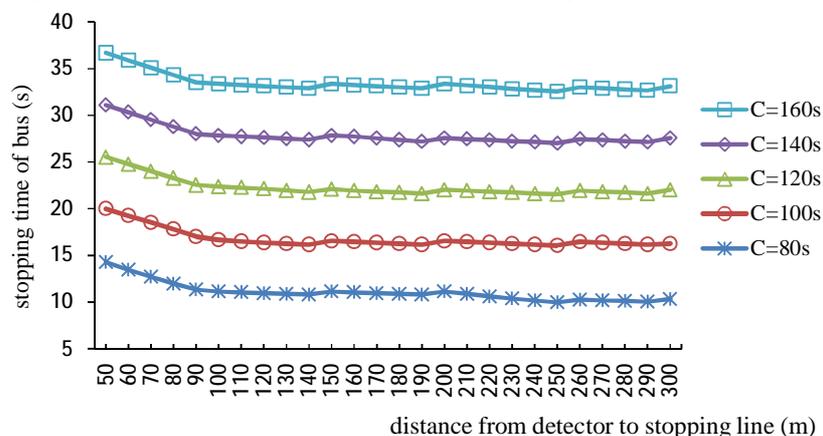


Fig. 5 Stopping time of BRT varies from detecting location under different cycle time

It can be concluded that the critical locations are all 90m in different cycle times. They are a

group of parallel curves with the same separation distance by 5s~6s which equals the difference of green times of priority phase. Therefore, cycle time just influences stopping time value, while doesn't effect on their relationship between stopping time and detecting location. In addition, the critical location is the same in various cycle times.

Conclusions

Signal priority is helpful to improve efficiency and travel speed of BRT. Detecting location has effect on its stopping time at intersection. This paper developed a model to describe the relationship between stopping time of bus and detecting location. Simulation results proved its correctness and effectiveness. The results show that there is critical location for detector to make stopping time quite small and this critical location is influenced by bus speed. Some further researches can focus on other different priority scenarios.

Acknowledgements

This research was funded by the Fundamental Research Funds for the Central Universities (2015YJS090), the National Basic Research Program of China (No. 2012CB725406) and the National Natural Science Foundation of China (71131001).

The authors also thank reviewers and editors for their suggestions to improve this paper.

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