Study on Tram Priority Control Strategy at an Intersection Based on Passenger Occupancy

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ABSTRACT

Tram signal priority (TSP) strategy at intersections is studied in this paper to improve the traffic efficiency, in the case that trams share right-of-way with vehicles. This paper presents a traffic responsive signal control model for tram signal priority at a typical intersection to minimize the total passengers’ delay at an intersection. Based on the estimated number of road vehicles and tram passenger occupancy, the model improves vehicle delays at the intersection and aims at minimizing total passenger delay through signal priority control strategy. The model determines whether to give priority to the tram according to the performance index (PI) of the difference of total passenger delay of the intersection with or without the tram signal priority. When the tram occupancy is more than the critical value, the more the tram load, the less the total delay at the intersection. The model has been tested through simulation at a complex signalized intersection with heavy traffic demands and a tram line traveling in opposite direction located in Chengdu, China. Further studies will focus on the multi-variable coordinated optimization control policy in considering of correlated intersections group as well as vehicle emission-reduction.

KEYWORDS: Transit Signal Control; Tram Signal Priority; Tram Passenger Occupancy; Total Passenger Delay; VISSIM Simulation; Intersection Efficiency;

1 INTRODUCTION

As a medium-capacity of rail transit, the flexible, environmental and comfortable modern tram is welcomed by a lot of citizens. However, compared with private vehicles and buses, trams have unique driving characteristics, thus the traditional signal control method will have a negative impact on trams’ operational efficiency and safety. According to the driving characteristics of trams and mixed traffic environment, it is an important topic about how to provide signal priority when trams cross the intersections.

The existing researches(Pitu B et al,2004; Zhong Jilin,2014; Zheng Chunhui,2014) are mostly about conventional public traffic priority control at the intersection, the research about tramcars signal control at intersection is commonly focused on the coordinated control between the time when tram reaches the intersection and the phase of the intersection without considering the impacts of auto vehicles on other directions(Wei Chao,2008, Guo Siyuan,2014). This paper analyzed the process from a tram leaving the stop to arriving at the intersection, determining the signal settings that minimize the total person delay based on the passenger occupancy and decreasing the negative impacts on the road vehicles. Then the model is tested on a specific case by VISSIM simulation.
2 LITERATURE REVIEW

Existing transit signal priority strategies fall into two major categories: passive and active priority strategies (KL Head, 1998). Active priority strategies mean that real-time signal control systems using detectors at upstream and/or downstream of an intersection to predict the traffic conditions to adjust the signal settings in time. While passive priorities are developed off-line based on historical data and do not require detecting equipment. At present, most TSP strategies take the active priority control strategy, which mainly includes the absolute priority strategy, relative priority strategy and partly priority strategy.

(1) Absolute Priority Strategy

When the detectors installed at the intersection detect the tram’s arrival, the traffic signal controller will unconditionally interrupt the current signal phase to allow the tram go through the intersection. When the detectors at the exit lane of intersections detect the leaving of the tram, the signal controller will return to the original signal phase. The absolute priority strategy ensures that tramcars can enjoy the right to go through the intersection whenever it arrives.

Although trams can pass the intersection without delay because of the absolute priority strategy, it will bring a serious impact to auto vehicles on the other directions of the intersection. When the road traffic volume is large, the control strategies may lead to traffic congestion at the intersection (Li Sheng, et al., 2005; ZHANG Wei-hua et al., 2005). Therefore the control strategy is often limited to be applied at the intersection with low traffic volume (ZHANG Yu et al., 2017).

(2) Relative Priority Strategy

Similar to the absolute priority strategy, the relative priority control strategy also needs the vehicle detectors at the intersection to detect the location of the tram, so as to determine whether to give the corresponding signal priority. What is different from the absolute priority strategy is that relative strategy makes sure the priority by optimizing phase splits and cycle lengths in time based on saturation levels as well as offsets so that traffic progression improvements can be achieved (Zou Wei, 2015; Luo Cong, 2015; Zhong Jilin, 2014; Chen zhizhou, 2016; Liu Lilong, 2015). Tram detectors’ installation position is related to tramcars’ average speed, intersection clearing time, safe braking distance and other factors.

Specifically, there are three basic ways to adjust the signal timing: green extension, red truncation and phase insertion.

(3) Partly Priority Strategy

The absolute priority and relative priority control strategies try to provide priority to every tram at the intersection. When the tram schedule is arranged intensively and the tramcar cannot arrive at the planned time, it may result in frequent adjustment of the signal phase at the intersection and serious impact on the auto vehicles from all directions (Ma, W., 2010). Therefore, we can take the option to provide priority signal to the tram vehicle, that is, partly priority strategy.

According to the specific circumstances, the selection criteria can be as follows: provide signal priority for tramcar at the peak time instead of off-peak period; balance the tram delay and road traffic delay to determine whether to give a tram signal priority (CAO Jie et al., 2012).

Compared to the relative priority strategy, the partial priority strategy can be widely applied in several situations. The complexity of the strategy also means that the implementation of it needs more additional information to make sure that tramcars enjoy the priority under the right conditions.

3 METHODOLOGY

The tram priority control model based on the passenger occupancy is one kind of the partly priority strategies. In simple terms, it is not scientific enough to determine whether to grant a tram priority right just according to the relationship between the time the tram arrived at the intersection and the signal phase of the intersection without taking the social and economic benefits into account. The passenger occupancy may be small in some lines or places, and if the tram priority right is given, it will decrease the overall efficiency of the intersection and lead to serious delay of other auto vehicles.
In this paper, we took the most common mixed road-rights intersection as the research object. Considering the feasibility of methods in the simulation, this paper focuses on the two major control strategies, including green extension and red truncation. In order to ensure the effectiveness of the active priority control strategy, besides the maximum green light time $G_{max}$ and the minimum green light time $G_{min}$, the following parameters need to be determined.

(1) Unit extension green time, $G_0$

The unit green time $G_0$ is the extensive green time when the subsequent tramcar’s arrival is detected. $G_0$ must ensure that the trolley leaving the detector can pass through the parking line of the intersection without green time loss, and the traffic efficiency of the intersection is improved as far as possible. The value of the unit green time $G_0$ is usually set as the average travel time required for the tram to travel from the detector to the intersection stop line.

(2) Performance Index, $PI$

We choose the difference of total delay at all directions of the intersection with and without the tram signal priority as a performance index ($PI$). If $PI < 0$, it means that the intersection overall delay declines and the tram signal priority should be given; if $PI > 0$, it means that the priority control strategies increase the total delay of intersection and the original signal timing scheme should not be changed.

(3) The tram weight

In view of the limitation of the data source and taking into account the priority of the tram signal priority implementation, combined with other related research, the weight calculation in this paper only takes into account the passenger occupancy.

**No priority strategy**

Assuming that the normal traffic flow follows a continuous average arrival rate based on historical data, the historical data is collected at a certain time interval. In this paper, the average arrival rate is the fixed value, that is, the Poisson arrival rate. When the arrival rate model is continuous linear, the total vehicle delay for each lane in a single signal cycle can be expressed by the delay equation proposed by Gerlough and Huber.

\[
D = \frac{qr^2}{2(1-\frac{q}{s})} \quad (1)
\]

Where:
- $D$: total delay time of single lane [veh * sec];
- $r$: effective red light time [sec];
- $q$: average arrival rate [veh/hr];
- $s$: saturation flow rate [veh/h].

The total delay of the intersection without priority strategies

\[
D_0 = D \times O_t + D \times O_v \times n \quad (2)
\]

Where:
- $D_0$: total delay time of the intersection without priority strategies [sec * person];
- $O_t$: passenger occupancy of the tram [pass/veh];
- $O_v$: passenger occupancy of the vehicles [pass/veh];
- $n$: number of lanes at the intersection.

**Green extension**

The green light extension principle aims to extend the green time such that an arriving tram can proceed through the intersection without stop. Specifically, when the detector located upstream of the intersection detects that the tram arrives at time $t$, if the signal phase is still green at $t + G_0$, no adjustment needs to be made; if not, green extension is considered to provide for the tram.

In order to reduce the impact on other vehicles, the average extensive green time or early broken red time shall not exceed 10% of the cycle length (LU X M, 2005). Green extension control implementation needs to meet the following conditions: the rest green time is not enough to make sure
the tram can pass the stop line without stop; the green time extension of current phrase cannot exceed the maximum green time, that is \( G + G_0 \leq G_{\text{max}} \); after implementation of extension the total delay at the intersection is decreased, which means \( PI < 0 \). If the above conditions are not met, no adjustment will be made. The implementation process of the green extension control measures is shown in Fig.1, where the judgment of the PI requires the calculation of the total delay with and without the priority strategies.

![Flowchart](image)

**Figure 1. Green extension control flow chart**

In order to facilitate the study, the extended green time is compensated by the green time of the next phase after performing the priority strategy. The total delay can be represented by the area of the shaded part of Fig.2.

The delay of social vehicles in the same direction of tram:
\[
D_1 = \frac{1}{2} \times \left( \frac{q_{\text{sns}}}{q_c} \times t_{\text{ext}} + r_1 - t_{\text{ext}} \right) \times \left( \frac{q_{\text{sns}}}{q_c} \times r_1 - q_{\text{sns}} \times t_{\text{ext}} \right)
\]  
(3)

The delay of social vehicles in the crossing direction of tram:
\[
D_2 = \frac{1}{2} \times \left( r_2 + \frac{q_{\text{ml}}}{q_1 - q_{\text{ml}}} \times r_1 \right) \times \left( \frac{q_{\text{ml}}}{q_1 - q_{\text{ml}}} \times r_1 - r_2 \right) - \frac{1}{2} \times \left( \frac{q_{\text{ml}}}{q_1 - q_{\text{ml}}} \times r_2 - t_{\text{ext}} \right) \times \left( \frac{q_{\text{ml}}}{q_1 - q_{\text{ml}}} \times r_2 \right)
\]
\[
= \frac{1}{2} \times \frac{q_{\text{ml}}}{q_1 - q_{\text{ml}}} \times r_1 \times \left( q_1 - q_{\text{ml}} \right) - r_2 \]
\[
D_{\text{el}} = D_1 \times D_0 + D_2 \times D_q \times n
\]
\[
P_{\text{le}} = D_{\text{el}} - D_0
\]
(4)
(5)
(6)

Where:
- \( q_{\text{sns}} \): average arrival rate in the straight lane of the south and north direction
- \( q_3 \): saturation flow rate in the straight lane of the south and north direction
- \( t_{\text{ext}} \): extensive green time [s]
- \( r_1 \): red time in the first phrase [s]
- \( r_2 \): red time in the second phrase [s]
When \( P_{I_t} = 0 \), which means that there is no obvious difference between the total delay with and without tram priority strategy. At this time the tram occupancy can be chosen as a critical value.

**Red truncation**

The principle of red truncation is that if the current tram direction is in the red light phrase and the next one is the tram phrase, then the current phase time is shortened and the tram direction phrase will convert to green light as soon as possible to reduce the tram waiting time. When the detector located upstream of the intersection detects the arrival of the tram at time \( t \), if the direction of the direction signal is red at \( t \) and \( t + G_0 \), the controller will judge whether the next phrase is green. If not, no adjustment needs to make; if so, red truncation is considered to provide for the tram.

Red truncation implementation need to meet the following conditions: when detecting the tram arrives, the current phase after \( G_0 \) is red and the next phase is green for the tram; the current phase has reached the minimum green time \( G_{min} \); \( PI > 0 \). If all the above conditions are met, the red light will be cut off early, otherwise no adjustment will be made. The implementation process of the red truncation control measures is shown in Fig.3, where the judgment of the PI requires the calculation of the total delay with and without the priority strategies.

![Red truncation control flow chart](image)

**Figure 3. Red truncation control flow chart**

In order to facilitate the study, the early broken time is compensated by the green time of the previous phase after performing the priority strategy. The total delay can be represented by the area of the shaded part of Fig.4.

The delay of social vehicles in the same direction of tram:

\[
D_3 = \frac{1}{2} \times q_{sni} (r_1 - r_{tuc})^2
\]

(7)

The delay of social vehicles in the crossing direction of tram:

\[
D_4 = \frac{1}{2} \times r_{tuc}^2 \times q_{ewl} + \frac{1}{2} \times (r_4 + r_1 - r_{tuc})^2 \times q_{ewl} - \frac{1}{2} \times (r_1 - r_{tuc})^2 \times q_l
\]

(8)
\[ D_{t2} = D_3 \times O_v \times n + D_4 \times O_v \times n \] (9)
\[ PL_2 = D_{t2} - D_0 \] (10)

Where:
- \( q_{sens} \): average arrival rate in the straight lane of the east and west direction [veh/s]
- \( r_{red} \): early break red time [s]
- \( r_1 \): red time in the first phrase [s]
- \( r_4 \): red time in the fourth phrase [s]
- \( q_{evr} \): average arrival rate in the left-turn lane of the east and west direction [veh/s]
- \( q_{sat} \): saturation flow rate in the left-turn lane of the East and West direction [veh/s]

When \( PL_2 = 0 \), which means that there is no obvious difference between the total delay with and without tram priority strategy. At this time the tram passenger load can be chosen as the other critical value.

4 APPLICATION OF THE METHODOLOGY

The proposed traffic signal priority strategies were applied to an intersection of Jiaozi and Yizhou Avenue, located in Chengdu, China, like Fig.3. There is one station set up in each road section, which is advisable to take the optimal control at every isolated intersection. According to traffic survey of the intersection and the future traffic flow prediction and the network flow balance, the vehicle flow data of the intersection is shown in table1.

![Figure 5. Intersection plan graph](image)

Table 1. Vehicle flow data of intersection

<table>
<thead>
<tr>
<th>Direction</th>
<th>Volume(veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>north</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>210</td>
</tr>
<tr>
<td>Straight</td>
<td>1419</td>
</tr>
<tr>
<td>Right</td>
<td>309</td>
</tr>
<tr>
<td>south</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>149</td>
</tr>
<tr>
<td>Straight</td>
<td>1149</td>
</tr>
<tr>
<td>Right</td>
<td>67</td>
</tr>
<tr>
<td>east</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>204</td>
</tr>
<tr>
<td>Straight</td>
<td>208</td>
</tr>
<tr>
<td>Right</td>
<td>274</td>
</tr>
</tbody>
</table>
The intersection timing has four phases, the tram and social vehicles of the north and south direction share the same phase. In normal circumstances, the order of the implementation of the phase is first the north and south straight, second the north and south left, third west and east straight, forth west and east left.

According to the Webster’s $C_0 = \frac{1.5L + 5}{1 - F}$, the timing of the intersection is set as follows: the cycle length is 120s, green time of the first phrase is 40s, the second phrase is 20s, and the third phrase is 22s, the forth phrase is 18s.

Using the VISSIM software simulates the intersection: there are eight loops in the cross designed to detect the arrival, stop and leaving of the tram, as the Fig.6. When the tram arrives at the station, according to the train stop time, it will send the departure time to the control machine of the intersection to make the tram pass the intersection.

![Figure 6. Detectors of the tram at the intersection](image)

The extensive green time and the early break red time is set as 12s because:
(1) Speed of trams is 40km/h, and deceleration is $1.5 m/s^2$, so the distance from $P_1$ to stop line is about 70m;
(2) The intersection is 30m wide and the distance from $P_2$ to intersection is 30m.

**RESULT ANALYSES**

Based on the calculation of the $PI$ value in the case of priority and no priority control, a critical value can be obtained. According to function(3)-(10) and known conditions, when $PI = 0$, the passenger occupancy of a tram is 55 persons, so the critical value is 55. Three different values of passenger occupancy are taken to perform simulation operations in VISSIM, and the difference of delays were listed.

1) **Passenger occupancy is 53**

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction</th>
<th>No priority control</th>
<th>priority control (with load of 53 pax/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Per capita delay(s)</td>
<td>Per capita delay(s)</td>
</tr>
<tr>
<td>Vehicles</td>
<td>South</td>
<td>straight 333.18</td>
<td>333.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left 28.51</td>
<td>28.51</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>straight 390.61</td>
<td>390.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left 50.91</td>
<td>50.91</td>
</tr>
</tbody>
</table>
Fig.7 and Fig.8 show the delay of fixed timing control and priority signal control when the tram load is 53 people. Fig.8 shows the total delay at the intersection in the case of fixed timing control and optimized model control. Fig.8 shows the delay comparison between the two different signal control strategies. Since 53 people are below the priority control threshold 55, this two signal control methods are the same and the results have no difference.

(2) passenger occupancy is 56

Table 3. Delays with and without priority control when passenger occupancy is 56

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction</th>
<th>No priority control</th>
<th>Priority control (with load of 56 pax/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Per capita delay(s)</td>
<td>Per capita delay(s)</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>straight</td>
<td>414.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>39.18</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>straight</td>
<td>609.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>206.9</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>straight</td>
<td>271.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>135.5</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>straight</td>
<td>180.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>61.16</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>309.79</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td></td>
<td>257.8</td>
</tr>
<tr>
<td></td>
<td>Total delay ( = Per capita delay * passenger load )</td>
<td>2236.03</td>
<td>1913.53</td>
</tr>
</tbody>
</table>
Fig.9 and Fig.10 show the delay of fixed timing control and priority signal control when the tram load is 56 people. The tram passenger load (56 people) is slightly higher than the priority control critical value (55 people), so when taking the signal priority control strategies in the simulation, the tram delays significantly reduced, so did the total delay in the intersection, as shown in Fig.9. At the same time, the vehicle delay in the north-south import straightway is correspondingly reduced, and except the east-west straight, the other directions of the vehicle delay has increased. Delay of vehicles in the left-turn lane in the north increased the most, which is due to that the second phase of the green time had to reduce 12 seconds to compensate the first phase green extension. The lane saturation rate is the largest compared to other left-turn lanes.

(3) passenger occupancy is 65

Table 4. Delays with and without priority control when passenger occupancy is 65

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction</th>
<th>No priority control</th>
<th>priority control (with load of 65 pax/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Per capita delay(s)</td>
<td>Per capita delay(s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehcles</td>
<td>South</td>
<td>straight</td>
<td>422.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>59.4</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>straight</td>
<td>602.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>200.3</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>straight</td>
<td>263</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>139.2</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>straight</td>
<td>187.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left</td>
<td>85.87</td>
</tr>
<tr>
<td>Trams</td>
<td>South</td>
<td></td>
<td>750.7</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td></td>
<td>463.74</td>
</tr>
<tr>
<td>Total delay ( = Per capita delay * passenger load )</td>
<td>3174.11</td>
<td>2007.66</td>
<td></td>
</tr>
</tbody>
</table>
Fig.11 and Fig.12 show the delay of fixed timing control and priority signal control when the tram load is 56 people. The passenger load (65 people) is higher than the priority control critical value (55 people), therefore when taking the signal priority control strategies in the simulation, the tram delays significantly reduced, so did the total delay in the intersection, as shown in Fig.11.

5 FINDINGS AND CONCLUSIONS

A real-time traffic responsive signal control strategy of TSP has been developed in this paper, and it was tested at an isolated intersection under varying traffic conditions in simulation according to a real testbed in Chengdu, China. The findings are as the following.

The TSP method assigns priority on account of tram occupancy at an intersection in a more equitable way. The optimized signal control strategy is much fairer to the travelers, for total passenger delay instead of vehicle or tram delay used as the PI in the model.

According to the simulation and experimental data analysis, the tram signal strategy maintains the original policy when the tram passenger number is less than the threshold. While the tram should be given priority control strategy, such as extending the green time or early breaking red time, when the tram passenger number is more than the critical value.

At the tram passenger number threshold, the total delay of the intersection will decline, the more the passenger load, the less the total passenger delays at the intersection. It is inevitable that the passenger delay in the conflicting phase will increase, but the increase is much less than the reduction of the tram passenger delays.

There are also some limits of this paper. Firstly, the threshold of the passenger number of the tram is relatively simple without considering about varying road traffic conditions. Secondly, a multi-variable coordinated optimization control strategies in considering of both correlated intersections and vehicle emission-reduction will be further studied.

6 ACKNOWLEDGEMENTS

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REFERENCE


