A Phase-by-phase Traffic Control Policy at Isolated Intersection Based on Cooperative Vehicle-Infrastructure System

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Abstract

The recently developed Cooperative Vehicle Infrastructure System (CVIS) enables the monitoring of high resolution vehicle probe data. In this paper, a phase-by-phase control policy was developed, which can optimize split and cycle under the concept of every vehicle on the road communicating to the controller at an isolated signalized intersection. The green time of each phase was determined at the beginning of itself subject to the corresponding approaches’ probe data. The proposed policy was compared with the pre-timed control policy by simulation experiments, and the results shown that our policy is better in terms of average queue length and total time spent by all the vehicles in the network (TTS).

Introduction

Signal control is an effective method to reduce the traffic congestion in modern society. But it is required to adapt to the dynamic traffic demand at the intersection. To account for the changing traffic situations, the theories of model-based predictive control, actuated control and adaptive control have been developed in the past few decades (B. Wu & Y. Li, 2009, D. Fajardo, 2011). Due to the limitation of the traditional traffic information collection, the model-based predictive traffic control cannot respond to the variation of traffic flow efficiently. Actuated control was found superior in the low-flow situation with a high variation, but cannot perform well at saturated signalized intersection. SCOOT (P. Hunt, et al., 1988) and SCATS (P.R. Lowrie, 1982) as the examples of adaptive control systems enabled controlling the signal on-line based on loop detectors. However, the loop data from one or two sections cannot describe the dynamic nature of traffic on motorways.

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An effective timely solution for traffic control relies on immediate and high-resolution data of the traffic arrivals, which become increasingly available in recent years. For example, Connected-Vehicle (2012) in the USA, Cooperative Vehicle-Infrastructure Systems (CVIS) (2011) in the Europe and Vehicle Information and Communication System (VICS) (2010) in Japan have been launched and partly completed. In a previous publication (X. G. Yang, et al., 2012), a proof of the concept for a prototype of Tongji Cooperative Vehicle Infrastructure System (TJ-CVIS) developed at the University of Tongji was presented, which provides vehicle a capability of communicating with other vehicles and the infrastructure. By adopting sensor technologies and standardized communication protocol, the vehicle probe data such as position, speed and pre-planned routes can be automatically collected with high frequency and accuracy in TJ-CVIS. Based on TJ-CVIS, we are aiming at responding the traffic demand timely, minimizing the green losses and optimizing split and cycle phase by phase subject to the vehicle probe data.

2. Phase-by-phase Traffic Control Policy

2.1. Primary Analysis and Strategies

Two types of inputs are applied in traffic control corresponding to different control modes. The first type, for the fix-time control, is the statistic data based on historical observations of traffic volume and off-line calculations. It is insufficient to obtain the variation of traffic flow in this situation. The second type, for the actuated control and adaptive control, is the real-time traffic volume collected by loop detectors. Most on-line optimization controls assume that, in a very short time, the traffic flow will not change or vary with the trend inferred from the data of previous one or more cycles. This assumption performs well in describing the feature (e.g., expected value of traffic volume or queue length) of traffic arrivals at the time scale that covers several cycles. But when we check the actual value (e.g., queue length) cycle by cycle, there is still a slight variation even in the continuous traffic flow. As a result, traffic signal timings are not reviewed and updated as often as they should be. The example shown in Fig. 1 indicates the green losses in a pre-timed green phase. To retrieve the green loss or to provide non-stop passing (e.g. the last vehicle in Fig. 1), some traditional on-line retiming control policies adjust green time during green phase based on loop detector, but the uncertain green time leads to several problems when determining the pedestrian crossing signal or showing the signal countdown to the drivers.

![Fig. 1 Green-Loss Phenomena.](image)
green time can be determined at the beginning of each phase, which can remain the signal countdown and further apply the countdown to speed adaption in the future CVIS environment.

2.2. Description of TJ-CVIS data

TJ-CVIS is constructed at Tongji University to develop cooperative vehicle infrastructure scenarios and achieve the goals of safety, mobility and environmental responsibility. Communications between On Board Units (OBU) and Road Side Units (RSU) utilize the Dedicated Short Range Communications (DSRC). In TJ-CVIS, the message format of vehicle probe data has already been specified, which mainly includes following contents (7):
- GPS Data (longitude, latitude, altitude);
- GPS Correction Message;
- Vehicle ID;
- Traveling Speed;
- Current Date and Time;
- Additional Message.

2.3. Derivation of the Control Policy

When developing the control policy, we hypothesize the intersection is isolated so that the assumption of continuously approaching flow with free-flow speed is reasonable. It is also assumed that every vehicle will send data from the probe to the controller in the communication range with high frequency (typically higher than once per second), and the probe data is specified as the TJ-CVIS data format introduced above. Fig. 2 indicates the schematic representation of the phase-by-phase control policy.

In Step I of the control shown in Fig. 2, a pre-planned timing schedule including cycle, phase order and split is determined on the basis of average arriving volume. For each phase, the pre-planned green time is shown as $T_P$ in Fig. 3. To cope with pedestrian crossing, a minimal green time is set shown as $T_{min}$ in Fig. 3 (a) and Fig. 3(b). And a maximal green time ($T_{max}$) for each phase is also set to avoid overlarge delay. The algorithm for calculating $T_P$, $T_{min}$ and $T_{max}$ can be found in the traditional pre-planned control policies (B. Wu & Y. Li, 2009).

The main task of Step II in Fig. 2 is to find out the “Control Tail” in the red light directions. Fig. 3 indicates the two types of “Control Tail”. $Q_{end}$ stands for the stopped queue tail of the disadvantaged approaches at the moment of $t_R$, and $\text{Veh}_i$ stands for the arriving vehicle that has not yet joined the stopped queue. In the first type of “Control Tail”, shown in Fig. 3 (a), the expected clear time $T_Q$ for $Q_{end}$ is shorter than $T_P$. Then add the interval...
of arriving vehicles to $T_Q$ as $T_{ct}$ until $T_{ct} > T_Y$. Hence $Veh_{i+1}$ in Fig. 3(a) is regarded as the “Control Tail”. For the second type, shown in Fig. 3 (b), if $T_Q$ is longer than $T_P$, then the last vehicle in the stopped queue will be regarded as the “Control Tail”. The algorithm for calculating $T_Q$ will be introduced in Part 3.

![Fig. 3 Schematic representation of “control tail” recognition.](image)

(a) “Control tail” recognition Type 1  
(b) “Control tail” recognition Type 2

![Fig. 4 Schematic representation of green time determining.](image)

The logic process of Step III in Fig. 2 is described in Fig. 4. When the signal control is actually running, the green time $T_Q$ for each phase should be determined at the moment of red end ($t_R$ in Fig. 5) subject to the “Control Tail”. In Fig. 5, $t_{G1}$, $t_{G2}$, $t_{G3}$ and $t_{G4}$ are the determined green end of the corresponding situation.
2.4. Algorithm for Implementation of the Control Policy

Algorithm for estimating the clear time of queue and extracting the “Control Tail” is developed in this part. Before presenting the equations, definition of the variables employed is necessary. To facilitate the presentation, all definitions and notations used hereafter are summarized below.

- $L_Q$ = the queue length (m)
- $V_Q$ = the estimated queue tail travel speed (m/s)
- $T_Q$ = the estimated queue clear time (s)
- $d_i$ = the distance from stop line to the approaching vehicle $i$ (m), ascending order, not including the queue; $i=1, 2, 3...$
- $v_i$ = the speed of approaching vehicle $i$ (m/s), $i=1, 2, 3...$
- $v_i'$ = the expected speed of vehicle $i$ when passing the stop line(m/s), $i=1, 2, 3...$
- $l_i$ = the length of road occupied by vehicle $i$ (m), $i=1, 2, 3...$
- $T_{Gi}$ = the candidate green time calculated by vehicle $i$ (s), $i=1, 2, 3...$
- $T_G$ = the final determined green time (s)

$L_Q$ is easy to find from the vehicle probe data. The relationship between $L_Q$ and $V_Q$ should be determined by the specific traffic condition. We will introduce an example of the relationship in Section III. The algorithm for determining the green time is shown by following equations:

$$T_Q = \frac{L_Q}{V_Q(L_Q)}$$  \hspace{1cm} (1)

If $T_Q > T_P$, $T_G$ should be extended subject to $t_{G3}$ or $t_{G4}$ in Fig. 5. If $T_Q < T_P$, $T_G$ should calculated iteratively based on the approaching vehicle probe data, hence the result of green end should be determined subject to $t_{G1}$ or $t_{G2}$ in Fig. 5 as follows.

The equations of the primary calculation of $T_{Gi}$ are:

$$v_i' = \begin{cases} 
  v_i, & \text{if } \left( \frac{d_i}{v_i} > T_Q \right) \\
  v_i' = \frac{d_i}{v_i} \left( T_Q \right), & \text{if } \left( \frac{d_i}{v_i} < T_Q \right) 
\end{cases} \hspace{1cm} (i = 1)$$  \hspace{1cm} (2)
The equations of the iterative calculation (with an upper boundary: \( T_P \)) of \( T_{Gi} \) are:

\[
T_{Gi} = \begin{cases} 
\frac{d_i}{v_i}, & \text{if } \left( \frac{d_i}{v_i} > T_{Qi} \right) \\
\frac{l_i}{v_i^i} + T_{Qi}, & \text{if } \left( \frac{d_i}{v_i} < T_{Qi} \right) 
\end{cases} \quad (i = 1)
\]

\[
T_{Gi} = \begin{cases} 
v_i^i, & \text{if } \left( \frac{d_i}{v_i} > T_{gi-1} \right) \\
v_i, & \text{if } \left( \frac{d_i}{v_i} < T_{gi-1} \right) 
\end{cases} \quad (i = 2, 3, \ldots)
\]

Finally, when \( T_{Gi} > T_P \)

\[
T_G = T_{gi-1} \quad (6)
\]

Fig. 6 indicates an example of the status of disadvantaged approaches at the moment of red end, and the determined green end \( t_G \).

### 3. Simulation Examples

Since the CVIS technology is not widely available in the real traffic environment, in this section, we illustrated the performance of the control policy by simulating against the pre-timed control policy in the condition of different saturation. Since the capability of reliable communication and position is essential to
realize the phase-by-phase control policy, basic characteristics of TJ-CVIS were introduced in this section. It includes communication performance and position performance, which are partly applied in the simulation. Finally, the performance was evaluated by average queue length and total time spent by all vehicles in the network (TTS). In addition, the driving-related parameters in simulation are extracted from the data of field test by TJ-CVIS (X. G. Yang, et al., 2012).

3.1. Basic Characteristics of TJ-CVIS

Communication performance

In a vehicle to infrastructure communication scenario, real time exchange is necessary since high-speed vehicles can travel large distances in a short time. Vehicle probe data monitoring requires a DSRC with very low latency (typically less than 100ms), packet loss rate (PLR) and packet error rate (PER) (typically less than 5%). Table 1 illustrates the performance of DSRC devices we used in TJ-CVIS in both the condition of campus environment (with no traffic) and a four-lane highway on Cao’an Road (a normal traffic environment).

<table>
<thead>
<tr>
<th>Traffic Condition</th>
<th>Max. range (m)</th>
<th>Average PER (%)</th>
<th>Average PLR (%)</th>
<th>Average Latency (ms)</th>
<th>Available Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Traffic</td>
<td>OBU-RSU</td>
<td>1203</td>
<td>0.25</td>
<td>0.13</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>OBU-OBU</td>
<td>895</td>
<td>0.56</td>
<td>0.32</td>
<td>2</td>
</tr>
<tr>
<td>Normal Traffic</td>
<td>OBU RSU</td>
<td>1016</td>
<td>1.41</td>
<td>0.83</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>OBU-OBU</td>
<td>804</td>
<td>0.95</td>
<td>0.98</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 1 shows that communication in TJ-CVIS meets the basic requirements. It’s also shown to support low latency and high reliability. The features discussed above indicate that the communication is qualified to be applied in the vehicle probe data monitoring (CONSORTIUM CVSC, 2005).

Positioning Performance

Another field test was conducted to test the dynamic positioning accuracy. Fig. 7 (b) (d) shows the test results about DGPS, which indicates that DGPS in TJ-CVIS can achieve real time sub-meter positioning accuracy with a probability of 98%. Since we collect the speed through vehicle’s Control Area Network (CAN) interface that provides an accuracy of 0.1m/s, we did not analyze the drift speed of DGPS.

![New Energy Automotive Engineering Center, Tongji University](image1)

(a) Test Site for Stationary Accuracy.

![Histogram of DGPS distance error](image2)

(b) Stationary Accuracy of DGPS.
The field test results of communication performance and position performance indicate that TJ-CVIS can provide a lane-level position service for the vehicle and control system with high reliability of message transfer, which enables the feasibility of phase-by-phase control. Moreover, the characteristic of position error is randomly generated in the simulation procedure.

3.2. Simulation Parameters

In the simulation procedure, we considered an isolated intersection with four inbounds, two lanes in each. It is shown in Fig. 8. For each street, a vehicle source is assumed to be located 400 m upstream and randomly generated as a Poisson process. The traffic volume and pre-planned timing schedule are shown in Table 2.

![Simulation scenario](image)

Table 2 Simulation Inputs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario (1)</th>
<th>Scenario (2)</th>
<th>Scenario (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume$_{1,4}$(pch/h)</td>
<td>750</td>
<td>840</td>
<td>945</td>
</tr>
<tr>
<td>Volume$_{3,4}$(pch/h)</td>
<td>500</td>
<td>560</td>
<td>630</td>
</tr>
<tr>
<td>$T_{p1,2}$(s)</td>
<td>24</td>
<td>33</td>
<td>48</td>
</tr>
<tr>
<td>$T_{p3,4}$(s)</td>
<td>17</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>$T_{w1,2}$(s)</td>
<td>36</td>
<td>42</td>
<td>55</td>
</tr>
</tbody>
</table>
To simplify the acceleration model of the queue, the queue tail travel speed $V_Q$ is applied here. Fig. 9 describes the relationship between $L_Q$ and $V_Q$ on the basis of vehicle probe data we collected from TJ-CVIS in real-traffic field test. “Speed” in Fig. 9 shows the travel speed of the queue tail vehicle from starting up to getting through the stop line. In the simulation procedure, we use equation (5) to determine $V_Q$ subject to different $L_Q$:

$$V_Q = 1.0052 \ln(L_Q) + 0.6131$$  \hspace{1cm} (7)

A computer program implementing the previous developed algorithm was prepared to test the phase-by-phase control policy (PPC) against pre-timed control policy (PTC). Since the expected traffic volume is already known in Table 2, the time schedule of PTC is fixed as $I_P$ for different saturations shown in Table 2. In addition, the simulation procedure of PPC and PTC is operated simultaneously with the same vehicle source generation process.

### 3.3. Simulation Evaluation Results

Table 3 indicates the comparison of the results of a 90-minutes simulation for each scenario.

<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>Scenario(1)</th>
<th>Scenario(2)</th>
<th>Scenario(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PPC(%)</td>
<td>PTC(%)</td>
<td>PPC(%)</td>
</tr>
<tr>
<td>Average travel time (s)</td>
<td>49.41</td>
<td>50.12</td>
<td>51.63</td>
</tr>
<tr>
<td>Average stopping time (s)</td>
<td>5.41</td>
<td>6.08</td>
<td>7.57</td>
</tr>
<tr>
<td>Average queue length (pce)</td>
<td>4.31</td>
<td>4.72</td>
<td>7.23</td>
</tr>
<tr>
<td>Total traffic volume (pceu)</td>
<td>3403</td>
<td>3401</td>
<td>4083</td>
</tr>
<tr>
<td>TTS(s)</td>
<td>168142</td>
<td>170458</td>
<td>210805</td>
</tr>
</tbody>
</table>

In the 90-minutes simulation, average travel time of PPC and PTC both increased with the increasing saturation. The same variation goes to average stopping time and average queue length. The differences of the evaluation index between PPC and PTC also increased. Through the results, the proposed policy is superior in non-saturated conditions.

### 4. Conclusions and Future Work

This paper introduced a phase-by-phase control policy optimizing split and cycle under the concept of every vehicle on the road communicating to the controller at an isolated signalized intersection. The research analyzed the drawbacks of the traditional pre-timed and retiming control policies, and then designed the logic method to
respond the slight variation of approaching traffic by cutting or extending the green time based on the vehicle probe data. The simulation results concluded that:

1. The proposed control policy can reveal current traffic needs in the non-saturated isolated intersection, and subsequently reduce the green losses to improve traffic efficiency;
2. The vehicle probe data in TJ-CVIS are applicable for the real-time optimizing control, especially for the control policy presented here.

In the near future, when new vehicles are all equipped with advanced CVIS module, the more flexible and intelligent control policy based on high-resolution vehicle probe data can be widely applied. Although the proposed policy is superior to pre-timed control, at least for the simulation scenarios illustrated above, it also has certain limitations, such as its performance in the situations of turning traffic and multi-intersections, which deserve further discussion.

Acknowledgements

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References

B. Wu, Y. Li (2009), Traffic Management and Control, China Communications Press.