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Research Article

Tram-Oriented Traffic Signal Timing Resynchronization

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Modernized trams usually run on exclusive rail lanes along urban streets, but they share the right of way with general vehicles at intersections and often get interrupted by traffic signals. We developed a mixed integer model to resynchronize traffic signal timings to favor tram movements. The objective is to balance the operational needs between minimizing bidirectional tram travel times and reducing the likelihood of activating the green extensions. The model depicts both tram and vehicle progressions in one signal timing plan, making it possible to control the impact of signal timing resynchronization through traffic. Trams following the tram bands produced by the proposed model are prevented from being stopped by red phases at signalized intersections. The applicability and effectiveness of the proposed model were demonstrated in a real-world case study. Compared with the state-of-the-art practice approach, the developed model reduced tram travel time by 10% with lower negative impacts on traffic on side streets. The reduction in tram travel time was obtained without sacrificing the mobility of through traffic.

1. Introduction

Modernized tram systems have been adopted as an environment-friendly transit mode in many cities. Compared with buses, modernized trams possess larger capacity, improved level of comfort, and a higher degree of right of way. Modernized trams, especially in Asian counties, run on exclusive rail lanes along urban streets, but they share the right of way with general vehicles at intersections [1]. As a result, tram operations are often interrupted by traffic signals at intersections, which slows down trams and degrades tram reliability.

Many methodologies have been proposed to optimize traffic signal timing to improve vehicle mobility and safety. For example, Webster [2] developed a method to optimize green time allocation at an isolated intersection. Robertson [3] and Little et al. [4] developed delay-based and bandwidth-based methods, respectively, to coordinate traffic signal timings in a corridor. To capture the interaction between traffic control and drivers' behavior, traffic assignments have been taken into account in traffic control optimization [5]. Sheffi et al. [6] developed a traffic signal timing optimization model considering equilibrium assignment. The combination of traffic control and traffic assignment in the case of emergency evacuation was specifically considered in Marciano et al. [7].

Transit Signal Priority (TSP) strategies are recognized as an effective way to alleviate the negative impacts of traffic signals on transit operations. TSPs are usually classified as either active or passive priority [8]. In active priority schemes, a transit vehicle sends out a priority request as it approaches a signalized intersection and the signal controller responds such that the vehicle could pass the intersection without stopping. Traditional active TSP strategies include "green extension", "red truncation", and "phase insertion" [9]. The strategy implemented depends on the predicted arrival times of transit vehicles at an intersection and multiple priority requests from different approaches [10]. The active TSPs could potentially reduce travel times of transit vehicles and improve schedule adherence [11]. But they may incur additional delays to traffic on side streets, especially when traffic demand is close to the intersection

capacity [12]. Traditional active TSPs have been implemented in several tram systems, such as Melbourne, Toronto, and Utah [13–15]. Recently, Li et al. [16] and Yang et al. [17] developed methodologies to jointly optimize offsets and green times in the active priority scheme. Shi et al. [1] considered the activation of TSP strategies in tram timetable development.

Passive TSP strategies synchronize traffic signal timings at adjacent intersections offline based on transit vehicle volumes and operational characteristics of transit vehicles. Typical passive TSPs originated from MAXBAND, which was developed for general vehicles [4]. Most related studies focused on buses. They maximized the bandwidths for buses by adjusting the offsets and phase sequences to smooth bus movements. Additionally, bus dwell time [18], dwell time variation, and capacity at bus stops [19] were considered in bus bandwidth optimization. Well-designed passive TSPs could enhance the reliability of transit operations [20] and improve transit mobility [21].

The bandwidth-maximization methods are suitable for bus systems. The band designed for buses could be well utilized since there are multiple bus lines on a corridor and bus frequencies are relatively high. Nevertheless, the bandwidth that is maximized for trams may be wasted since there is usually one tram line on a corridor and trams operate with relatively low frequencies. For example, tram frequencies in many cities in China, such as Shenyang and Suzhou, are above 10 mins.

Jeong et al. [22] proposed a model to maximize the bandwidths for general vehicles given a fixed tram bandwidth based on the MAXBAND model. Their model may result in relatively long tram travel times. San Diego implemented a practical strategy to instruct trams to pass multiple signalized intersections without stopping [23]. A tram dwells at a station until the next green light at the immediately downstream intersection starts. Then the tram departs within five-second departure window. If the tram misses the departure window, it must wait for the next green light. The strategy ensures that the tram will receive green lights at the following intersections until it reaches the next station if the tram leaves the station during the departure window.

Assuming that signal timing plans that have been optimized for general vehicles are given, we propose a methodology to resynchronize traffic signal timings in a subsystem to favor tram movements. Trams are instructed to follow the tram progressions optimized by the proposed methodology, leading to smooth and safe tram movements. Our work falls into the category of passive TSPs. It is different from existing studies mainly in the following.

(1) The objective of existing studies is to maximize the bandwidth for general vehicles or transit vehicles. But our objective is to balance the operational needs between minimizing bidirectional tram travel times and reducing the likelihood of activating the green extensions. Few studies have considered the active TSPs in transit progression design.

(2) We depict both tram and vehicle progressions in one signal timing plan, making it possible to control the influence of signal timing resynchronization on through traffic.

This paper is organized as follows. Section 2 describes the proposed methodology and Section 3 evaluates the effectiveness of the proposed methodology in a real-world case study. Section 4 summarizes the paper and discusses possible directions for future research.

2. Methodology

2.1. Scenario Descriptions. We considered tram and vehicle progressions in a subsystem as shown in Figure 1. Trams run on exclusive median rail lane. The left-turn lane for general vehicles is adjacent to the median rail lane. The two stations beyond the subsystem are referred to as major stations. Stations within the subsystem are referred to as minor stations. For simplicity, the proposed methodology only considered straight tram movements. It could be applied to right- or left-turn tram movements with minor revisions. Intersections in the subsystem adopt the same cycle length. But the green times for trams differ across intersections.

Assuming that signal timing plans that have been optimized for general vehicles are given, the proposed methodology optimized tram progressions by adjusting the offset and phase sequence at each intersection. Tram and vehicle progressions are represented by tram and vehicle bands, respectively. The left side of a tram band depicts ideal tram movements. Trams following planned tram progressions could go through signalized intersections without stopping.

A tram driver was informed of suggested speeds via an on-board user interface to follow the planned tram progression. Tram locations and traffic signal timings were assumed to be available in real time. The suggested speed was dynamically updated based on the deviation of a tram from the left side of the planned tram band. When a tram was ready to depart from a station, we estimated the speed v_e for the tram to reach the immediately downstream intersection at the left side of the planned tram band. Let v_m represent the maximum tram speed. The suggested speeds were produced based on the following rules.

(1) If $v_e \leq v_m$, the suggested speed was set as v_e.

(2) If $v_e > v_m$, but the tram could reach the immediately downstream intersection before the right side of the planned tram band with the speed v_m, the suggested speed was set as v_m.

(3) Otherwise, the tram was instructed to wait until the appearance of the next tram band.

When a tram was running along the road, the suggested speed was updated with v_e or v_m at a fixed frequency, depending on which one was smaller.

2.2. Model Formulation. The parameters and variables used in this study are summarized in Table 1. All time related variables are in unit of the cycle length, C, for convenience.

Figure 2 illustrates the parameters and variables representing vehicle and tram progressions. A node in the vertical axis represents an intersection ($i \in I$) or a tram station ($s \in S$). The vehicle and tram bandwidths in direction d are represented by b_d and tb_d, respectively. At intersection node i, the green times for straight-moving vehicles and trams

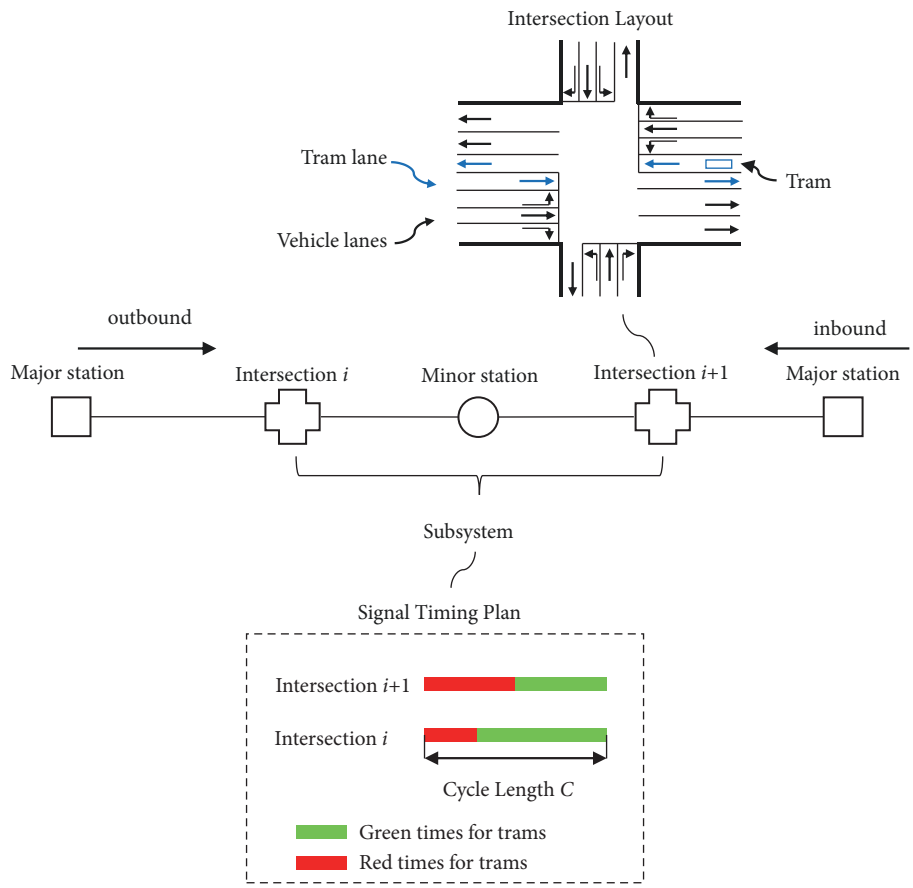

FIGURE 1: Problem context.

in direction d are represented by $G_{d,i}$ and $tg_{d,i}$, respectively. Their lengths may differ, depending on the phase sequence. The time lags from the right side of the green phase to the right edges of b_d and tb_d are denoted by $w_{d,i}$ and $tw_{d,i}$, respectively. The time to clear vehicle queues at intersection node i in direction d is represented by $\tau_{d,i}$.

Vehicle and tram travel times in direction d from intersection i to its immediately downstream intersection is represented by $VT_{d,i}$ and $tt_{d,i}$, respectively. Let $dt_{d,i}$ denote tram dwell time at a station between intersection i and its immediately downstream intersection in direction d.

We used initialized phase time to represent signal coordination in a subsystem. For convenience, the initialized phase times are defined based on directions and transportation modes. The initialized phase times $\theta_{d,i}$ and $t\theta_{d,i}$ denote the starting time of the first green phase for straight-moving vehicles and trams, respectively, at intersection i in direction d.

Tram travel time, T_d, between two major stations consists of two components: the time from the upstream major station to the first intersection of the subsystem, $T_{d,1}$, and the time from the first intersection of the subsystem to the downstream major station $T_{d,2}$. The first component $T_{d,1}$ depends on the time when the tram is ready to depart from the upstream major station. Thus, it varies across trams. The second component $T_{d,2}$ is constant since we assumed that trams could follow the planned tram progressions. The expectation of T_d can be obtained as follows:

$$\begin{aligned} E[T_d] &= E[T_{d,1}] + T_{d,2} \\ &= \mu_d + \int_0^{1-tw_d-tb_d} (1 - tw_d - tb_d - z) f(z)\, dz \\ &\quad + \int_{1-tw_d}^{1} (2 - tw_d - tb_d - z) f(z)\, dz + T_{d,2} \end{aligned} \tag{1}$$

where μ_d denote the minimum tram travel time, in the unit of a cycle length, from the upstream major station to its immediately downstream intersection. Let z represent the earliest arrival time of a tram at the intersection and $f(z)$ represent the distribution of z over a cycle length. $f(z)$ is influenced by scheduled tram headway, the cycle lengths of the given subsystem, and the upstream subsystem. When no *a priori* information about $f(z)$ is available, it is reasonable to assume that z follows uniform distribution and (1) is reduced to

$$\begin{aligned} E[T_d] &= \mu_d + \left(\frac{1 + tb_d^2}{2} - tb_d\right) + T_{d,2} \\ &= \mu_d + \left(\frac{1 + tb_d^2}{2} - tb_d\right) + \sum_{i \in I} (tt_{d,i} + dt_{d,i}) \end{aligned} \tag{2}$$

Table 1: Parameters and variables.

Notation	Description
	Indices and Sets
D	Set of direction, $d \in D = \{out, in\}$.
I	Set of intersections in the subsystem.
S	Set of tram stations.
i'	Intersection immediately downstream of intersection i.
	Parameters
B_d	Predetermined vehicle bandwidth in direction d in the subsystem.
C	Cycle length of the subsystem.
$G_{d,i}$	Green time for straight-moving vehicles at intersection i in direction d.
$L_{d,i}$	Green time for left-turn vehicles at intersection i in direction d.
TC_i	Time needed for a tram to pass intersection i safely.
$VT_{d,i}$	Vehicle travel time in direction d from intersections i to i'.
η_d	Scale factor for vehicle bandwidth B_d, ranging from 0 to 1.
$\tau_{d,i}$	Queue clearance time at intersection i in direction d.
	Auxiliary Variables
$tg_{d,i}$	Green time for trams at intersection i in direction d.
$t\theta_{d,i}$	Initialized phase time for trams at intersection i in direction d.
$p_{d,i}$	Binary variables indicating whether the tram in direction d could pass intersection i without activating the green extensions. If so, $p_{d,i} = 0$. Otherwise, $p_{d,i} = 1$.
	Decision Variables
b_d	Vehicle bandwidth in direction d in the subsystem.
tb_d	Tram bandwidth in direction d in the subsystem.
$tw_{d,i}$	Time from the right side of $tg_{d,i}$ to the right edge of tb_d.
$tt_{d,i}$	Tram travel time from intersections i to i' in direction d.
$dt_{d,i}$	Dwell time at a station between intersections i and i' in direction d.
$x_{d,i}$	Integer variables used to represent vehicle band between intersections i and i' in direction d.
$y_{d,i}$	Integer variables used to represent tram band between intersections i and i' in direction d.
$w_{d,i}$	Time from the right side of $G_{d,i}$ to the right edge of b_d.
$\theta_{d,i}$	Initialized phase time for straight-moving vehicles at intersection i in direction d.
$\alpha_i, \beta_i, \gamma_i$	Binary variables indicating the phase sequence at intersection i.

We developed a mixed integer model to optimize tram bands by adjusting the offset and phase sequence at each intersection. The objective function consists of two components:

$$\min \sum_{d\in D}\left(\left(\frac{1+tb_d^2}{2}-tb_d\right)+\sum_{i\in I}\left(tt_{d,i}+dt_{d,i}\right)\right) + \sum_{d\in D}\sum_{i\in I}\omega\times p_{d,i} \tag{3}$$

The objective balanced the operational needs between minimizing bidirectional tram travel times and reducing the frequency of activating the green extensions. The first component represents the expected bidirectional tram travel times. The second component is the penalty for activating the green extensions, where $p_{d,i}$ is a binary variable indicating whether the tram band in direction d requires activating the green extensions at intersection node i. If so, $p_{d,i} = 0$. The negative impact of activating the green extensions is quantified by the value of w, which ranges from zero to one. For example, $w = 1$ indicates that one unit of the cycle length would be added to the objective function for activating the green extensions at an intersection. If $w = 0$, the green extensions would be activated whenever needed.

The optimization is subject to a series of constraints regarding signal timings, vehicle, and tram progressions.

Phase Sequence Constraints

$$\alpha_i + \beta_i + \gamma_i \le 2 \tag{4}$$

$$\alpha_i - \beta_i + \gamma_i \ge 0 \tag{5}$$

$$\alpha_i + \beta_i - \gamma_i \ge 0 \tag{6}$$

$$\alpha_i - \beta_i - \gamma_i \le 0 \tag{7}$$

$$tg_{d,i} = G_{d,i} - \gamma_i L_{d,i} \tag{8}$$

$$d \in D,\ i \in I \tag{9}$$

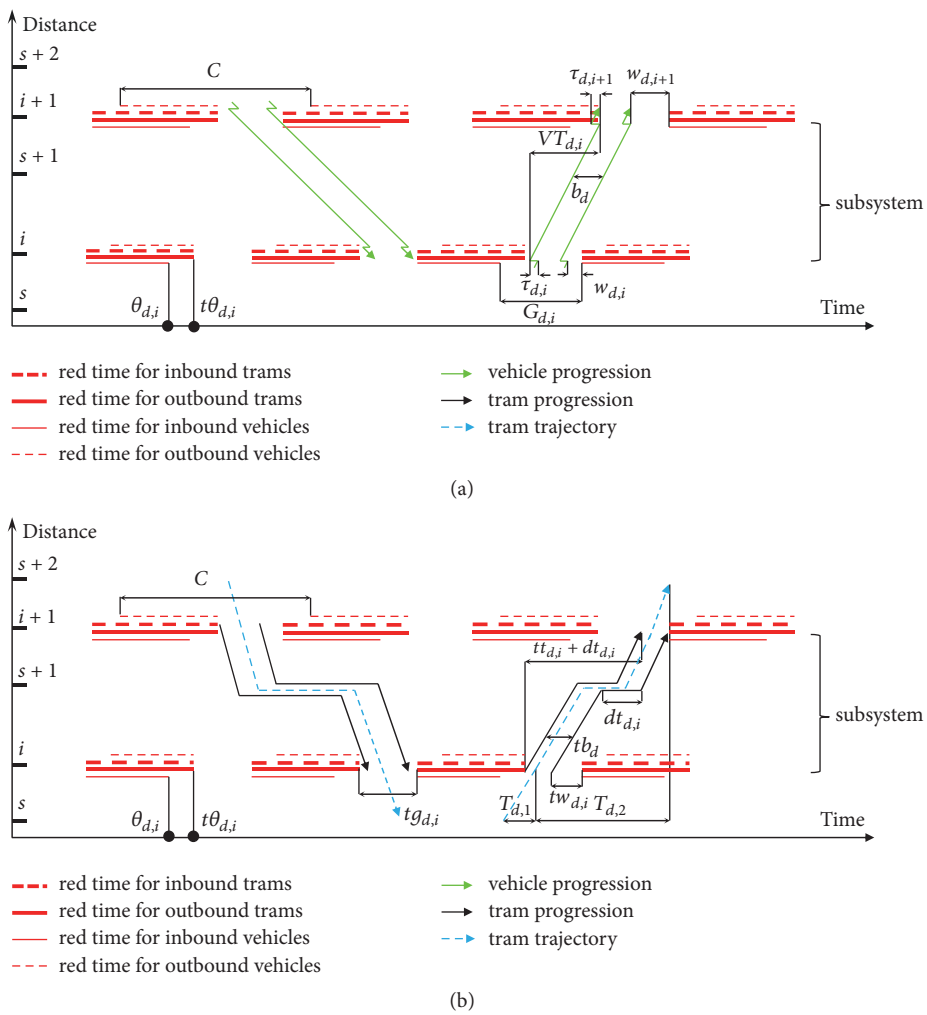

Figure 2: Illustration of (a) vehicle progression and (b) tram progression.

The binary variables α_i, β_i., and γ_i in constraints (4)-(7) define four-phase sequence patterns as illustrated in Figures 3(a)–3(d). "Lead" and "Lag" herein refer to the relative sequence of the phase for outbound and inbound left-turn vehicles, respectively. For example, if $\alpha = 0$, $\beta = 1$, and $\gamma = 1$, the lead-lag sequence is adopted (Figure 3(a)). Outbound straight-moving vehicles can use both the first and second phases. But outbound straight-moving trams can only use the second phase, since they will conflict with left-turn vehicles in the first phase. If $\alpha = 0$, $\beta = 0$, and $\gamma = 0$, the lead-lead sequence is adopted (Figure 3(c)). The green times for straight-moving vehicles and trams are equal. Constraint (8) defines the relationship between the green times for straight-moving vehicles and trams.

Initialized Phase Time Constraints

$$\theta_{in,i} = \theta_{out,i} + L_{out,i}\beta_i - L_{in,i}\alpha_i \tag{10}$$

$$t\theta_{out,i} = \theta_{out,i} + \frac{L_{out,i}\left(-\alpha_i + \beta_i + \gamma_i\right)}{2} \tag{11}$$

$$t\theta_{out,i} = t\theta_{in,i} \tag{12}$$

$$i \in I \tag{13}$$

Constraints (10)-(12) define the relationship of the initialized phase times at one intersection, which reconcile vehicle and tram progressions in one signal timing plan. The relationship depends on the phase sequence adopted. Constraint (10) defines the relationship between the initialized phase times for straight-moving vehicles in outbound and inbound directions. Constraint (11) defines the relationship between the initialized phase times for straight-moving vehicles and trams in the outbound direction. Constraint (12) indicates that the initialized phase times for straight-moving trams in both directions are equal. Once one of the initialized phase times is determined, the others could be derived based on the phase sequence.

Vehicle Progression Constraints

$$w_{d,i} + b_d + \tau_{d,i} \le G_{d,i} \tag{14}$$

$$\theta_{d,i} + G_{d,i} - w_{d,i} + VT_{d,i} - \tau_{d,i} = \theta_{d,i'} + G_{d,i'} - w_{d,i'} + x_{d,i} \tag{15}$$

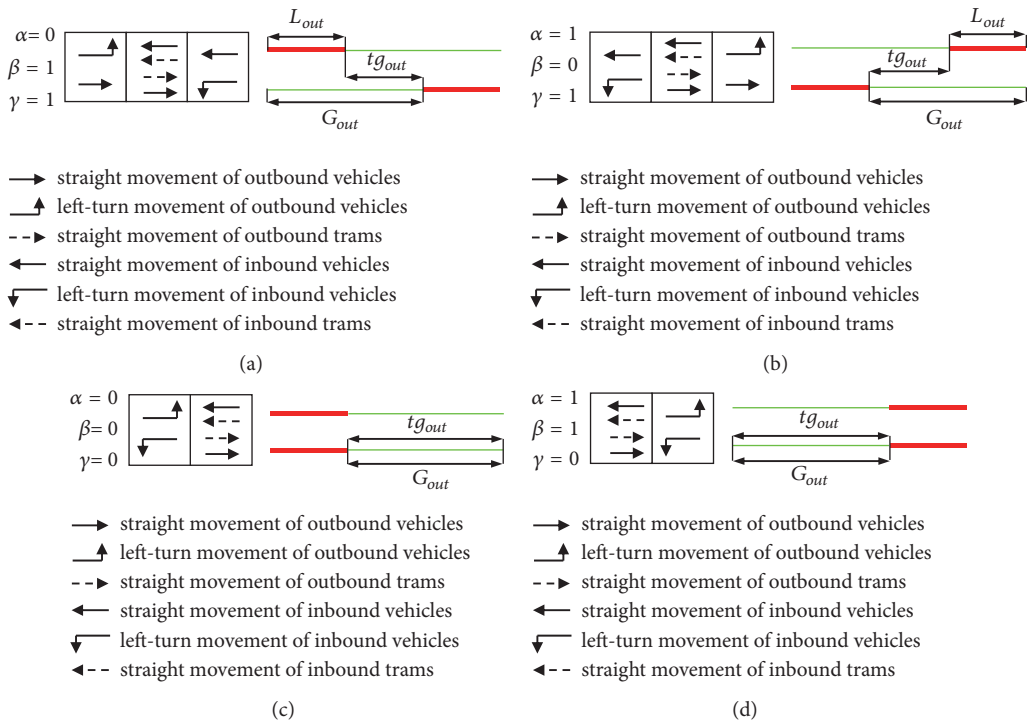

Figure 3: Phase sequence pattern: (a) Lead-Lag; (b) Lag-Lead; (c) Lead-Lead; (d) Lag-Lag.

$$b_d \geq \eta_d B_d \tag{16}$$

$$d \in D,\ i, i' \in I \tag{17}$$

Constraints (14)-(15) depict vehicle progression in the subsystem. Constraint (14) ensures that vehicle progression is within the green time window at each intersection. Constraint (15) describes vehicle progression from one intersection to its immediately downstream intersection, where $x_{d,i}$ is an integer variable. Constraint (16) is specified to balance the needs of granting tram priority and improving vehicular mobility. Bandwidth B_d was predetermined based on vehicle flows. The parameter η_d is the trade-off factor. If $\eta_d = 1$, the signal timings would be adjusted without sacrificing vehicle bandwidth. Smaller η_d may result in shorter tram travel times, but would incur additional delays to through traffic.

Tram Progression Constraints

$$tw_{d,i} + tb_d \leq tg_{d,i} \tag{18}$$

$$t\theta_{d,i} + tg_{d,i} - tw_{d,i} + tt_{d,i} + dt_{d,i} = t\theta_{d,i'} + tg_{d,i'} - tw_{d,i'} + y_{d,i} \tag{19}$$

$$TT_{d,i}^{\min} \leq tt_{d,i} \leq TT_{d,i}^{\max} \tag{20}$$

$$DT_{d,i}^{\min} \leq dt_{d,i} \leq DT_{d,i}^{\max} \tag{21}$$

$$tw_{out,1} + tb_{out} = tg_{out,1} \tag{22}$$

$$tw_{in,|I|} + tb_{in} = tg_{in,|I|} \tag{23}$$

$$d \in D,\ i, i' \in I \tag{24}$$

Constraints (18)–(21) regulate tram progression in the subsystem. Constraint (18) ensures that tram progression is within the green time window at each intersection. Constraint (19) describes tram progression from one intersection to its immediately downstream intersection, where $y_{d,i}$ is an integer variable. Constraints (20)-(21) restrict tram travel times along the roads and dwell times at stations, respectively. Constraints (22) and (23) require the tram band to initialize immediately when the green phase starts at the intersections immediately downstream of major stations. As a result, trams waiting at major stations could start moving as early as possible.

Active TSP Constraints

$$M \times (p_{d,i} - 1) \leq TC_i - tw_{d,i} \leq M \times p_{d,i}, M \text{ is a large number} \tag{25}$$

$$d \in D,\ i \in I \tag{26}$$

Constraint (25) defines the relationship between variables $tw_{d,i}$ and $p_{d,i}$. TC_i represents the time needed for a tram to pass intersection i safely. If $tw_{d,i} > TC_i$, the tram band does not require activating the green extensions and $p_{d,i} = 0$. Otherwise, $p_{d,i} = 1$ and the green extensions would be activated to ensure safe tram movements.

The proposed model can be solved using commercial software of CPLEX [24].

Table 2: Traffic volumes and traffic signal timings.

Intersection No. and approach		Traffic volumes (vph) Left	Through	Right	$G_{out,i}$	$G_{in,i}$	$L_{out,i}$	$L_{in,i}$	$\tau_{out,i}$ (s)	$\tau_{in,i}$ (s)
1	Eastbound	229	816	95	0.32	0.32	0.18	0.18	20	10
	Westbound	100	405	84						
	Southbound	105	430	71						
	Northbound	107	407	193						
2	Eastbound	202	823	89	0.33	0.33	0.16	0.16	20	10
	Westbound	103	412	68						
	Southbound	56	229	37						
	Northbound	149	394	167						
3	Eastbound	218	785	43	0.36	0.36	0.20	0.20	15	10
	Westbound	75	410	113						
	Southbound	120	275	53						
	Northbound	123	430	183						
4	Eastbound	212	822	54	0.42	0.42	0.22	0.22	15	10
	Westbound	101	396	89						
	Southbound	83	181	69						
	Northbound	92	313	293						

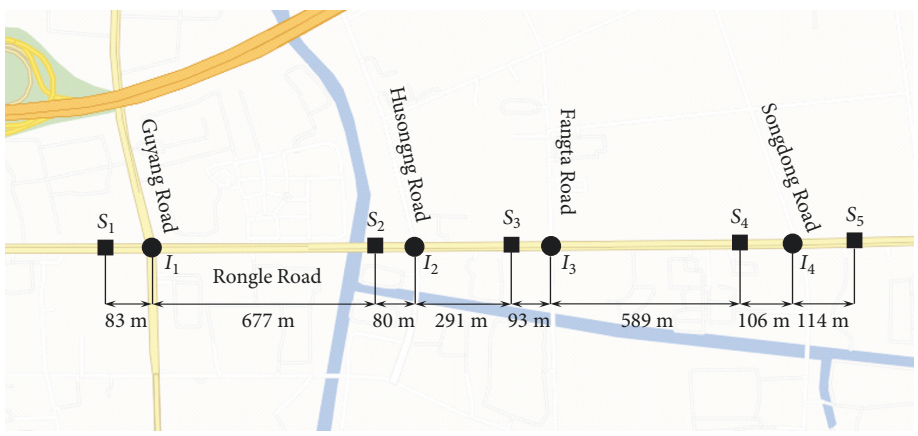

Figure 4: Intersections and tram stations considered in case study.

3. Case Study

The proposed methodology was evaluated numerically on Tram Line T1 in Songjiang District of Shanghai. Line T1 is 11.6 km in length and serves 18 stations including terminals. It was designed to operate on exclusive median rail lanes. The evaluation considered a subsystem on Rongle road, which is illustrated in Figure 4. There are three stations S_2–S_4 within the subsystem. Traffic volumes in the evening peak hours and traffic signal timings that were optimized based on traffic flows are presented in Table 2. Traffic signal parameters are presented in the unit of the cycle length, which was 110 s. Vehicle progressions were optimized using the MAXBAND model. The resulting vehicle bandwidths were 16 and 15 s for the outbound and inbound directions, respectively.

The proposed model was applied given the signal timing plan optimized for general vehicles. Key parameters used in the proposed model are listed as follows:

(i) The speed of general vehicles was 30 km/h based on empirical data.

(ii) Maximum tram speed was 45 km/h

(iii) The minimum tram dwell time at all stations was 30 s and the maximum was 90 s.

We evaluated and compared the operations of trams and general vehicles in deterministic and stochastic environments in three scenarios. Scenarios 1 and 2 were based on the original traffic signal timings. Scenario 3 resynchronized traffic signal timings using the proposed model to favor tram movements. Vehicle bandwidths are equal in three scenarios.

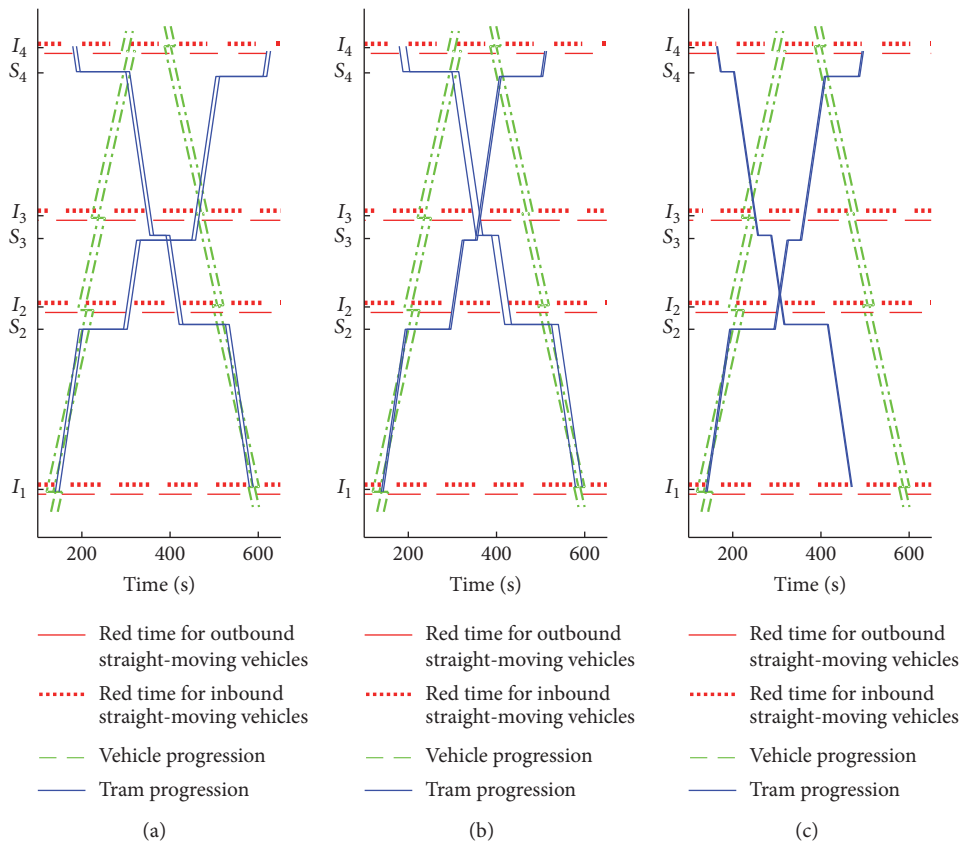

Figure 5: Vehicle and tram progressions in (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

The proposed model was applied to produce tram bands without modifying traffic signal timing plan in Scenarios 1 and 2. The parameter ω was set to be one in Scenario 1, indicating that the resulting tram bands would not require activating the green extensions. In contrast, the parameter ω was set to be zero in Scenario 2, indicating that the green extensions would be activated whenever needed. In Scenario 3, the parameter ω was set to be one. Scenario 3 was the proposed approach and Scenario 2 was considered as the state-of-the-art practice approach.

3.1. Deterministic Evaluation. Given deterministic tram travel times and dwell times, Figure 5 presents the resulting vehicle and tram progressions in three scenarios. It was revealed that the green extensions in Scenario 2 and signal timing resynchronization in Scenario 3 could effectively reduce tram travel times. In Scenario 1, dwell time at station S_3 for outbound trams were relatively long, which was reduced by the green extensions in Scenario 2 and by signal timing resynchronization in Scenario 3. The outbound tram travel times in three scenarios were 550, 440, and 424 s, respectively, and the inbound tram travel times were 470, 470, and 375 s, respectively.

Sensitivity analyses were performed to investigate the influence of the bandwidth control parameter η and the penalty coefficients ω on tram travel times in Scenario 3. Figure 6 presents the expected bidirectional tram travel times

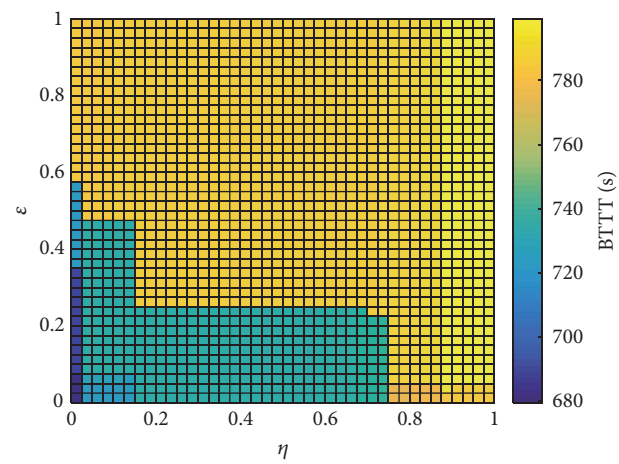

Figure 6: Influence of the bandwidth control parameter ω and the penalty coefficients η on tram travel times.

(BTTT) between two major stations given various combinations of η and ω. Generally, tram travel time increased with η and ω. The results are understandable. Smaller values of η and ω mean a lager feasible region where the proposed model could search for the optimal results. Nevertheless, the gain obtained by reducing the values of η and ω could be small. For example, given that $\omega = 1$, tram travel time was

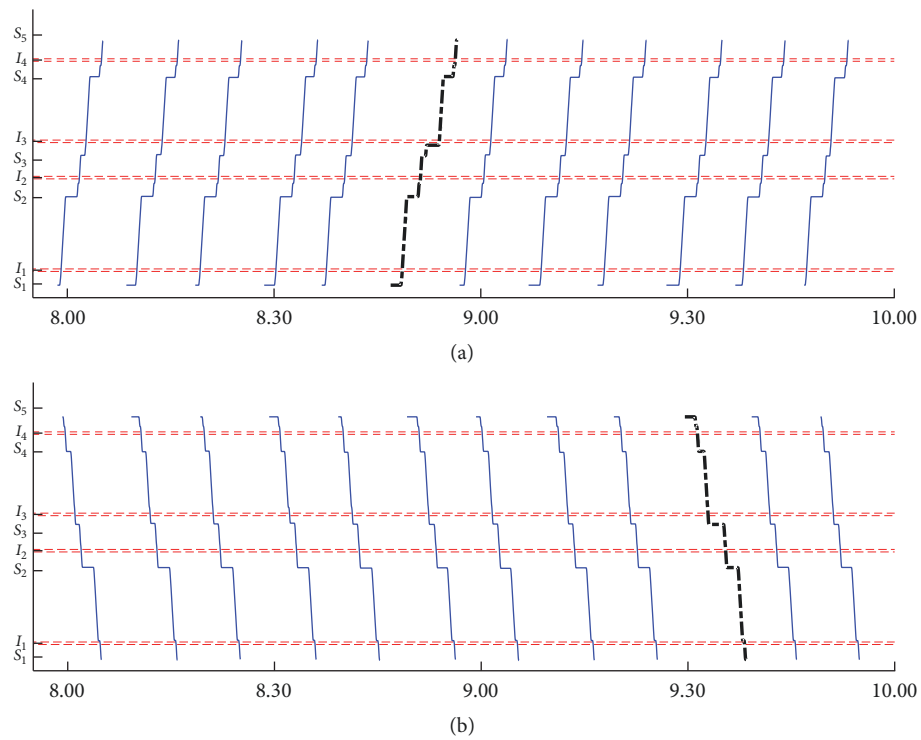

Figure 7: Simulated tram trajectories in Scenario 3: (a) outbound; (b) inbound.

only reduced by 1% if we decreased the value of η from 1 to 0.8.

3.2. Stochastic Evaluation. To further illustrate the applicability of the proposed model and explore the influence of the signal timing resynchronization on general vehicles, we employed TransModeler [25] to evaluate the operations of trams and general vehicles in the stochastic environment. After fine-tuning simulation parameters, traffic flows were well represented. For example, the simulated turning movements were close to the field measurements in Table 2. The resulting mean absolute percentage error (MAPE) equaled 6%, which was relatively low.

The simulation produced tram trajectories using the following setups:

(1) Tram acceleration and deceleration rates follow uniform distribution between 0.7 and 1.3 m/s^2, which was based on the field survey on a tram line of Suzhou, China.

(2) Tram dwell time follows a nonnegative truncation of normal distribution with a mean of 30 s and a standard deviation of 18% of the mean [26].

(3) To reflect the fact that drivers may not be able to follow the suggested speeds on the on-board user interface, it was assumed that the actual speed follows a nonnegative truncation of normal distribution with a mean of suggested speed and a standard deviation of 7% of the suggested speed.

(4) Maximum green extension was 10 s.

(5) Scheduled tram headway was 10 mins for each direction.

Tram progressions were produced in all scenarios and drivers were instructed to follow planned tram progressions. Green extensions were not allowed in Scenario 1, but they would be granted in Scenarios 2 and 3 when necessary. Although tram progressions in Scenario 3 did not require activating green extensions, green extensions were allowed to prioritize tram movements since trams may not be able to strictly adhere to the planned progressions in the stochastic environment. For each scenario, fourteen simulation experiments were executed with different random seeds. Each experiment emulated traffic operations in two-hour evening peak period of a day.

Figure 7 illustrates simulated tram trajectories in Scenario 3. Due to the randomness of tram speeds and dwell times, trams may not be able to adhere to the planned progressions. For example, the trajectory represented by black dashed line in Figure 7(a) was behind the planned progression because it was stopped by the red phase at intersection I_3. The trajectory represented by black dashed line in Figure 7(b) waited for the next tram band since it was delayed be excessively long dwell time at station S_3. Among 168 tram runs in fourteen experiments, 3 and 5 tram runs were behind the planned progressions in the outbound and inbound directions, respectively.

Figure 8 presents the boxplot of tram travel times in three scenarios. The green circles represent the expected travel times in the deterministic environment. The outliers indicated by red crosses were tram runs behind the planned

Table 3: P-values of the Wilcoxon sign-rank test on tram travel time.

Direction	Scenario 2-Scenario 1	Scenario 3-Scenario 1	Scenario 3-Scenario 2
Outbound	6.00E-05	6.00E-05	4.00E-04
Inbound	6.00E-04	6.00E-05	6.10E-05

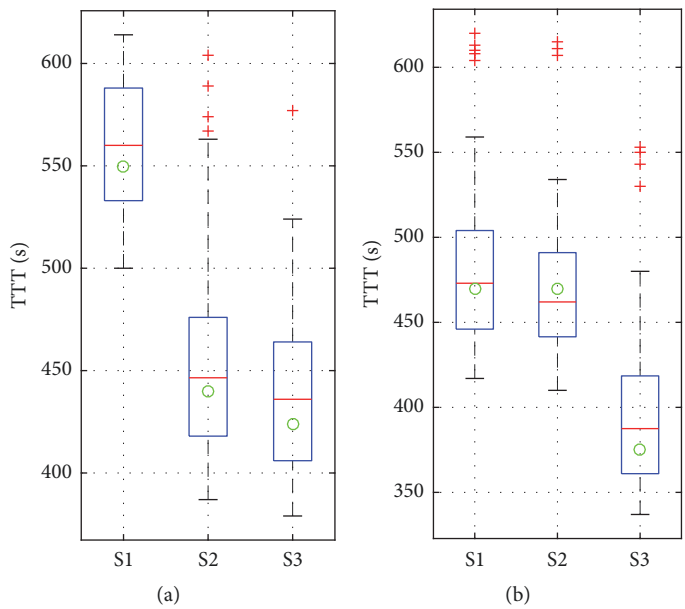

Figure 8: Boxplots of tram travel time (TTT) in three scenarios: (a) outbound and (b) inbound.

progressions. The results in the stochastic environment were consistent with those in the deterministic environment. Specifically, in the outbound direction, the mean tram travel times in Scenarios 2 and 3 were 19% and 22% lower than those in Scenario 1. In the inbound direction, the mean tram travel times in Scenarios 1 and 2 were close, which were reduced by 17% in Scenario 3. The effects of the green extensions in Scenario 2 and signal resynchronization in Scenario 3 on tram travel time variation were limited. In the outbound direction, the standard deviations of tram travel times were 32, 42, and 35 s in Scenarios 1, 2, and 3, respectively, while they were 41, 36, and 40 s in the three scenarios, respectively.

We conducted the Wilcoxon signed-rank test [27] to evaluate the effects of the green extensions in Scenario 2 and signal timing resynchronization in Scenario 3 on tram mobility. The Wilcoxon signed-rank test is commonly used to test for a difference of paired observations, where the observations are taken before and after an action. The null hypothesis is that the median of the probability distribution of the difference equals zero. The alternative hypothesis is that the median is less than zero. If the null hypothesis is rejected, we conclude that the action is effective.

Table 3 summarizes the results of the Wilcoxon signed-rank test on tram travel time. The resulting p-values are all close to zero, suggesting the effectiveness of the green extensions in Scenario 2 and signal timing resynchronization in Scenario 3 in reducing tram travel times. Tram travel times in Scenario 3 were significantly lower than those in Scenario 2, demonstrating the robustness of the proposed methodology.

Figure 9 presents the boxplots of travel times for through vehicles. Since vehicle bandwidths in three scenarios are equal, vehicle travel times in three scenarios were close, suggesting limited effects of green extensions in Scenario 2 and traffic signal timing resynchronization in Scenario 3 on the mobility of through vehicles.

Green extensions were allowed in Scenarios 2 and 3, which may incur additional delays to traffic on side streets. Figure 10 quantifies vehicle delays on side streets. Since no green extensions were triggered at Guyang-Rongle and Songdong-Rongle intersections, vehicle delays at Guyang Road and Songdong Road in three scenarios were close, which was shown in Figures 10(a) and 10(d). Figure 10(b) shows that the median vehicle delays in three scenarios were close at Husong road, which was due to the fact that the frequency of green extension activations was relatively low in both Scenarios 2 and 3. Nevertheless, the green extensions increased the variation of vehicle delays and resulted in relatively long delays in some signal cycles. At Fangta-Rongle intersection, the green extensions in Scenario 2 were activated more frequently than in Scenario 3. As a result, the median and maximum delays in Scenario 2 were 18% and 38% higher than those in Scenario 1, respectively. They were 12% and 26% higher than those in Scenario 3, respectively.

Table 4 summarizes tram travel time, travel time of through vehicles, and vehicle delay on side streets. The

Table 4: A summary of three scenarios.

	Scenario 1	Scenario 2	Scenario 3
Tram travel time (s)	520.0	459.2 [-11%]	413.3[-20%]
Vehicle travel time (s)	439.8	435.4 [-1.0%]	438.9[-0.2%]
Vehicle delay on Guyang (s)	33.8	34.5 [+2%]	34.2[+1%]
Vehicle delay on Husong (s)	35.0	37.5[+7%]	37.1[+6%]
Vehicle delay on Fangta (s)	28.3	33.6[+19%]	30.5[+8%]
Vehicle delay on Songdong (s)	36.2	36.2[+0%]	35.1[-3%]

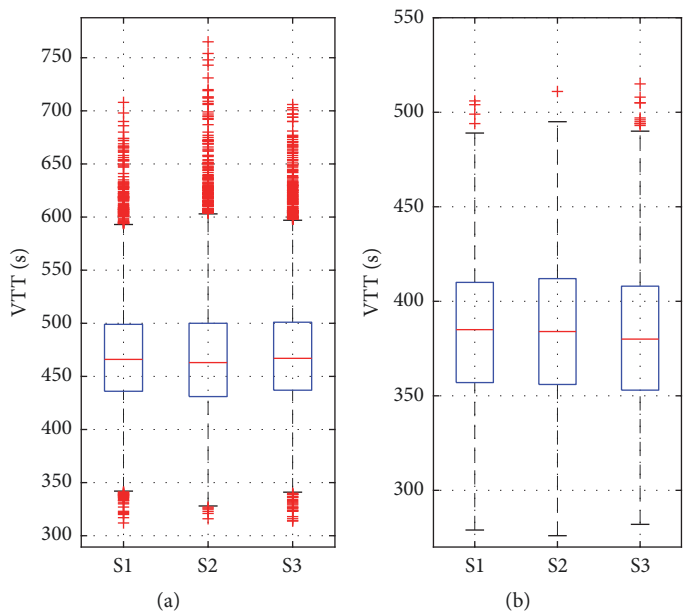

Figure 9: Boxplots of vehicle travel times (VTT): (a) outbound and (b) inbound.

comparison of tram travel time revealed that tram mobility was improved by green extensions in Scenario 2, which was further improved by signal timing resynchronization in Scenario 3. But the green extensions in Scenario 2 would increase vehicle delays on side streets. Signal timing resynchronization in Scenario 3 reduced the negative impacts on traffic on side streets by decreasing the frequency of the green extension activations. The effects of the green extensions and signal timing resynchronization on through traffic were limited. Compared with the state-of-the-art practice approach (Scenario 2), the proposed approach (Scenario 3) reduced tram travel time by 10% with lower negative impacts on vehicles on side streets.

4. Conclusion and Future Research

We developed a mixed integer model to resynchronize traffic signal timings to favor tram movements. The objective of the developed model balanced the operational needs between minimizing bidirectional tram running times and reducing the likelihood of activating the green extensions. Trams following the tram bands produced by the proposed model are prevented from being stopped by red phases at signalized intersections. The effectiveness of the developed model was demonstrated in a real-world case study. Compared with the state-of-the-art practice approach, the developed model reduced tram travel time by 10% with lower negative impacts on traffic on side streets. The reduction in tram travel time was obtained without sacrificing the mobility of through traffic.

Empirical studies have revealed that transit drivers would respond positively to real-time information to keep on schedule [28]. That is, drivers will adjust speeds along the roadways and dwell times at stations to keep on schedule. The on-board user interface provides suggested speeds to facilitate tram drivers. The deployment of Automatic Vehicle Location (AVL) systems and the positive responses of transit drivers to real-time information make it feasible to apply the proposed model in practice.

The results presented demonstrated that the proposed methodology is promising. Investigating the value of the proposed methodology in a pilot study is the next step we are pursuing. In addition, our model was developed assuming deterministic tram travel times and dwell times. How to consider the variations of tram operations in the model is reserved for future research.

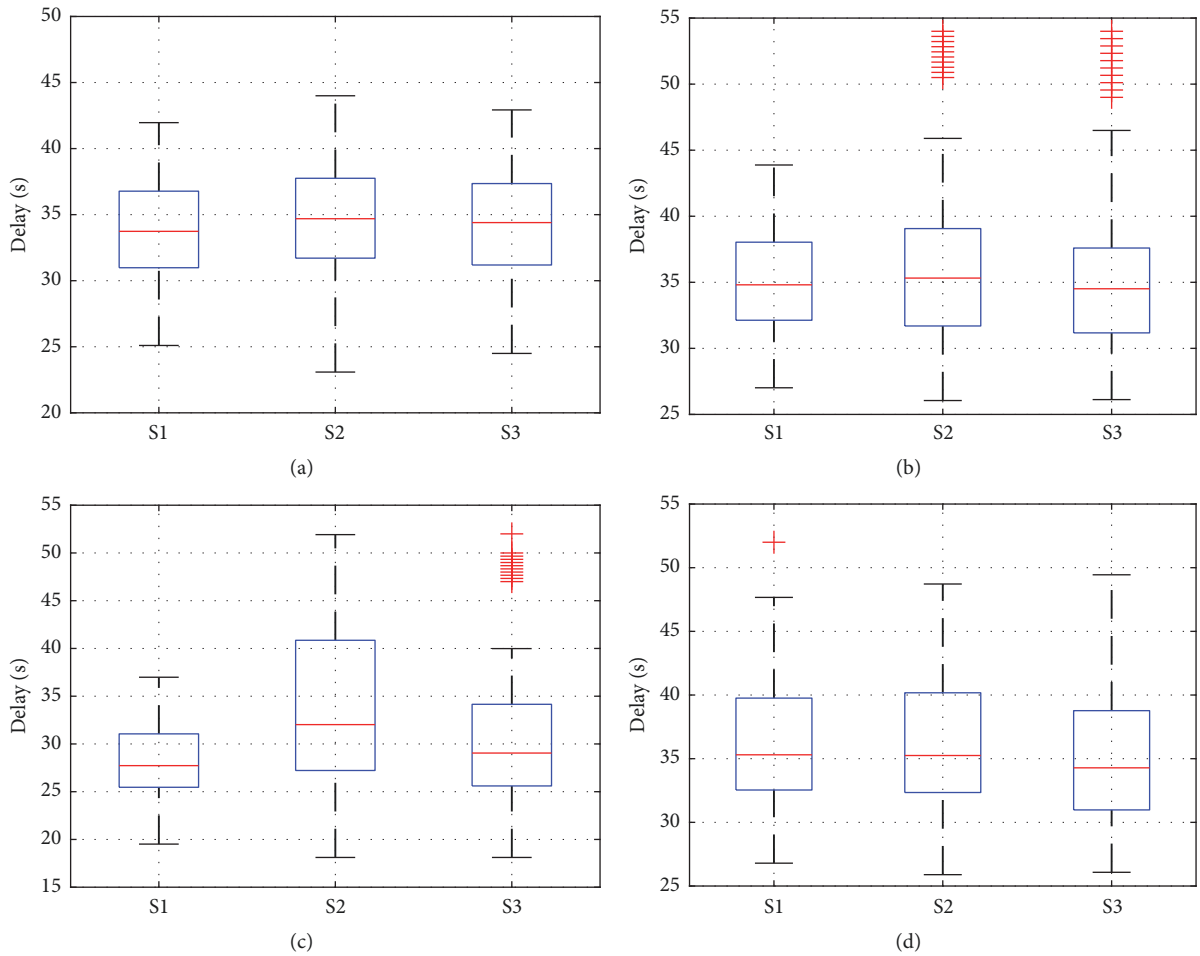

Figure 10: Vehicle delays in side streets: (a) Guyang Road; (b) Husong Road; (c) Fangta Road; and (d) Songdong Road.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] J. Shi, Y. Sun, P. Schonfeld, and J. Qi, "Joint optimization of tram timetables and signal timing adjustments at intersections," *Transportation Research Part C: Emerging Technologies*, vol. 83, pp. 104–119, 2017.

[2] F. V. Webster, "Traffic signal settings," Road Research Technical Paper No. 39, Road Research Laboratory, London, UK, 1958.

[3] D. I. Robertson, "TRANSYT Method for area traffic control," *Traffic Engineering & Control*, vol. 10, no. 6, pp. 181-182, 1969.

[4] J. D. C. Little, M. D. Kelson, and N. H. Gartner, "MAXBAND: a program for setting signal on arteries and triangular network," *Transportation Research Record*, no. 795, pp. 40–46, 1981.

[5] H. Taale and Z. H. J. Van, "The Combined Traffic Assignment and Control Problem - An Overview of 25 Years of Research," in *Proceedings of the Selected Proceedings of the World Conference on Transport Research*, 2001.

[6] Y. Sheffi and W. B. Powell, "Optimal signal settings over transportation networks," *Journal of Transportation Engineering*, vol. 109, no. 6, pp. 824–839, 1983.

[7] F. A. Marcianò, G. Musolino, and A. Vitetta, "Signal setting optimization on urban road transport networks: The case of emergency evacuation," *Safety Science*, vol. 72, pp. 209–220, 2015.

[8] A. Skabardonis, "Control strategies for transit priority," *Transportation Research Record*, vol. 1727, no. 1584, pp. 20–26, 2000.

[9] Y. Lin, X. Yang, N. Zou, and M. Franz, "Transit signal priority control at signalized intersections: a comprehensive review," *Transportation Letters*, vol. 7, no. 3, pp. 168–180, 2015.

[10] W. Ma, Y. Liu, and X. Yang, "A dynamic programming approach for optimal signal priority control upon multiple

high-frequency bus requests," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, vol. 17, no. 4, pp. 282–293, 2013.

[11] M. Li, Y. Yin, W.-B. Zhang, K. Zhou, and H. Nakamura, "Modeling and implementation of adaptive transit signal priority on actuated control systems," *Computer-Aided Civil and Infrastructure Engineering*, vol. 26, no. 4, pp. 270–284, 2011.

[12] M. T. Islam, J. Tiwana, A. Bhowmick, and T. Z. Qiu, "Design of LRT signal priority to improve arterial traffic mobility," *Journal of Transportation Engineering*, vol. 142, no. 9, 2016.

[13] F. J. McGinley and D. R. Stolz, "The design of tram priority at traffic signals," *Journal of Advanced Transportation*, vol. 19, no. 2, pp. 133–151, 1985.

[14] G. Currie and A. Shalaby, "Active transit signal priority for streetcars: experience in Melbourne, Australia, and Toronto, Canada," *Transportation Research Record*, no. 2042, pp. 41–49, 2008.

[15] M. Zlatkovic, P. T. Martin, and A. Stevanovic, "Predictive priority for light rail transit: University light rail line in Salt Lake County, Utah," *Transportation Research Record*, no. 2259, pp. 168–178, 2011.

[16] M. Li, G. Y. Wu, Y. Li, F. Bu, and W.-B. Zhang, "Active signal priority for light rail transit at grade crossings," *Transportation Research Record*, no. 2035, pp. 141–149, 2007.

[17] M. Yang, J. Ding, W. Wang, and Y.-Y. Ma, "A coordinated signal priority strategy for modern trams on arterial streets by predicting the tram dwell time," *KSCE Journal of Civil Engineering*, vol. 22, no. 2, pp. 823–836, 2018.

[18] G. Y. Dai, H. Wang, and W. Wang, "Signal optimization and coordination for bus progression based on MAXBAND," *KSCE Journal of Civil Engineering*, vol. 20, no. 2, pp. 890–898, 2016.

[19] Y. Cheng, X. Yang, and G. Chang, "A bus-based progression system for arterials with heavy transit flows," in *Proceedings of the Transportation Research Board 94th Annual Meeting*, Washington, DC, USA, 2015.

[20] W. Ma and X. Yang, "A passive transit signal priority approach for bus rapid transit system," in *Proceedings of the IEEE Intelligent Transportation Systems Conference (ITSC '07)*, pp. 413–418, Seattle, Wash, USA, October 2007.

[21] M. Estrada, C. Trapote, M. Roca-Riu, and F. Robusté, "Improving bus travel times with passive traffic signal coordination," *Transportation Research Record*, vol. 2111, no. 9, pp. 68–75, 2009.

[22] Y. Jeong and Y. Kim, "Tram passive signal priority strategy based on the MAXBAND model," *KSCE Journal of Civil Engineering*, vol. 18, no. 5, pp. 1518–1527, 2014.

[23] S. Celniker and E. W. Terry, "Trolley priority on signalized arterials in downtown San Diego," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1361, pp. 184–187, 1992.

[24] CPLEX, User's Manual for Cplex, 2012.

[25] Caliper Co. (2014). Transmodeler 4 Help.

[26] N. Van Oort and R. Van Nes, "Improving Reliability in Urban Public Transport in Strategic and Tactical Design," in *Proceedings of the Transportation Research Board 87th Annual Meeting*, Washington, DC, USA, 2008.

[27] M. Hollander and D. A. Wolfe, *Nonparametric statistical methods*, John Wiley & Sons, Inc., Danvers, MA, USA, 1999.

[28] Y. Ji, L. He, and H. M. Zhang, "Bus drivers' responses to real-time schedule adherence and the effects on transit reliability," *Transportation Research Record*, vol. 2417, pp. 1–9, 2014.