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A Study of Applying Eco-Driving Speed Advisory System on Transit Signal Priority

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Abstract

Transit Signal Priority (TSP) has long been seen as a cost-effective way to reduce bus delays at intersections. With Connected Vehicle (CV) technology, speed advisory system guides buses to pass intersections in an energy-saving way. The integration of TSP and speed advisory may reduce bus delays and enhance energy consumption performances. This study proposed a system of integrating eco-driving speed advisory on TSP under CV environment. A TSP strategy based on intersections passing probability is designed. In addition to signal priority, this study designed and implemented an eco-driving speed advisory algorithm. A real electric bus route in Tainan City, Taiwan is used for the case study. Intersection layout and traffic related parameters are established in microscopic traffic simulation software SUMO (Simulation of Urban Mobility) to verify the effectiveness of the proposed model. The results provide an insight of how cooperation between signals and vehicles can enhance performances of energy consumption and signal-incurred traffic delays.

1 Introduction

In metropolitan cities, transit vehicles serve as a type of transportation means to move a large number of passengers efficiently. Increasing transit system ridership has also been viewed as one of the potentially effective ways to diminish traffic congestion. Transit Signal Priority (TSP) is a collection of techniques that provide transit vehicles moving through signalized intersections smoothly. A TSP system has been seen as a cost-effective method to improve regional mobility. With the adjustment of signal settings, TSP not only reduce the delay of transit buses but enhance operation reliability (Smith et al., 2005).

In the past decades, many studies have proposed various TSP strategies. In general, they can be classified into two types: passive control or active control. Based on off-line information of bus routes and ridership patterns, passive TSP is a fixed time signal plan that favors bus operation. The objective functions of such system include maximizing the progression band or minimizing total bus delays. Most

Passive TSP strategies are developed for high bus volume systems such as Bus Rapid Transit (BRT) since frequent TSP requests may have negative impacts on side street traffic and negate the benefits of priority control (Ma et al., 2007, Cheng et al., 2015, Kim et al., 2019). Active TSP (ATSP) requires the placement of detectors to track bus real-time location information and calculates the adjustment of traffic signal plans accordingly. ATSP control can be further divided into two categories: unconditional and conditional. Unconditional ATSP conducts green time extension or red time truncation without any condition (Lee et al., 2005). Despite the effectiveness of the unconditional ATSP on improving bus efficiency, it may disturb original signal plan and deteriorates non-prioritized traffic dramatically if limitations on the amount of priority time are not considered. Thus, some studies deal with the problems by limiting activation times of TSP upon frequent request or buses ahead of schedule condition (Dion et al., 2002, Lee et al., 2005).

It is noted that two-way communications between buses and Road Side Units (RSUs) installed on traffic signals are established under Connected Vehicle (CV) environment. In such communication On-Board Units (OBUs) can give bus driver speed guidance to coordinate traffic signal plan. Deployment of TSP system with CV technology in BRT system is presented in a previous study (Wang et al., 2014). However, the study only provides signal count down information for drivers. To decrease the times of priority requests, a study that integrates Green Light Optimized Speed Advisory (GLOSA) into TSP strategy is proposed (Seredynski et al., 2019). The performance results indicate that GLOSA can partially replaces TSP under certain traffic conditions. However, the study assumes buses riding on exclusive lane, the effects of mixed traffic circumstance remain unknown.

With the advent of electric vehicles, electric buses have gradually been adopted due to the advantages of low noise and air pollution. However, in most cases, electric transit vehicles can charge electricity only when returning to their terminals. It would be a problem if the vehicles run out of energy during operation. Therefore, approaches to enhance the efficiency of electric energy consumption are important. Two previous studies compare the efficiency of electric consumption of two electric bus routes (Institute of Transportation, 2014; Institute of Transportation, 2016). One is riding on expressway and the other is on general road. The results show bus riding efficiency on expressway is better than on general road due to less traffic disturbances from traffic signals. In general road, traffic signals are key control facilities which can dramatically affect the efficiency of traffic operation. This study proposes a Cooperative ATSP method (ATSP-C) which contains ATSP and eco-driving speed guidance. The objective is to improve electric transit vehicles' riding efficiency and energy consumption. This study formulates TSP and eco-driving speed advisory model respectively. A microscopic traffic simulation software Simulation of Urban Mobility (SUMO) is applied to verify the effectiveness of the proposed models.

This study is organized as follows: The assumptions and the key features of ATSP-C in the next section, followed by description of ATSP-C flow chart and model formulation. The simulation platform, simulation case study and evaluation results are then presented. Finally, conclusions and suggestions are discussed in the last section.

2 Methodology

2.1 Control framework of ATSP-C

The flow chart of ATSP-C is presented in Figure 1. The whole control framework contains three components. After the system detects buses are approaching, as shown in component I, the RSU computes intersection passing probability according to predicted bus arrival time. If the probability is less than the threshold, TSP calculation will be activated. Finally, the signal timing information will send to OBUs to perform eco-driving speed advisory computation in component II. Both RSU and OBU perform once for one bus. OBU gets latest signal timing information to perform eco-driving speed calculation.

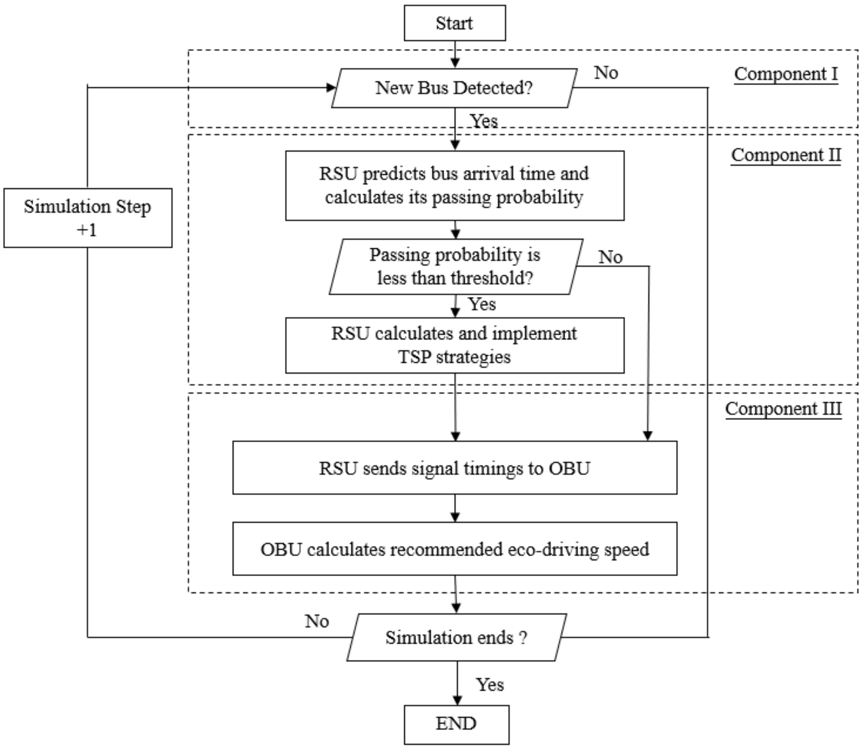


Figure 1 The flowchart of ATSP-C

2.2 Assumptions

For model simplicity, the following assumptions are made in this study:
1. All transit vehicles are installed with On-Board Units (OBUs).
2. All traffic signals are installed with Road-Side Units (RSUs).
3. Overtaking and lane-changing behavior are not taken into consideration.
4. Bus drivers fully comply with the advisory driving speed guidance.
5. One bus request can be served per cycle on a first-come, first-served basis.
6. The effects of dwell times at bus stop are not taken into consideration.

2.3 Calculation of transit vehicle's passing probability at an intersection

The make TSP control and eco-driving advisory effective, precise prediction of buses arrivals at intersections is essential. Since transit vehicles run under mixed traffic circumstance, the prediction results may be biased if a simple calculation of arrival time (i.e. distance to the intersection divided by bus current speed) is adopted. To take the uncertainty nature of arrival time into consideration, this study assumes the arrival time of bus b at intersection i is a random variable $T_{i,b}^{B}$, which follows a normal distribution with standard error σ_i.

This idea is demonstrated in Figure 2. At time t_0, there is a bus b with a speed v_b riding towards intersection i. We assume the bus will maintain its speed to the stop bar, thus the mean value $E(T_{i,b}^{B})$ is calculated by the distance to intersection i (L_i) divided by bus current speed (v_b). The standard error (σ_i) is a function related with bus current distance to stop bar. Hence, we can calculate passing probability with cumulative density function of normal distribution by integrating green duration.

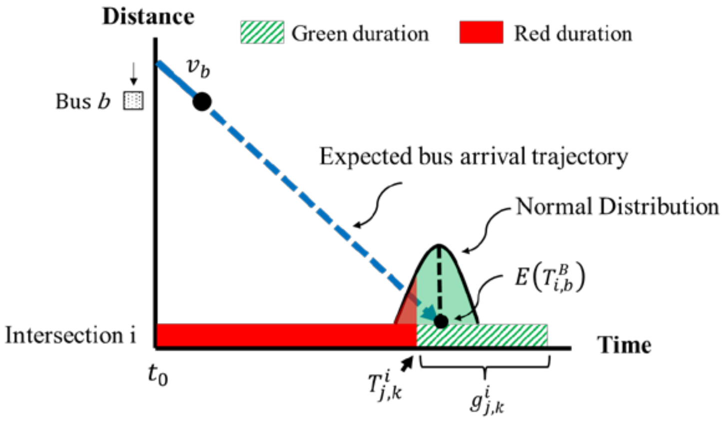


Figure 2 Concept of bus arrival formulation

2.4 TSP strategy

As shown in Figure 3, a rule-based TSP strategy is proposed. According to the arrival time range, the arrival of each bus is classified into four cases. For transit vehicles that arrives before start time of green phase, they are classified as case 1. Case 2 and 3 are buses that earliest and latest arrival time are in different phases. Case 4 refers to those arrive after green phase. The planning horizon is two cycle length.

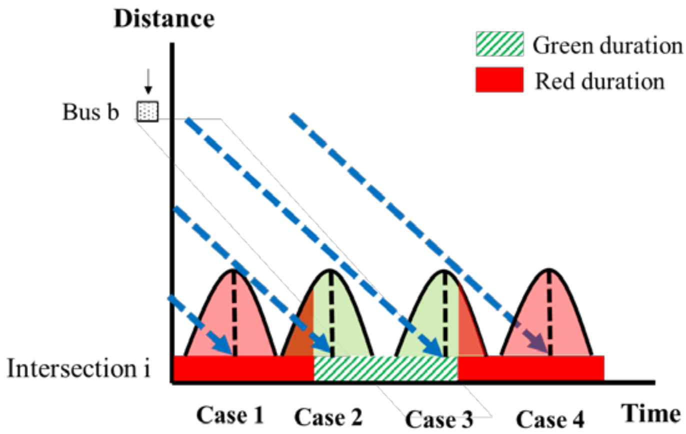


Figure 3 Cases of TSP strategies

As shown in Figure 4, two phase adjustment technique are used: green extension of intersection i, phase j and cycle k ($y^{I}_{\mathrm{i,j,k}}$) and red truncation of intersection i, phase j and cycle k ($y^{II}_{\mathrm{i,j,k}}$). For case 1 and 2, the TSP adopts red truncation. For case 3 and 4, both green extension and red truncation are used.

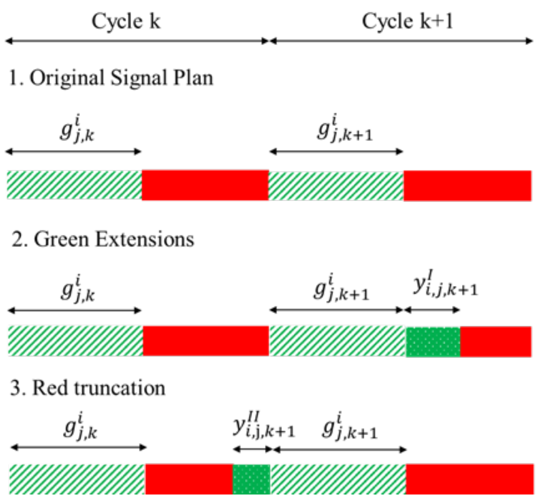


Figure 4 Types of phase duration adjustment

The process of determining priority values is listed as follows:
Step 1: The system produces arrival time range and identify the case.
Step 2: Initialize $y^{II}_{\mathrm{i,j,k}}$ and $y^{I}_{\mathrm{i,j,k}}$ as 0.
Step 3: Increment $y^{II}_{\mathrm{i,j,k}}$ or/and $y^{I}_{\mathrm{i,j,k}}$.
Step 4: Compute passing probability.
Step 5: Repeat **Step 3** to **Step 4** ***until*** one of the following conditions is fulfilled: (1) Passing probability is larger than a threshold or (2) priority value equals maximum priority value (y_{max}).

Step 6: If priority value equals maximum priority value (y_{max}) but passing probability does not fulfill the threshold, minimization red duration strategy, which truncates red duration y_{max} seconds, is adopted.

2.5 Eco-driving speed advisory

Eco-driving speed advisory aims to provide a driving speed advisory that minimizes acceleration and deceleration. The logic is formulated as a decision tree demonstrated in Figure 5. At the beginning, the OBU calculates passing probability based on signal timing plan and expected arrival time. If the probability is larger than threshold, then the system will recommend maintaining its current speed (V_b^c). Otherwise, it will compute eco-driving speed. If any solution exists, it will provide recommended eco-driving speed (V_b^r), or it will give a continuous slow down speed (V_b^{fg}).

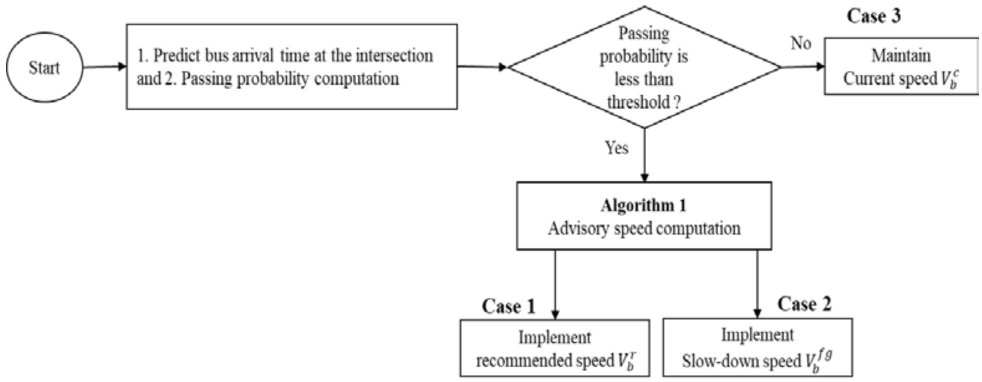


Figure 5 Flow chart of Eco-driving speed advisory

The detail of the algorithm is show in Algorithm 1. The goal is to find a speed v which fulfills the threshold of passing probability. Line 1 is initialization of variables. Note that maximum passing probability is initialized as passing probability threshold. Line 2 to line 3 is the process of enumerating speed variable for speed list (i.e. $[0.7v_{lim}, 1.1v_{lim}]$). The lower and upper bound of speed list are set as 70% and 110% multiple road speed limit (v_{lim}). Through line 4 to 6, the passing probability of each speed is computed and replace maximum one if the value is larger than it. In line 7, the recommended eco-driving speed (V_b^r) is returned.

Algorithm 1: Finding an advisory speed
Input: bus order (b), bus speed (v_b), intersection (i), distance to intersection i (L_i), signal plan of intersection i $(SignalPlan[i])$ **Output:** advisory driving speed (V_b^r)
1. Initialization: set passProb = 0, $OptimalSpeed = v_b$, Max_PassProb = $PassProbThreshold$ 2. **For** $v \in [0.7v_{lim}, 1.1v_{lim}]$ **do** : 3. passProb = **Passing_Probability_Computation(input:** $\boldsymbol{b}$,$\boldsymbol{v_b}$,$\boldsymbol{L_i}$, $\boldsymbol{SignalPlan[i]}$**)** 4. **If** passProb > Max_PassProb **then**: 5. Max_PassProb = passProb 6. $V_b^r = v$ 7. **Return** V_b^r

If Algorithm 1 fails to find a feasible eco-speed, the system will implement "slow-down speed" strategy (Case 2 in Figure 5). With bus initial speed (v_b), slow-down speed ($V_{b,t}^{fg}$) at time t can be calculated through equation 1 to 3.

$$L_i = v_b t + \frac{1}{2} a t^2 \tag{1}$$

$$a = \frac{(L_i - V_0 T) \cdot 2}{T^2} \tag{2}$$

$$V_{b,t}^{fg} = V_{b,t-1}^{fg} + a \tag{3}$$

3 Experiment design

3.1 Simulation platform and settings

This study chooses Simulation of Urban Mobility (SUMO) as simulation platform (Lopez et al., 2018). A real intersection located in Tainan City, Taiwan is adopted. It's a four-leg intersection with left-turn bay (Figure 6). The signal is four phases including a protected left-turn phase. The phase order and respective direction is illustrated in Table 2. There are two electric bus routes riding through the intersection: Bus 1 and Bus 2. The headway of Bus 1 is 900 seconds, and Bus 2 is 1200 seconds.

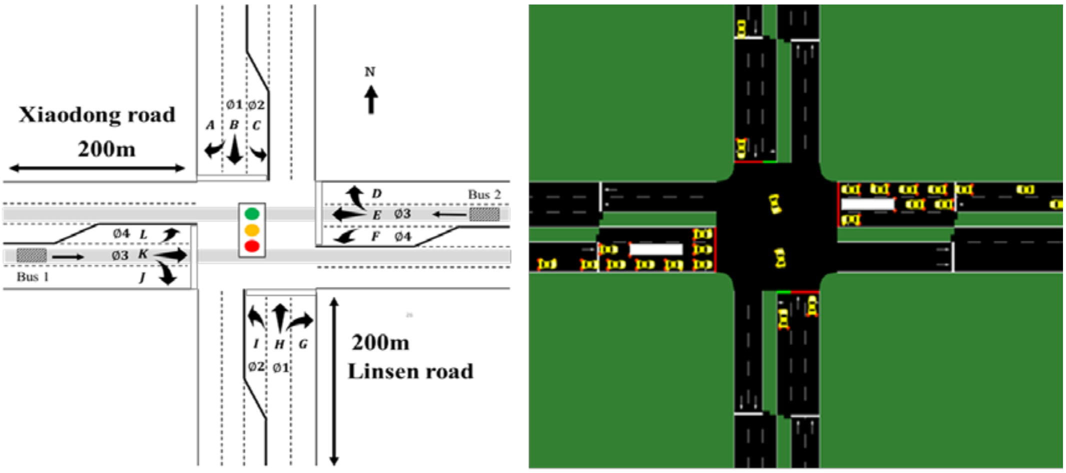


Figure 6 Layout of the intersection

The traffic volumes (veh/hr) are listed in Table 1. To test the effectiveness under different traffic congestion level, two different V/C ratio (i.e. 0.5 V/C ratio and 0.9 V/C ratio) are designed. Background signal timing settings are listed in Table 2. The green duration is 34, 11, 43, 12 seconds with respect to phase 1, 2, 3 and 4. The yellow and all-red time are 3 and 2 seconds.

Table 1 Traffic volume of each direction

Movement (veh/hr)	A	B	C	D	E	F
V/C = 0.9	45	543	83	80	1147	131
V/C = 0.5	23	272	42	40	574	66
Movement (veh/hr)	*G*	*H*	*I*	J	K	L
V/C = 0.9	82	530	161	129	814	55
V/C = 0.5	41	265	81	65	407	28

Table 2 Signal timing parameters

Phase	Ø1	Ø2	Ø3	Ø4
Movement	A, B, H, G	C, I	D, E, K, J	L, F
Green (sec)	34	11	43	12
Yellow (sec)	3	3	3	3
All-red (sec)	2	2	2	2
Cycle length (sec)	120			

The parameters of the electric buses are listed in Table 3. SUMO supports electric vehicle settings and energy consumption model. With these parameters set as input, this study retrieves corresponding energy consumption results.

Table 3 Parameters of electric transit vehicles

Parameter	Value
Length (m)	12
Width (m)	2.55
Height (m)	3.5
empty weight (kg)	11800
Full-loaded weight (kg)	16000
Average power (Kw)	206
Nominal electric capacity (Kwh)	200

3.2 Experiment scenarios

Two experiments are designed in this study:

1. Activation of TSP and eco-driving speed advisory.
2. Sensitivity test of maximum priority time.

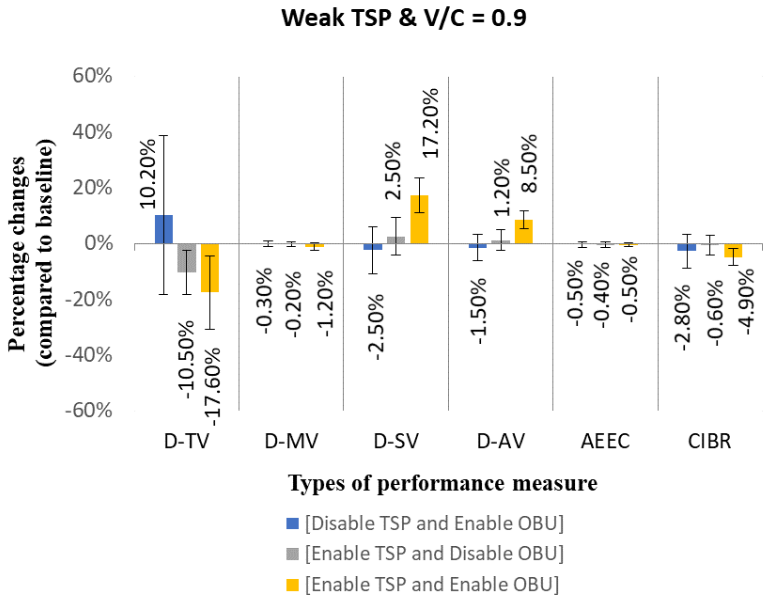
The purpose of the first experiment is to evaluate the results of various combination of activation on TSP and eco-driving speed advisory. Here we design four scenarios: Background signal plan (Disable TSP and Disable OBU), ATSP-C with only eco-driving speed advisory (Disable TSP and Enable OBU), ATSP-C with only TSP (Enable TSP and Disable OBU), ATSP-C with both TSP and OBU (Enable TSP and Enable OBU). "Background signal plan" scenario serves as the baseline. The second experiment is the sensitivity test of maximum priority time. The study designed two cases: Weak TSP and Strong TSP (i.e. weak and strong maximum priority time) to evaluate the effects. The maximum priority time of Weak TSP is set as 10 seconds, and Strong TSP is set as 20 seconds. Both experiments are tested under two V/C ratios: 0.9 and 0.5. The simulation time of each scenario is 2 hour and 5 times run, excluding 5 minutes warm-up time. A random seed is set as 8.

3.3 Performance measures

Four intersection-based performance measures are introduced: average Delay of Transit Vehicles (D-TV), average Delay of Main-street Vehicle (D-MV), average Delay of Side-street vehicle (D-SV) and average Delay of All Vehicle (D-AV). These measures aim to evaluate the operation efficiency of the intersection. Two measures are designed for bus riding: Average Electric Energy Consumption (AEEC) and Comfort Index of Bus Riding (CIBR). AEEC is the average electric energy usage of each transit vehicle. CIBR is calculated by averaging absolute acceleration and deceleration rate of each bus, which is used for indicating the level of comfort.

4 Results analysis

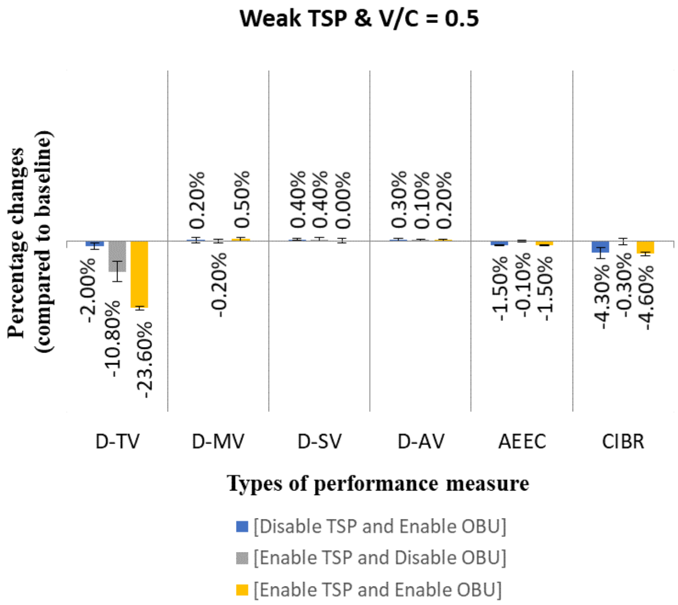
Figure 7 illustrates the results of weak TSP experiment under 0.9 V/C ratio. Compared to baseline, the delays of transit vehicles (D-TV) decrease 10.05% in "Enable TSP and Disable OBU" and 17.6% in "Enable TSP and Enable OBU" under 0.9 v/c ratio, both are statically significant at p-value < 0.5. An increase in D-TV (10.2%) is presented in "Disable TSP and Enable OBU" scenario. One possible reason for the result is that effects of queueing vehicle is not involved in the speed advisory algorithm, OBU may give less precise speed advice under near-saturated traffic and results in the increase in D-TV. Also, the increase is not statically significant at 0.5 p-value.



Note: Error bars show 95% confidence intervals

Figure 7 Simulation results - Weak TSP with 0.9 v/c ratio

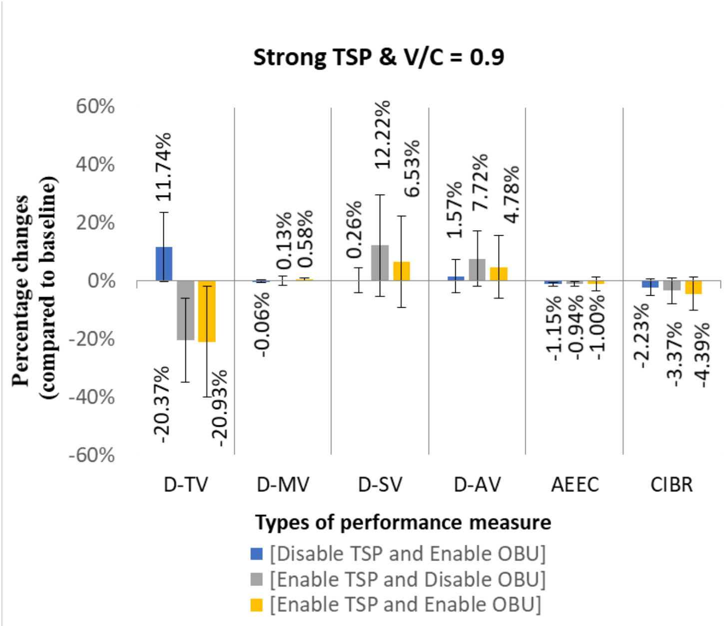
For 0.5 v/c ratio case shown in Figure 8, significant decreases in D-TV are presented in "Disable TSP and Enable OBU" scenario. In contrast to 0.9 v/c ratio, the D-TV decreases from 10.02% to -2.00%. This represents the eco-driving speed advisory has greater positive effects on decreasing delays under lighter traffic volume. The change in D-TV is -23.60% in "Enable TSP and Enable OBU" scenario, which is more than the changes in 0.9 v/c ratio (-17.60%). At the same time, the delay changes in side-street vehicle (D-SV) remains nearly unchanged. The results indicate the cooperation between TSP and OBU can enhance delays of transit vehicles without dramatically deteriorating non-prioritized traffic under 0.5 v/c ratio.



Note: Error bars show 95% confidence intervals

Figure 8 Simulation results - Weak TSP with 0.5 v/c ratio

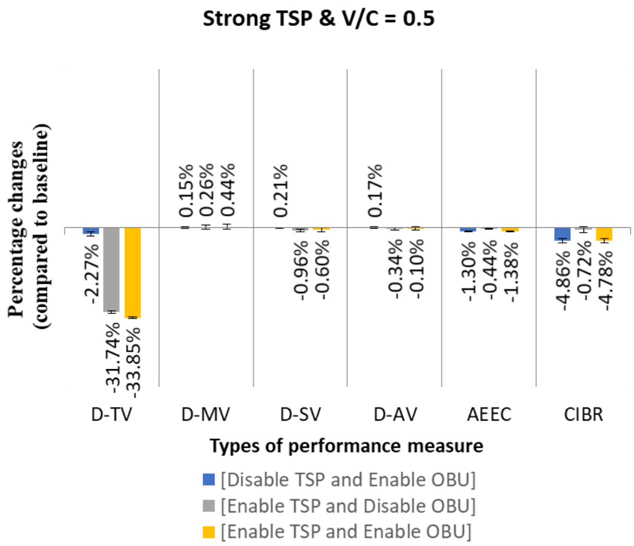
Figure 9 demonstrates the results of Strong TSP experiment under 0.9 v/c ratio. Delays of transit vehicles in"Enable TSP / Disable OBU" decrease from -10.05% to -20.37%, and "Enable TSP / Enable OBU" decrease from -17.60% to -20.93% compared to Weak TSP experiment. It is evident that strong TSP can significantly improve delays of the transit vehicles. However, negative impacts on side-street traffic (i.e. D-SV) of "Enable TSP and Disable OBU" increase from 2.5% to 12.22%, while "Enable TSP / Enable OBU" decrease from 17.20% to 6.53%. With facility of larger priority time, TSP can enhance delays of buses but deteriorate the delay performances of non-prioritized traffic. However, due to speed guidance provided by OBU, it ameliorates the negative impacts of TSP without increase delays of transit vehicles, which brings about the decrease in D-SV in "Enable TSP / Enable OBU" scenario.



Note: Error bars show 95% confidence intervals

Figure 9 Simulation results - Strong TSP with 0.9 v/c ratio

For 0.5 v/c ratio shown in Figure 10, D-TV decreases from -10.8% to -31.74% in “Enable TSP / Disable OBU” and from -23.6% to -33.85% in “Enable TSP / Enable OBU” compared to Weak TSP (Figure 8), while D-SV has little changes compared to baseline (only about -0.7%). This shows that in medium traffic volume, since TSP provides sufficient favors for buses, the delays of transit vehicles are near the same regardless of the activation of OBU.



Note: Error bars show 95% confidence intervals

Figure 10 Simulation results - Strong TSP with 0.9 v/c ratio

5 Conclusions

This study proposed an integrated system named ATSP-C, which focuses on exploring the potential benefits on integrating eco-driving speed advisory system and transit signal priority. This study assumes electric transit vehicles riding under mixed circumstance traffic and designs several performance measures and simulation-based experiments to evaluate proposed model. Experiment results indicate ATSP-C can enhance electric consumption efficiency and riding comfort in all cases. In near-saturated traffic, standalone eco-driving advisory yields worser delays of transit vehicles because of inaccurate arrival time prediction. In comparison to only TSP strategy, a significant amelioration of the adverse impacts on side-street traffic can be found when both TSP and OBU are applied, which shows great benefits of the signal-vehicle cooperative control.

Some limitations of the study may improve in future works. For eco-driving speed advisory model, the experiment results suggest that speed advisory may worsen delay performance during near-saturated traffic since levels of traffic congestion and queue saturation time are not taken into consideration. Future studies can involve traffic queueing such as Webster delay model into the algorithm to enhance the performance. The assumption of bus drivers fully comply with the speed guidance is hard to implement real world, more research on the effects of rates of compliance should be done. Finally, this study adopts rule-based TSP strategy, which may not be optimal in different traffic scenarios. Future studies can make detailed exploration on TSP designs.

Data Availability

The data is generated by a simulation program, and part of the program files included in this study are available by sending request to the author.

Conflicts of Interest

The author declares no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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