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Research Article

Integrated Optimization of Tram Schedule and Signal Priority at Intersections to Minimize Person Delay

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Modern trams, as a rapidly developed high-volume transport model, have strict requirements on schedule, because the delay will reduce the attractiveness of public transportation to passengers. To improve punctuality and reliability, Transit Signal Priority (TSP) has been employed at intersections, which can extend or insert green phase to trams. However, extending or inserting the green phase for every tram might lead to heavy delays to crossing vehicles. To address this problem, this study developed an integrated optimization model on tram schedule and signal priority which can balance the delay between trams and other vehicles to minimize person delay. Three conditional strategies named early green, green extension, and phase insertion are proposed for the signal priority. Simultaneously, arrival time, departure time of trams at stations, and stop line are optimized as well. The proposed model is tested with a numerical case and a real-world case at Ningbo tramline in China. The results indicate that the integrated optimization can reduce the average delay of all passengers on trams and other vehicles, compared to timetable optimization only and TSP only. It is also found that the proposed model is able to adapt to the fluctuation in the ratio of tram passenger to auto vehicle user, compared with only minimizing tram passenger delay or auto vehicle user delay.

1. Introduction

Modern trams have been developed rapidly in many cities across the world. In China, for example, tram services were provided in 14 cities by the end of 2017, which is 7 times that in 2010. In most cities, Semi-exclusive rights-of-way (ROW) have been adopted where trams have an exclusive lane in the road section and share ROW with other vehicles at the intersection. Apparently, trams might be interrupted by other vehicles or by a red signal at intersections.

To reduce the stop of trams at intersections, Transit Signal Priority (TSP) has been applied, which allows preferential treatment of transit vehicles at signalized intersections. In general, TSP can be divided into two main types: passive priority and active priority. Passive priority is to create a green wave band for transit vehicles by adjusting the sequence and shift of signaling phases among successive intersections. Ideally, trams travelling at the recommended speed can pass through all intersections without a stop. However, the practical performance of passive priority might deteriorate due to interruptions at stations and intersections. For example, longer boarding time than the scheduled one will cause the pre-set green wave to fail, which means that the tram might hit a red signal if it still travels at the recommended speed.

Different from the passive priority, active priority can detect trams and give green phase to trams whenever they are approaching the intersection. This makes the active priority less sensitive to the disturbance of tram service. The strategies of active TSP can be further classified into unconditional and conditional. Unconditional active TSP, which gives an absolute priority to trams at intersections, is able to minimize tram travel time at the expense of imposing heavy delays to non-priority vehicles at intersections. Although unconditional TSP always provides transit vehicles with green, it inevitably causes disturbances to non-priority vehicles. On the opposite, conditional active TSP only grants priority based on a set of conditions and rules, such as whether

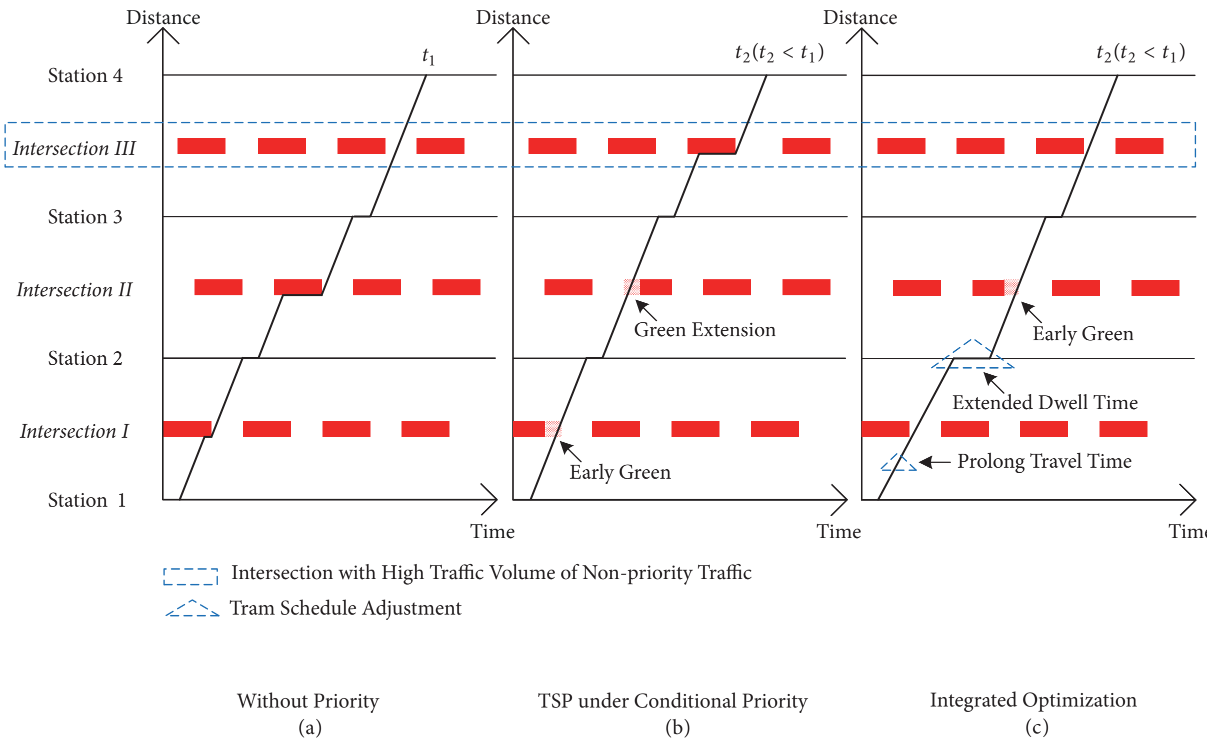

Figure 1: Benefits of integrating conditional active TSP strategy and tram schedule adjustment.

or not the disturbance to non-priority vehicles exceeds the threshold value and the transit vehicle is already delayed. In other words, conditional active TSP considers the trade-off between trams and other vehicles. It has been proposed to minimize the average travel time of each person on trams and other vehicles at intersections. Compared to unconditional active TSP, conditional active TSP only has minor impacts on other vehicles.

In addition to TSP, tram timetable optimization is another way to reduce the potential stop of trams at intersections. By adjusting timetable, e.g., the run-time on inter-station section and the dwell time at stations, trams can be scheduled to arrive at intersections during a green time. However, in practice the adjustment range on the timetable is limited. This is because the minimal run-times and dwell times of trams are constrained by the speed limits and the numbers of boarding and alighting passengers. The maximum run-times and dwell times are also specified to keep a reasonable service level. Therefore, tram timetable optimization is unable to ensure all the trams meeting green signal at intersections. Compared with only optimizing tram timetable or sole TSP, the integrated optimization on tram timetable and conditional active TSP might further reduce the average travel time of passengers on both trams and other vehicles. Figure 1 demonstrates the possible benefits of integrated optimization. Without TSP, as shown in Figure 1(a), the tram, operating with original timetable, meets red signals at intersections *I* and *II*, which prolongs tram travel time.

With conditional active TSP, as shown in Figure 1(b), early green and green extension are employed at intersections *I* and *II* respectively, to allow tram meeting green signals at these two intersections where the traffic volumes of non-priority vehicles are relatively lower. At intersection *III*, the active TSP strategy would not be triggered due to the higher traffic volume of non-priority vehicles, which indicates that the tram with original timetable might hit red signals. Compared to the case (a) with no TSP, the average travel time of passengers on both trams and other vehicles could be reduced in case (b) where the conditional active TSP is applied.

With integrated optimization on conditional active TSP strategy and tram timetable, only early green is activated at intersection *II* as shown in Figure 1(c). By prolonging travel time during station 1 and intersection *I*, the tram can avoid red signal at intersection *I* without TSP, which means that other non-priority vehicles will not be interrupted. Meanwhile, the tram does not experience red signal at intersection *III*, which is the combined effect of prolonging the travel time during station 1 and station 2 and extending dwell time at station 2. In other words, the duration time of tram waiting at a red light at intersection *III* is transferred to the prolonged time during section and the extended dwell time at station 2. Thus no TSP strategy is required to activate at intersection *III*. Therefore, the delays imposed on non-priority vehicles are smaller than those in case (b) while the tram travel time remains, which indicates less average travel time of passengers on both trams and other vehicles.

As discussed above, this integrated optimization model of conditional active TSP and tram schedule can further reduce tram stops at intersections than previous studies which only focus on TSP or tram timetabling. At the same time, interruptions to other non-priority vehicles can be reduced, which means that all passengers on trams and auto vehicles are considered in the proposed optimization model to achieve higher operational efficiency of the whole system.

The remainder of this paper is organized as follows. The literature review of the problem is elaborated in Section 2. Then the problem has been described in Section 3, which is followed by the formulation of the integrated optimization model on conditional active TSP and tram timetable in Section 4. The methodology to solve the proposed model is developed in Section 5. Case studies are conducted to investigate the performance of the proposed method in Section 6 followed by summarizing the conclusions of this study in Section 7.

2. Literature Review

TSP allows preferential treatment of transit vehicles at signalized intersections. It gives transit vehicles a little extra green time or a little less red time at traffic signals to reduce the time wasted on stop or deceleration [1]. The implementation of TSP strategies can contribute to lower delays for priority transit vehicles and auto vehicles that travel in the same directions [2, 3]. Other potential benefits include improved transit schedule reliability, increased passenger comfort and ultimately increased the attractiveness of the transit service [4–6].

Passive priority strategy and active priority are the two main types of the TSP strategies [7]. Passive priority is to create a green wave band for transit vehicles along their trips by adjusting the sequence and shift of signaling phases among different intersections [8]. MAXBAND, MULTIBAND and AM-BAND are the three classical models for signal control with passive priority. MAXBAND aims to find the optimal signaling parameters and to maximize the bandwidth of green wave [9–11]. MULTIBAND is able to expand the bandwidth of green wave attained by MAXBAND, by relaxing the constraint of equal width on green wave band at different sections [12–14]. AM-BAND further releases the symmetrical constraint on green wave band, which improves the utilization of green time and decreases stops and delays of vehicles at intersections [15]. The practical performance of passive priority might be deteriorated due to disturbance of tram service, which is not uncommon in practice.

Different from passive priority, active priority is widely used because of its flexibility. Active priority strategy grants green signal to trams by adjusting the start time and/or end time of the stage or phase giving transit vehicles right away in each signal cycle [16, 17]. The common strategies to carry out the active TSP include green extension, early green and phase insertion [18–20]. Green extension prolongs the green time when a tram arrives at intersections just behind the end of a green phase. Early green shortens the time of the phase ahead of green when a tram arrives at intersections just before the start of a green phase. Phase insertion denotes that a special green phase is inserted within the red phase. The phase insertion is generally adopted when a tram arrives at intersections at the middle of the red phase [21, 22].

The active priority can be further classified into unconditional and conditional [23]. Unconditional priority strategies grant an absolute priority to transit vehicles once they are detected at the upstream of the intersections. There are no differential treatments between the type of transit vehicle and the state of non-priority vehicles [24–27]. Although unconditional TSP always provides transit vehicles with green phase and speeds up transit vehicles by guaranteeing no red signals at intersections, it inevitably causes disturbances to non-priority vehicles, particularly when the volume of non-priority vehicles is high [28–30]. Wahlstedt [31] indicated that TSP results in shorter travel times for buses and longer travel times for crossing traffic and traffic following the prioritized buses in one direction. Skabardonis and Christofa [32] confirmed that, under high traffic volume conditions, the provision of transit signal priority could deteriorate the Level of Service (LOS) on cross-streets by up to two levels.

The conditional priority strategies based on a set of conditions and rules have also been developed to reduce disturbances to non-priority vehicles [23]. Conditional TSP balances the benefits to trams and the disruptions to non-priority traffic and is only granted for trams if the disruption is beyond a certain range. Altun and Furth [33] indicated that, compared to unconditional active TSP, conditional active TSP resulted in only minor impacts on non-priority traffic. Furth and Muller [34] proposed a conditional priority method for buses and the results show that, compared to no priority, absolute priority caused severe increases in delay, while conditional priority had almost no impact. Similarly, Kenny and Amer [35] showed that the proposed conditional control policy could effectively reduce the transit headway deviation and causes smaller disturbance to cross street traffic compared with the existing unconditional transit signal priority algorithm.

Additionally, tram schedule optimization can also decrease stops of trams at intersections. The traditional scheduling problem is to define a series of trips with prescribed starting and ending times, with the objective of minimizing costs, including capital costs for required buses and operating costs based on traveling distance and idle time [36]. The majority of existing studies focus on railway and subway system, while scheduling problems in the tram system are quite limited in the literature. Nachtigall and Voget [37] developed a timetabling model for the railway system, which is to minimize the passenger waiting time at stations. Wong and Ho [38] presented the application of a dynamic programming approach, with the aid of an event-based model, to devise an optimal set of dwell times and run times for trains under given operational constraints over a regional level. Niu and Zhou [39] applied a timetable optimization approach for the urban rail system. The objective was to minimize passengers' waiting time at stops and also reduce the waiting time passengers who were not able to board their desired service suffered because of congestions. Robenek et al. [40] highlighted the consideration of passenger satisfaction in the design of train timetables. Zhou et al. [41] developed an integrated optimization model on train control and timetable to minimize the net energy consumption. However, tram scheduling problems cannot be solved by these present models. The reason is that the operating environment of the

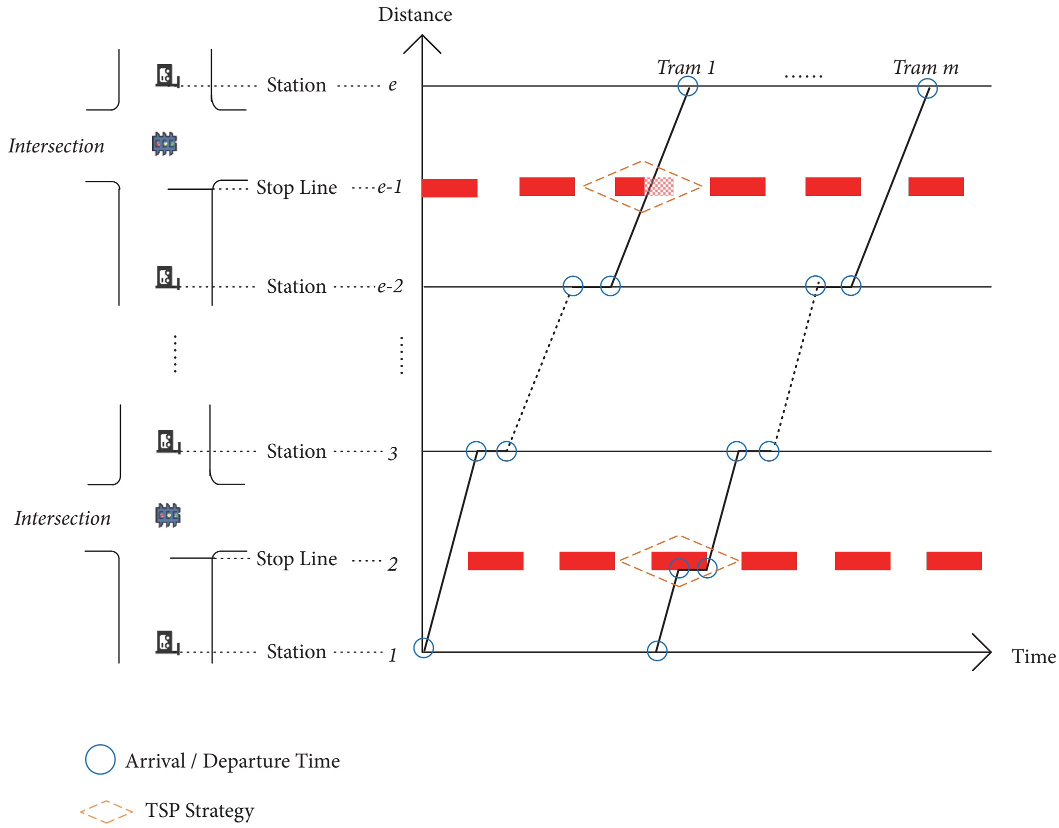

FIGURE 2: Integrated optimization on signal priority and tram scheme.

tram is different from that of the railway and subway system. Train operation would not be influenced by other traffic along its rail track, while trams share intersections with other traffic and tram operations are inevitably affected at the intersection.

Conditional active TSP and tram schedule adjustments still have their limitations when they are applied separately. Therefore by integrating conditional active TSP and tram schedule adjustment, fewer stops of tram at intersections than they are applied separately. Recently, Shi et al. [42] have explored at the planning level the benefits of coordinating tram movements and signal timings at controlled intersections. Its objective is to minimize the weighted sum of the total tram travel time and TSP'S negative impacts on other traffic. However, Shi et al. [42] applied unconditional TSP and give trams absolute priority, which means that the negative impacts on other traffic are not the minimum. The disturbances to other traffic can be reduced without sacrificing the total tram travel time if conditional TSP is applied. Moreover, Shi et al. [42] only considered tram operations and ignored the operations of auto vehicles, which cannot maximize the operational efficiency of the whole intersections.

This paper aims to propose an integrated optimization model on conditional active TSP and tram schedule adjustments to minimize person delay of the whole system referring to all trams and non-priority vehicles along intersections. By applying conditional active TSP, minor impacts are imposed on other traffic compared to the unconditional one. Considering each person on trams and auto vehicles rather than only one transportation mode can contribute to the higher operational efficiency of the whole intersections. TSP disturbance is measured as auto vehicle delay caused by TSP activation, which is more adaptable to changes in signal timing and traffic volume.

3. Problem Description

With semi-exclusive ROW, trams will not be disturbed at any road section between successive intersections. They only stop at the station for passenger boarding and alighting or stop at intersection stop line to wait for a red signal. Therefore, stop lines at intersections and stations along the tramline are considered as the critical nodes ($1 \ldots e$) for TSP strategy and timetable optimization, as shown in Figure 2. This paper integrally optimizes TSP strategy at each intersection and tram schedule along the tramline to minimize average person delay. The conditional active TSP strategies at intersections, the signal offsets among different intersections, and tram schedule are the decision variables to be optimized in the discussed problem.

The proposed conditional active TSP strategies consist of three parts: (1) whether TSP measures are activated for the incoming tram, (2) which specific TSP measure is applied for the tram, and (3) how long the TSP measure will continue. These three parts are defined by three variables which are μ_{sk}, μ_{sk}^{w} and t_{skNj}^{w}. The first part is to estimate whether the

Table 1: Decision variables.

t_{me}^{A}	Arrival time of tram m at node e
t_{me}^{D}	Departure time of tram m from node e
t_{ik}^{GS}	The original green start of lane group j during phase n in cycle k at intersection i
t_{ik}^{GE}	The original green end of lane group j during phase n in cycle k at intersection i
μ_{ik}^{T}	1, if a TSP measure is taken in cycle k at intersection i; 0, otherwise
μ_{ik}^{W}	1, if green extension/phase insertion/early green is taken in cycle k at intersection i; 0, otherwise
t_{ik}^{W}	Extra green time for a TSP action in cycle k at intersection i
$t_{ik\alpha}^{E}$	The end time of green extension α in cycle k at intersection i
$t_{ik\beta}^{S}$	The start time of phase insertion β in cycle k at intersection i
$t_{ik\beta}^{E}$	The end time of phase insertion β in cycle k at intersection i
$t_{ik\gamma}^{S}$	The start time of early green γ in cycle k at intersection i

arrival time of the tram is during green phase. If tram arrives at intersections during green phase, no TSP is activated. Otherwise, TSP is activated depending on the efficiency of the whole system. In other words, no TSP is activated even trams hit red phase at intersections if the activation causes too much delay to auto vehicles and results in lower efficiency of the whole system. The second part is to decide whether to implement green extension, phase insertion, or early green. The decision is made according to the arrival time of the tram at intersection. If the tram will arrive at intersection during the beginning of the red phase, green extension is applied. If the tram will arrive during the end of the red phase, early green is applied. If the tram will arrive at the middle of red phase, phase insertion is applied. In the third part, the duration of the specific TSP measure is specified based on the minimal person delay.

The decision variables with respect to tram schedules could be denoted by tram arrival and departure time at each node denoted as t_{me}^{A} and t_{me}^{D}. If a tram arrives at an intersection during a green phase or TSP measures are activated when a tram hits the red signal at intersections, the arrival time is equal to the departure time. As for tram 1 in Figure 2, its arrival time is equal to departure time at node 2 and node *e-1*. If trams arrive at intersections during red phase with no TSP measure activation, trams depart from intersections at the beginning of the next green phase.

The average person delay of the whole system involves both auto vehicle user delay and tram passenger delay. Auto vehicle delay is calculated based on a classical vehicle delay model proposed by the Australian Road Research Board (ARRB) [43]. The ARRB model is applicable to both under-saturated and over-saturated conditions [44]. Tram delay is defined as the difference between the actual travel time and the minimum travel time, which is the time that trams run at the highest speed and do not experience any red phase at intersections.

In order to formulate the integrated optimization of signal priority and tram schedule, the following assumptions are made throughout this paper. Tram is the only public transit mode along the road. All intersections are equipped with TSP control devices. Similar to the metro timetable optimization in Niu et al. [39] and Yang et al. [45], only schedules for trams heading in one direction are considered. For tramlines, tram headway is rather long and there is little chance that two trams may meet at the same intersections. Thus trams in the other direction can be optimized in the same way.

4. Mathematical Model

4.1. Notations. See Tables 1 and 2.

4.2. Objective Function. To improve punctuality and reliability of trams, TSP strategies have been employed at intersections, which might lead to heavy delays to auto vehicles. To address this problem, tram schedules and TSP strategies are integrally optimized to balance the delay between trams and other vehicles. The proposed model aims to increase the efficiency of the whole system considering both tram passengers and auto vehicle users. Therefore, the weighted average delay of both auto vehicle users and tram passengers is chosen as the objective of the proposed model to be minimized, as shown in Eq. (1). In this study, a higher weight is assigned to tram passengers. The reason is that public transit should be granted more priorities to increase the attractiveness to passengers, thereby reducing traffic congestion.

$$\min \frac{\sum_{\mathrm{i},k} \xi_a Q_i \overline{D}_{iknj} + \eta \cdot \sum_{i,\mathrm{s}} \xi_t \sigma_{s,s+1}^{m} \left| t_{mi}^{A} - t_{mi}^{A'} \right|}{\sum_{\mathrm{i},k} \xi_a Q_i + \sum_{\mathrm{m,s}} \xi_t \overline{\sigma}^{m}} \tag{1}$$

The weighted factor η decides the degree of priority assigned to tram passengers, which should be greater than one.

4.3. Auto Vehicle Delay. Auto vehicle delay model is the primary tool to analyze vehicle delay for signalized intersections. Four auto vehicle delay models are widely used to analyze vehicle delay for signalized intersections, including the Webster model, the ARRB model, the HCM1985 model, and the HCM2000 model. Yao et al. [46] analyze the applicability of four vehicle delay models for signalized intersections and design experimental environments on the basis of certain traffic demands and signal control. The results shown that, for isolated signalized intersections, the ARRB model displays the best performance in vehicle delay estimation. Thus the ARRB model is applied to calculate auto vehicle delay in this paper.

TABLE 2: Notations and parameters.

General notations	
e	Index of nodes, including stations and intersections
i	Index of intersections
s	Index of stations
m	Index of trams
w	Index of TSP actions, where green extension, phase insertion and early green are denoted as α, β, γ respectively
j	Index of approach lane direction, where through, left-turning and right-turning are denoted as z, l,r, respectively.
Tram parameters	
$t_{me}^{A'}$	Arrival time of tram m at node e based on the minimal travel time schedule
$t_{me}^{D'}$	Departure time of tram m from node e based on the minimal travel time schedule
$\rho_{e,e+1}^{\min}$	Minimum running time for each tram from node e to node $e+1$
$\rho_{e,e+1}^{\max}$	Maximum running time for each tram from node e to node $e+1$
$\theta_s^{\min}$	Minimum dwell time for each tram at station s
$\theta_s^{\max}$	Maximum dwell time for each tram at station s
h_a	Minimum headway between two consecutive trams arrivals at the same station
h_d	Minimum headway between two consecutive trams departures at the same station
h_a^d	Minimum headway between a tram departure and another tram arrival at the same station
$\sigma_{s,s+1}^m$	Load factor of tram m between two consecutive stations
$\overline{\sigma}^i$	Average load factor of tram m along the tramline
ξ_m	Fixed passenger occupancy of tram m
η	Weight factor determining tradeoff of person delay between tram and auto vehicles
Signal parameters	
k	Index of signal cycle at intersection i
n	Index of phase in cycle k for intersection i
N	The phase serving tram, which is also called critical phase
$\tau_{n=N}$	1, if phase n is the critical phase N; 0, otherwise
$\tau_{n=N-1}$	1, if phase n is the previous phase before critical phase N; 0, otherwise
C_{ik}'	The unadjusted cycle length in cycle k at intersection i
g_{iknj}'	The unadjusted green duration of lane group j during phase n in cycle k at intersection i
λ_{iknj}^W	Green ratio of lane group j during phase n in cycle k at intersection i
$\delta_{\min}^W$	Minimum green duration for TSP actions
$\delta_{\max}^W$	Maximum green duration for TSP actions
$\varphi_{\min}$	Minimum red time between two green phases in a signal cycle
μ_{ik}	1, if a TSP action is taken in cycle k at intersection i; 0, otherwise
Traffic parameters	
D_{iknj}	Average vehicle delay of lane group j during phase n in cycle k at intersection i
$\overline{D}_{ik}$	Average vehicle delay in cycle k at intersection i
q_{iknj}'	Original traffic volume of lane group j during phase n in cycle k at intersection i
Δq_{iknj}^W	Variation of traffic volume caused by applying TSP strategy
x_{iknj}	Saturation of lane group j during phase n in cycle k at intersection i
F_{iknj}	Saturation volume of lane group j during phase n in cycle k at intersection i
c_{iknj}	Capacity of lane group j during phase n in cycle k at intersection i
ω_{iknj}^{mA}	1, if tram m arrives at intersection i during phase n in cycle k; 0, otherwise
Q_{ik}	Auto traffic volume of intersection i in cycle k
ξ_a	Passenger occupancy of an auto vehicle

The ARRB model is formulated from Eq. (2) to Eq. (4). Eq. (2) defines auto vehicle delay of a lane or a lane group. Eq. (3) specifies that flow ratio is calculated based on traffic volume and saturation flow. Eq. (4) describes the saturation calculation when average overflow queue is approximately zero.

$$D_{iknj} = \begin{cases} \dfrac{C_k\left(1-\lambda_{iknj}\right)^2}{2\left(1-y_{iknj}\right)} + \dfrac{c_{iknj}x_{iknj}T}{4q_{iknj}}\left[\left(x_{iknj}-1\right)+\sqrt{\left(x_{iknj}-1\right)^2+\dfrac{12\left(x_{iknj}-x_{0iknj}\right)}{c_{iknj}T}}\right], & x_{iknj} > x_{0iknj} \\ \dfrac{C_{ik}\left(1-\lambda_{iknj}\right)^2}{2\left(1-y_{iknj}\right)}, & x_{iknj} \le x_{0iknj} \end{cases} \tag{2}$$

$$y_{iknj} = \frac{q_{iknj}}{F_{iknj}} \tag{3}$$

$$x_{0iknj} = 0.67 + \frac{F_{iknj}g_{iknj}}{600} \tag{4}$$

Vehicle delay at one intersection can be calculated by the aggregated vehicle delay in each lane or lane group, as shown in Eq. (5).

$$\overline{D}_{iknj} = \frac{\sum_{n,j} D_{iknj}q_{iknj}}{\sum_{n.j} q_{iknj}} \tag{5}$$

Green ratio, capacity, and saturation are all calculated from green duration, cycle length, traffic volume, and saturation flow. Especially, the value of saturation flow only depends on intersection infrastructure, which means that the value of saturation flow in one specific lane is constant. Therefore, the ARRB model depends on three variables, which are green duration, cycle length, and traffic volume. Thus auto vehicle delay of an intersection is simplified as Eq. (6).

$$\overline{D}_{iknj} = d_a^r\left(g_{iknj}, \mathrm{C}_{ik}, q_{iknj}\right) \tag{6}$$

With given green duration, cycle length, and traffic volume at different intersections, auto vehicle delay of each intersection can be calculated.

Scenario 1: Green Extension Activation. Eq. (7) to Eq. (10) describe the change of green duration, cycle length, and traffic volume when the green extension is activated. Each lane group j during phase n in cycle k at intersection i is the calculation object in this paper. The phase served tram is considered as critical phase, which is denoted as N. Green extension strategy is applied only when the tram arrives at intersections during phase *N+1*, which is the next phase after the critical phase N.

$$\tau_{n=N} = \begin{cases} 1, & if\ n = N \\ 0, & otherwise \end{cases} \tag{7}$$

$$g_{sknj} = g'_{sknj} + \tau_{n=1}t^{\alpha}_{skNj} \tag{8}$$

$$C_{sk} = C'_{sk} + t^{\alpha}_{skNj} \tag{9}$$

$$q_{sknj} = q'_{sknj} + \tau_{n=1}\Delta q^{\alpha}_{skNj} \tag{10}$$

Eq. (7) identifies whether the current phase is in the critical phase N or not.

Eq. (8) describes the change of green duration when the green extension is activated. Once the green extension strategy is activated, green duration of the critical phase N is extended by t^{α}_{skNj} and green duration of other phases is still the same.

Eq. (9) describes the change of cycle length when the green extension is activated. Because the green duration of critical phase N is increased by t^{α}_{skNj} and other phases keep the same, the cycle length of cycle k is increased by t^{α}_{skNj} as well.

Eq. (10) describes the change of traffic volume when the green extension is activated. Green extension strategy leads to the green duration of phase N increasing. Meanwhile, traffic volume increases by Δq^{α}_{skNj}.

Above all, auto vehicle delay of one intersection when the green extension is activated is simplified as Eq. (13).

$$\overline{D}^{\alpha}_{sknj} = d_a^r\left(g'_{sknj} + \tau_{n=1}\mathrm{t}^{\alpha}_{skNj}, C'_{sk} + t^{\alpha}_{skNj}, q'_{sknj} + \tau_{n=1}\Delta q^{\alpha}_{skNj}\right) \tag{11}$$

Scenario 2: Early Green Activation. Eq. (12) to Eq. (15) describe the change of green duration, cycle length, and traffic volume when the early green strategy is activated. Early green strategy is applied only when the tram arrives at intersections during phase *N-1*, which is the last phase before the critical phase N.

$$\tau_{n=N-1} = \begin{cases} 1, & if\ n = N-1 \\ 0, & otherwise \end{cases} \tag{12}$$

$$g_{sknj} = g'_{sknj} + \left(\tau_{n=N} - \tau_{n=N-1}\right)t^{\gamma}_{skNj} \tag{13}$$

$$C_{sk} = C'_{sk} \tag{14}$$

$$q_{sknj} = q'_{sknj} + \left(\tau_{n=N} - \tau_{n=N-1}\right)\Delta q'_{sknj} \tag{15}$$

Eq. (12) identifies whether the current phase is in the phase *N-1* or not.

Eq. (13) describes the change of green duration when the early green strategy is activated. Early green is also called red truncation, which means the red phase is reduced. Once the early green strategy is activated, the green duration of phase *N-1* is shortened by t^{γ}_{skNj} and green duration of other phases is still the same.

Eq. (14) describes that cycle length does not change when the early green strategy is activated. The extra green duration for phase N is at the cost of reducing the green duration of phase N-1. Thus the cycle length is the same as the original one.

Eq. (15) describes the change of traffic volume when the green extension is activated. The green duration of phase N-1 is shortened by t^{γ}_{skNj} and traffic volume is reduced by $\Delta q^{\gamma}_{sk,N-1,j}$. In terms of the residual phases, traffic volume is kept the same.

Above all, auto vehicle delay of one intersection when the early green is activated is simplified as Eq. (16).

$$\begin{aligned}\overline{D}^{\gamma}_{sknj} = d^{r}_{a} \Big(& g'_{sknj} + \left(\tau_{n=N} - \tau_{n=N-1}\right) t^{\gamma}_{skNj}, C'_{sk}, q'_{sknj} \\ & + \left(\tau_{n=N} - \tau_{n=N-1}\right) \Delta q^{\gamma}_{sknj} \Big)\end{aligned} \tag{16}$$

Scenario 3: Phase Insertion Activation. Eq. (17) to Eq. (25) describe the change of green duration, cycle length, and traffic volume when the phase insertion strategy is activated. Once phase insertion is active, an extra phase in granted for trams denoted as N^1. The extra phase N^1 is inserted to another phase n^T according to tram arrival time at intersections. Phase n^T is interrupted and thus divided into two phases n^1 and n^2. The residual phases do not get any influence which are denoted as n^0.

$$\tau_{n=n^0} = \begin{cases} 1, & if\ n = n^0 \\ 0, & otherwise \end{cases} \tag{17}$$

$$\tau_{n=N^1} = \begin{cases} 1, & if\ n = N^1 \\ 0, & otherwise \end{cases} \tag{18}$$

$$\tau_{n=n^1} = \begin{cases} 1, & if\ n = n^1 \\ 0, & otherwise \end{cases} \tag{19}$$

$$\tau_{n=n^2} = \begin{cases} 1, & if\ n = n^2 \\ 0, & otherwise \end{cases} \tag{20}$$

$$\begin{aligned} g_{sknj} = {} & \tau_{n=n^0} g'_{skn^0 j} + \tau_{n=N^1} t^{\beta}_{skNj} \\ & + \tau_{n=n^1} \left(t^{GE}_{sknj} - t^{S}_{skNj\beta} \right) \\ & + \tau_{n=n^2} \left(t^{GE}_{sknj} - t^{S}_{skNj\beta} \right) \end{aligned} \tag{21}$$

$$C_{sk} = C'_{sk} + t^{\beta}_{skNj} \tag{22}$$

$$\begin{aligned} q_{sknj} = {} & \tau_{n=n^0} q'_{skn^0 j} + \tau_{n=N^1} \Delta q^{\beta}_{skN^1 j} \\ & + \tau_{n=n^1} q^{\beta}_{skn^1 j} + \tau_{n=n^2} q^{\beta}_{skn^2 j} \end{aligned} \tag{23}$$

$$q^{\beta}_{skn^1 j} + q^{\beta}_{skn^2 j} < q'_{sknj} \tag{24}$$

Eq. (17) - (19) identify the category of the current phase.

Eq. (20) describes the change of green duration when the phase insertion strategy is activated. For unaffected phases, the green duration is the same as the original ones. For the extra phase N^1, the starting time and the end time are denoted as $t^{S}_{skNj\beta}$ and $t^{E}_{skNj\beta}$. Obviously $t^{\beta}_{skNj} = t^{E}_{skNj\beta} - t^{S}_{skNj\beta}$ is the green duration of the extra phase N^1. For the two divided phases, the total green duration of the two phases is still the same.

Eq. (21) describes the change of cycle length when the phase insertion strategy is activated. The cycle length is increased by the green duration of the extra phase N^1, which is t^{β}_{skNj}.

Eq. (22) describes the change of traffic volume when green extension is activated. For unaffected phases, the traffic volume is the same as the original one. For extra phase N^1, the traffic volume is based on the green duration of phase N^1. The traffic volume during phase N^1 is denoted as $\Delta q^{\beta}_{skN^1 j}$. For the two divided phases n^1 and n^2, traffic volume is not the same as before.

As described in Eq. (24), the sum of traffic volume during phases n^1 and n^2 is smaller than the traffic volume during the former intact phase n^T. Because the continuous traffic flow is disrupted by the inserted phase, traffic flow is shortened.

Above all, auto vehicle delay of one intersection when the phase insertion strategy is activated is simplified as Eq. (25).

$$\overline{D}^{\beta}_{sknj} = d^{r}_{a} \left(g_{sknj}, C_{sk}, q_{sknj} \right) \tag{25}$$

4.4. Constraints

4.4.1. Signal Constraints. Signal constraints deal with signal variables to address the TSP strategy and the signal timing of each intersection.

(1) Constraint of Green Extension. Once the green extension action is activated in cycle k at intersection s, the extended green time is between $\delta^{\alpha}_{\min}$ and $\delta^{\alpha}_{\max}$.

$$\mu^{\alpha}_{ik} \delta^{\alpha}_{\min} \le t^{\alpha}_{ikNj} \le \mu^{\alpha}_{ik} \delta^{\alpha}_{\max} \tag{26}$$

Green extension action is applied only when trams arrive during phase *N+1*.

$$\mu^{\alpha}_{ikNj} = \mu_{ikNj} \cdot \omega^{mA}_{ik,N+1,j} \tag{27}$$

(2) Constraint of Phase Insertion. Once the phase insertion action is applied in cycle k at intersection s, the green duration of the insertion phase is between $\delta^{\beta}_{\min}$ and $\delta^{\beta}_{\max}$.

$$\mu^{\beta}_{ik} \delta^{\beta}_{\min} \le t^{\beta}_{ikNj} \le \mu^{\beta}_{ik} \delta^{\beta}_{\max} \tag{28}$$

Table 3: Numbers of variables and constraints in the model.

Type	Name	Theoretical dimension
Continuous variable	t_{me}^{A}, t_{me}^{D}	$\|M\| \cdot \|E\|$
	t_{ik}^{W}	$\|W\| \cdot \|I\| \cdot \|K\|$
	t_{ik}^{GS}, t_{ik}^{GE}	$\|I\| \cdot \|K\|$
	$t_{ik\alpha}^{E}, t_{ik\beta}^{S}, t_{ik\beta}^{E}, t_{ik\gamma}^{S}$	$\|I\| \cdot \|K\|$
Binary variable	$\mu_{ik}^{T}, \mu_{ik}^{W}$	$\|W\| \cdot \|I\| \cdot \|K\|$
Constraints	Constraint (26)-(33)	$\|I\| \cdot \|K\|$
	Constraint (34)	$\|M\| \cdot \|S\|$
	Constraint (35)	$\|M\| \cdot \|E-1\|$
	Constraint (36)-(38)	$\|M-1\| \cdot \|E\|$

(3) Constraint of Early Green. Once early green action is activated in cycle k at intersection s, the advanced green time is between $\delta_{\min}^{\gamma}$ and $\delta_{\max}^{\gamma}$.

$$\mu_{ik}^{\gamma}\delta_{\min}^{\gamma} \leq t_{ikNj}^{\gamma} \leq \mu_{ik}^{\gamma}\delta_{\max}^{\gamma} \tag{29}$$

Early green action is applied only when trams arrive during phase *N-1*.

$$\mu_{ikNj}^{\gamma} = \mu_{ikNj} \cdot \omega_{ik,N-1,j}^{mA} \tag{30}$$

(4) The Minimum Time Gap between Two Green Phases. The starting time of the inserted phase β is at least φ_{min} later than the ending of the previous green phase.

$$t_{ikNj\beta}^{S} - t_{ikNj}^{GE} \geq \varphi_{\min} \tag{31}$$

The end time of the inserted phase β is at least φ_{min} earlier than the start of the next green phase.

$$t_{ikNj\beta}^{E} - t_{ik+1,Nj}^{GS} \geq \varphi_{\min} \tag{32}$$

(5) Activate a TSP Action One Time in a Cycle. The following relation holds in practice, which means no more than one TSP action can be applied in one signal cycle at an intersection.

$$\sum_{w}\mu_{ik}^{w} \leq 1 \tag{33}$$

4.4.2. Tram Schedule Constraints. Tram schedule constraints deal with tram variables to address the arrival and departure time of tram at each station.

(1) Dwell Time. A feasible range for dwell time is enforced as follows:

$$\theta_{s}^{min} \leq t_{ms}^{D} - t_{ms}^{A} \leq \theta_{s}^{max} \tag{34}$$

(2) Link Travel Time. The travel time between two nodes is also adjustable:

$$\rho_{e,e+1}^{max} \leq t_{m,e+1}^{A} - t_{me}^{D} \leq \rho_{e,e+1}^{min} \tag{35}$$

(3) Headway. The minimum headway between arrivals of trams m and *m+1* at station s is described as follows.

$$t_{m+1,s}^{A} - t_{ms}^{A} \geq h_{a} \tag{36}$$

The minimum headway between departures of trams m and *m+1* at station s is described as follows.

$$t_{m+1,s}^{D} - t_{ms}^{D} \geq h_{d} \tag{37}$$

The minimum headway between the departure of trams m and the arrival of tram *m+1* is described as follows.

$$t_{m+1,\mathrm{e}}^{A} - t_{me}^{D} \geq h_{a}^{d} \tag{38}$$

5. Methodology

5.1. Complexity of Formulation. According to the optimization model formulated in Section 4, all the variables can be classified into two types. The first type refers to continuous decision variables including arrival time and departure time of trams, the duration of TSP strategies, and the signal offsets among different intersections. The second type is binary decision variables including whether or not TSP measures are activated for the incoming tram and which specific TSP measure is applied for the tram. It is obvious that the formulated model in Section 4 is a non-linear programming model. The numbers of variables and critical constraints of the problem are given in Table 3.

The complexity of the formulated model is mainly affected by the number of trams —*M*—, the number of intersections —*I*—, and the number of stations —*S*—. According to Table 3, the quantity of model variables is 89 when one tram passes by one intersection and one station. However, the total number of variables becomes 89^2 when another intersection and another station are taken into account. As the quantity of variables exponentially increases with the scale of tramlines, enumeration solution might be unable to find the optimal solution within limited computing time. Therefore, GA is adopted to solve the proposed model for its high efficiency, because the formulated problem turns out to be a large scale problem in practice.

5.2. The Solution Method. As stated above, the formulated problem turns out to be a large scale problem that the

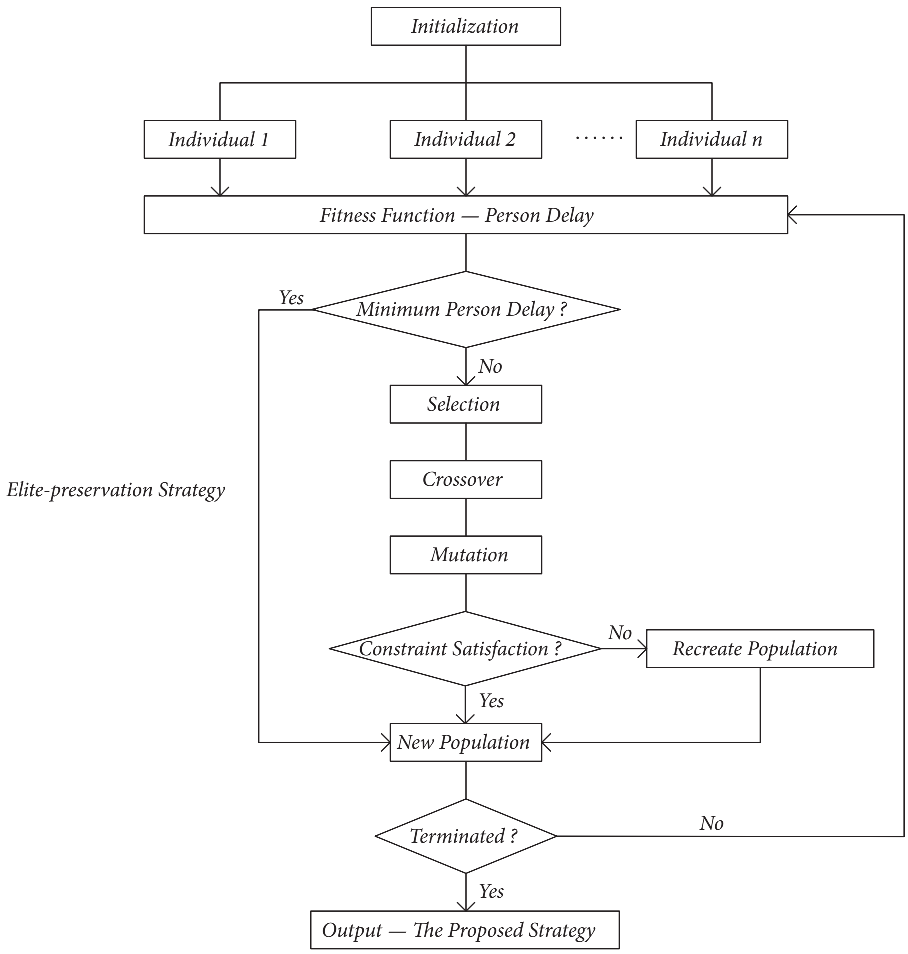

Figure 3: Flowchart of GA algorithm.

enumeration solution cannot address it effectively [47]. Therefore an intelligent search algorithm, Genetic Algorithm (GA), is applied to solve the model. The GA is a powerful multi-objective evolutionary algorithm which is competent to quickly find satisfied solutions of large scale problems. Figure 3 gives the flowchart of employing the GA to solve the formulated model.

The pseudocode of the GA is presented in Algorithm 1. The inputs include the number of nodes, the distance between each node and constraints. The output is the solution to the proposed problem, which consists of arrival and departure time of trams, unadjusted signal timing, and TSP strategies. The first step of the proposed GA is chromosome encoding, as shown in Figure 4. Real-number encoding is used to represent the chromosomes. The second step is to initialize populations. Random initialization within a certain range has been applied, where each chromosome is initialized based on the constraints of the proposed model to make sure it is a feasible solution. Thirdly, taking person delay as an objective, the delay of each chromosome will be calculated. Then the chromosome with the minimal person delay is selected into the new population directly, which is called the elite-preservation strategy. After that, the remaining chromosomes are input to the process of crossover and mutation. Each individual is checked again whether they are satisfied with constraints after crossover and mutation. The individual with the minimal average person delay is the last generation and is the attained solution of the proposed model. The evolution of GA populations stops when the pre-determined maximum generation is reached.

5.2.1. Chromosome Encoding and Initialization. At the beginning stage of GA, an initial parent population is generated based on the practical timetable configurations. Real number coding method is adopted to represent the chromosomes of individuals. The tramline covers $|I|$ intersections and $|S|$ stations, which involves $|E|$ critical nodes. There are $|M|$ trams scheduled in the given time $|K|$. Each chromosome can be mainly divided into two parts: tram schedule and signal timing, as shown in Figure 4. The length of each gene part is equal to the quantity of its corresponding variables.

5.2.2. Selection, Crossover, and Mutation. Selection, crossover, and mutation are the main genetic operators to generate offspring. In this study, the solutions in the parent population are selected by spinning the roulette wheel to produce

```
Input: Tramline Distance (TD)
       Quantity of Trams, Intersections and Stations (QM, QI, QS)
       Quantity of Tram Passengers and Auto Vehicle Users (QTP, QAV)
       Constraints (C)
Output: Tram Arrival Time (AT)
       Tram Departure Time (DT)
       Unadjusted Signal Timings (ST)
       TSP strategies (TSP)
initialPopulation ⟵Initialization (TD, QM, QI, QS, QTP, QAV, C)
newPopulation⟵ ∅
repeat
       for each individual ∈ initialPopulation do
          if fitnessCalculation (individual)=minimum person delay;
              newPopulation ⟵ newPopulation ∪ individual;
          else
              currentPopulation ⟵ initialPopulation;
          end
       end
       selectedCouples ⟵ selection (currentPopulation);
       crossedCouples ⟵ crossover (selectedCouples);
       offspring ⟵ mutation (crossedCouples)
       newPopulation ⟵newPopulation ∪ offspring;
until termination criterion
```

Algorithm 1: A Genetic Algorithm to solve the proposed model.

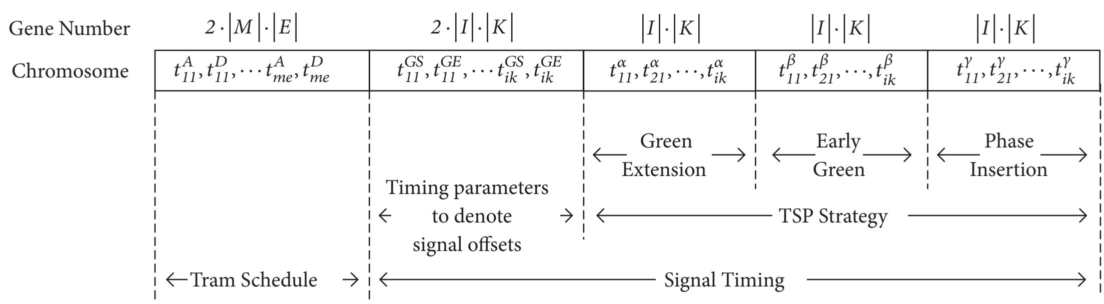

Figure 4: Chromosome encoding.

offspring. The crossover operator employed in this study only occurs amongst the same group of genes as illustrated by the Figure 5. The mutation operator modifies the value of a randomly designated gene in a chromosome with a predetermined probability.

6. Case Study

6.1. Numerical Case. Four trams running on a tramline covering two stations and two intersections, as shown in Figure 6, are employed here to demonstrate the performance of the proposed approach. Traffic volume, signal timings, lane direction, and the number of the lanes of the two intersections are specified in Table 4.

6.1.1. Performance Comparison with and without Integration. Figure 7 shows the schedules of four trams during one hour in detail. When the second tram arrives at intersection I, green extension strategy is triggered to grant the tram with green signal. Shown by the third and fourth trams, trams can arrive at the intersection during green signal, by increasing the travel time between the stations and the intersections. Thus it reduces the possibility of triggering TSP strategy, which causes delay to auto vehicles.

In order to further demonstrate the performance of the integrated model, the computational results with and without the integration of conditional active TSP and tram schedule are compared. In detail, without integration can be divided into only optimizing tram schedule and only applying TSP strategy which is subdivided into unconditional TSP and conditional TSP.

Compared with the integrated model, as shown in Table 5, only optimizing tram schedule leads to higher tram passenger delay and person delay. Auto vehicle user delay is reduced because no TSP is activated. The reduction of auto vehicle user delay is at the cost of increasing tram passenger

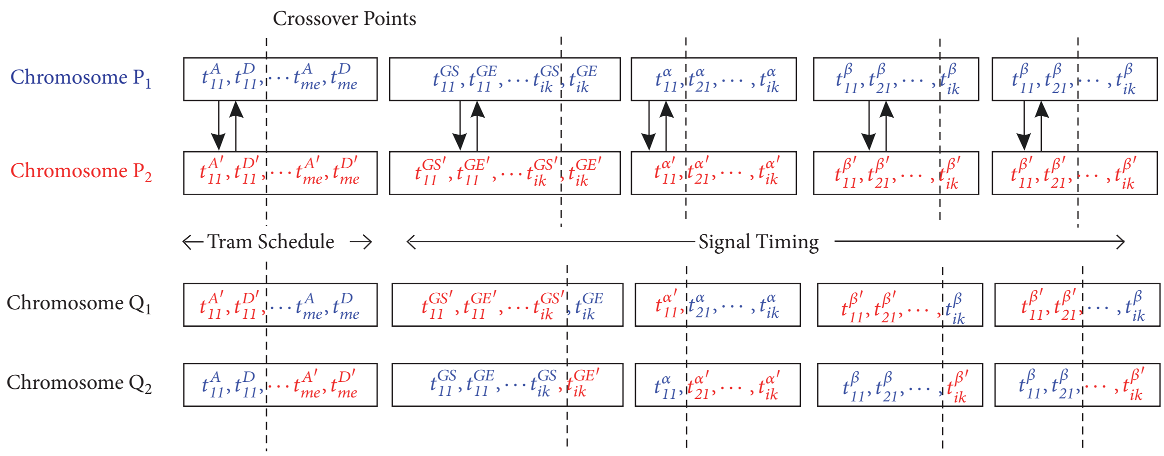

FIGURE 5: Crossover.

TABLE 4: Traffic volume and signal timings.

Intersection		Traffic flow (Number of Lane) Left	Through	Right	Split (Cycle 180 sec) Left	Through	Intersection		Traffic flow (Number of Lane) Left	Through	Right	Split (Cycle 180 sec) Left	Through
S1	South	152(1)	1020(2)	88(1)	25	90	S2	South	148(1)	1084(2)	96(1)	22	90
	North	147(1)	1016(2)	44(1)	25	90		North	153(1)	1096(2)	2(1)	22	90
	East	144(1)	512(2)	372(2)	23	42		East	148(1)	527(2)	212(2)	23	45
	West	142(1)	492(2)	16(1)	23	42		West	146(1)	518(2)	16(1)	23	45

TABLE 5: Performance comparison with and without the integration of the numerical case.

Delay/s (Variation rate/%)	Schedule only	TSP only unconditional	TSP only conditional	Integrated model
Tram passenger	60.9 (+95.34%)	0	39.2(+25.58%)	31.2
Auto vehicle user	39.1 (-8.45%)	89.2 (+108.45%)	48.2 (+12.68%)	42.8
Average person	40.7 (+6.25%)	61.1 (+59.38%)	43.7 (+14.06%)	38.3
Weighted average person	45.3 (+28.57%)	59.7 (+69.64%)	39.0 (+10.71%)	35.2

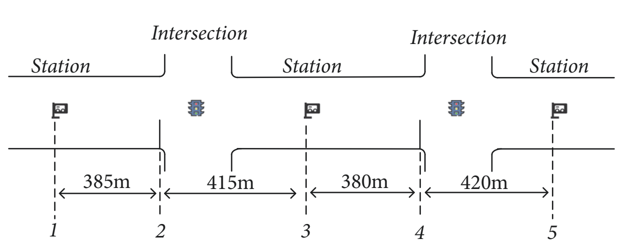

FIGURE 6: The layout of the tramline in the numerical case.

delay. Due to travel time limits between each link, only adjusting tram schedule is not able to reduce delay for tram passengers and each person of the whole system.

When unconditional TSP is applied, tram passenger delay is zero. Although tram passengers do not suffer from any delay, auto vehicle user delay is extremely high, which due to unconditional TSP does not take into account the operation of auto vehicles. When the number of auto vehicles is larger than that of tram passenger at intersection, higher auto vehicle user delay will lead to higher person delay of the whole system.

When only conditional TSP is applied, in order to trade off auto vehicle user and tram passengers, trams are not always granted priority to pass intersections without stops. As a result, tram passenger delay increases. The integrated model can further reduce auto vehicle user delay than conditional TSP because tram can be scheduled to arrive at intersections during green signals. Thus no TSP is required to activate and no delay is imposed to auto vehicle. Compared with unconditional TSP, conditional TSP can greatly reduce person delay of the whole system, although it increases tram passenger delay. Thus, conditional active priority is more suitable for system optimization.

6.1.2. Comparison between the Enumeration Solution and GA Solution. In this paper, genetic algorithm (GA) is adopted to solve the problem. Since GA is an intelligent search algorithm, the global optimal solution cannot be achieved.

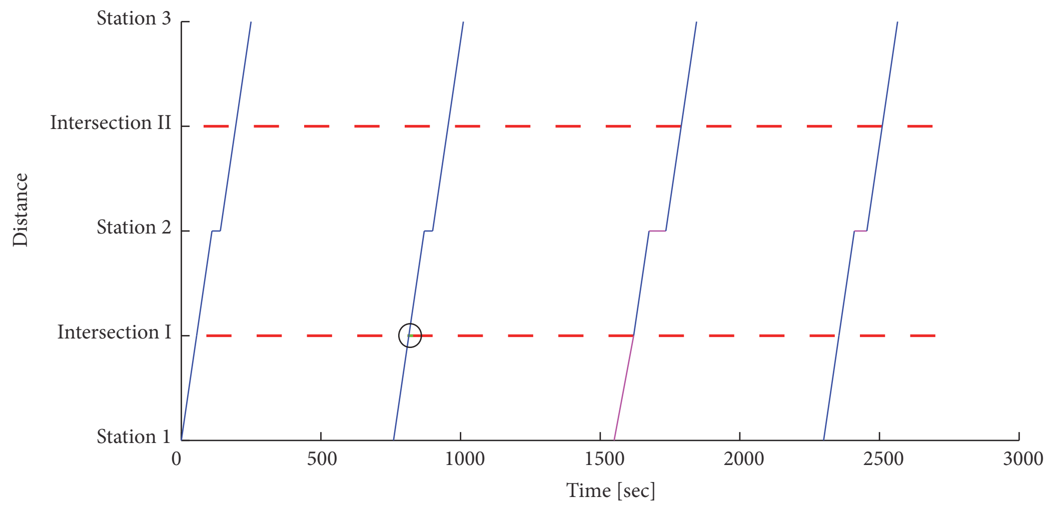

Figure 7: Tram schedule of four trams.

Table 6: Performance comparison of GA and enumeration.

Quantity of trams	Quantity of nodes: Intersections	Quantity of nodes: Stations	Method	CPU time (sec)	Objectives (sec)	Gap (%)
4	2	3	Enumeration	3954	34.7	–
			GA	2361	35.2	1.4%
	4	5	Enumeration	12814	42.3	–
			GA	1600	43.0	1.6%
8	5	7	Enumeration	>21600	54.8∗	–
			GA	2473	54.6	-0.4%
	8	9	Enumeration	>21600	70.9∗	–
			GA	3521	70.3	-0.8%
12	10	11	Enumeration	>21600	82.1∗	–
			GA	3864	80.4	-2.1%
	12	13	Enumeration	>21600	89.6∗	–
			GA	4057	88.5	-1.2%

(The value with ∗ is the current optimal solution in a given CPU time)

In order to testify the accuracy of the proposed GA, compared the proposed GA with enumeration solution. The pseudocode of the enumeration procedure is presented in Algorithm 2.

In the enumeration procedure, all possible combinations of decision variables of the proposed model are listed and evaluated first, followed by choosing the group of decision variables which leads to the minimal average person delay as the optimal solution. In the resubmitted manuscript, the pseudocode of the enumeration procedure has been supplemented to explain how it finds the global optimal solution. In this study, the decision variables of the proposed model include the signal offsets among all intersections, tram schedules and TSP strategies. The outer layer of the enumeration procedure lists all signal offsets among different intersections without changing the signal cycle length and green duration. The inner layer of the enumeration procedure then lists all possible groups of tram schedules and TSP strategies for each signal offset produced in the first step.

It should be noted that TSP strategies might affect the departure time of trams at intersections, which is a component of tram scheme. As a result, within the inner layer of the enumeration procedure, the departure time of the first tram from the first station is enumerated at first, followed by attaining all possible groups of arrival and departure time of the first tram at the other stations, considering each possible TSP strategy at each intersection, each possible inter-station run-time and station dwell time in their valid ranges. Once all possible schedules of the first tram are attained, the possible schedules of the other trams are enumerated one by one taking into account the valid ranges of tram headways, inter-station run-time and station dwell time, as well as the TSP strategies.

As shown in Table 6, when the problem is getting large, the enumeration is not capable of finding the optimal solution in a given time. The minor gap between enumeration solution and GA shows that the proposed GA has a high accuracy. In the case of 5 nodes including 2 intersections and 3 stations with 4 trams scheduled, the CPU time of enumeration and

```
Input: Quantity of trams (m)
       Nodes / Intersection / Station (N / I / S)
       Arrival / Departure time constraints (AT / DT constraint)
       Dwell / Link travel time constraints (DT / LT constraint)
       Signal timing constraint (ST constraint)
       TSP strategy constraint (TSP constraint)
Output: Solutions; The best solution
repeat
    for each intersection do
        Unadjusted signal timing ⟵ Initialization (ST constraint)
    end
    for each unadjusted signal timing do
        for each tram do
            Arrival time ⟵ Initialization (AT constraint)
            for each node N do
                if node N ∈ Station
                    Departure time ⟵ Initialization (DT constraint)
                else
                    if Arrival time during Green phase
                        Departure time = Arrival time
                    else
                        TSP strategy ⟵ Initialization (TSP constraint)
                        for each TSP strategy do
                            if TSP measure is activated
                                Departure time = Arrival time
                            else
                                Departure time = Arrival time + Waiting time
                            end
                        end
                    end
                end
            end
        end
    end
    Solutions ⟵ {Unadjusted signal timing; Arrival time; Departure time; TSP strategy}
    Person delay ⟵ Calculation (Solutions)
    The best solution ⟵ Minimum (Person delay)
until finding The best solution
```

Algorithm 2: The enumeration procedure for the numerical case.

GA both is acceptable, and the gap is 1.4%. When the quantity of nodes and trams becomes larger, especially in the case of 17 nodes including 8 intersections and 9 stations with 8 trams to schedule, enumeration solution cannot find the global optimal solution in 6 hours. Obviously the length of CPU time depends on the combinations of the quantity of trams and the quantity of nodes. Thus either the quantity of trams or the quantity of nodes becomes larger and the CPU time prolongs.

6.2. Case Study in Ningbo Tramline. A section of a tramline in Ningbo, a city of China, is employed to evaluate the proposed model. The tramline section consists of 5 stations and 7 intersections. The layout of intersections and stations is given in Figure 8. The maximum carrying capacity on one tram is 368 passengers. Taking peak-hours, for example, traffic volume, original signal timings at different intersections where the cycle time is 180 s, are presented in Table 7. The range of dwell time at different stations and the range of travel time as well as the loading factor of each link are specified in Table 8.

6.2.1. Performance Comparison by Different Objectives. The objective of the proposed model is to minimize person delay of the whole system including tram passengers and auto vehicle users. In order to further demonstrate the benefit of minimizing person delay, the computational results of three different objectives are compared. Beside the proposed objective, other two objectives are to minimize tram passenger delay and to minimize auto vehicle user delay.

Compared with the proposed objective, as shown in Table 9, only minimizing tram passenger delay reduces tram passenger delay to zero and results in a significant increase in auto vehicle user delay. When the number of auto vehicles is larger than that of trams at intersections, auto vehicle user delay has significant influence on person delay of the

Table 7: Traffic volume and signal timings at intersections along the Ningbo tramline.

Intersection		Traffic flow (Number of Lane)			Split (Cycle 180 sec)		Intersection		Traffic flow (Number of Lane)			Split (Cycle 180 sec)	
		Left	Through	Right	Left	Through			Left	Through	Right	Left	Through
S1	South	152(1)	1020(2)	88(1)	25	90	S5	South	140(1)	1008(2)	60(1)	27	90
	North	147(1)	1016(2)	44(1)	25	90		North	142(1)	1024(3)	168(2)	27	90
	East	144(1)	512(2)	372(2)	23	42		East	157(1)	470(2)	214(2)	23	40
	West	142(1)	492(2)	16(1)	23	42		West	212(2)	468(2)	74(1)	23	40
S2	South	148(1)	1084(2)	96(1)	22	90	S6	South	144(1)	1178(2)	362(2)	25	86
	North	153(1)	1096(2)	2(1)	22	90		North	137(1)	1032(2)	58(2)	25	86
	East	148(1)	527(2)	212(2)	23	45		East	240(2)	408(2)	410(2)	34	35
	West	146(1)	518(2)	16(1)	23	45		West	144(1)	412(3)	72(1)	34	35
S3	South	134(1)	1064(2)	24(1)	27	90	S7	South	146(1)	1052(2)	258(1)	26	77
	North	146(1)	1004(2)	20(1)	27	90		North	141(1)	1003(2)	82(1)	26	77
	East	132(1)	510(2)	120(2)	23	40		East	142(1)	522(2)	120(1)	36	41
	West	138(1)	512(2)	108(1)	23	40		West	137(1)	514(2)	132(1)	36	41
S4	South	148(1)	1056(2)	60(1)	21	90							
	North	139(1)	1096(2)	176(1)	21	90							
	East	148(1)	482(2)	132(1)	26	43							
	West	144(1)	512(2)	80(1)	26	43							

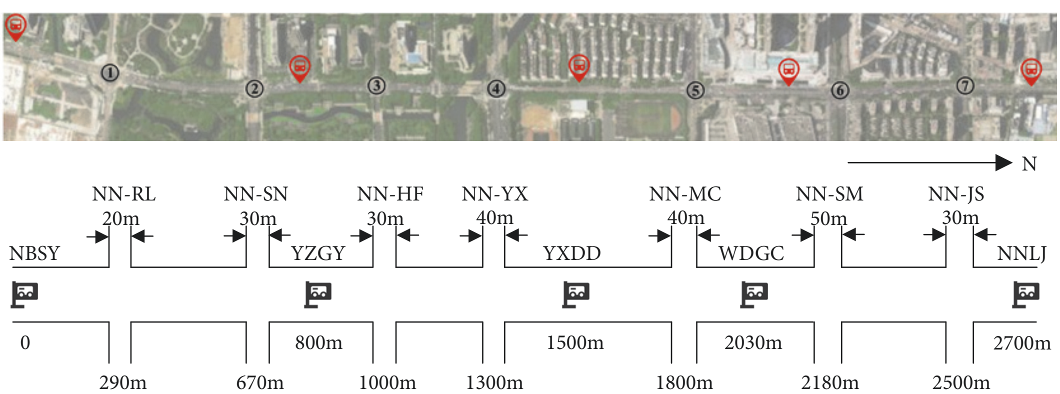

Figure 8: Layout of the Ningbo tramline.

Table 8: Tram timetable formulation parameters and loading factors.

Station	Range of dwell time [sec]	Link	Range of travel time [sec]	Loading factor
NBSY	(10,20)	NBSY- YZGY	(105,125)	0.7
YZGY	(15,25)	YZGY- YXDD	(101,121)	0.9
YXDD	(20,30)	YXDD- WDGC	(85,105)	0.8
WDGC	(20,30)	WDGC- NNLJ	(99,119)	0.6
NNLJ	(10,20)			

Table 9: Performance comparison by different objectives.

Delay/s (Variation rate/%)	Minimizing tram passenger delay	Minimizing auto vehicle user delay	The proposed model
Tram passenger	0	83 (+93.02%)	43
Auto vehicle user	148 (+108.45%)	48 (-32.39%)	71
Average person	102 (+59.38%)	67 (+4.69%)	64
Weighted average person	95 (+69.64%)	75 (+33.39%)	56

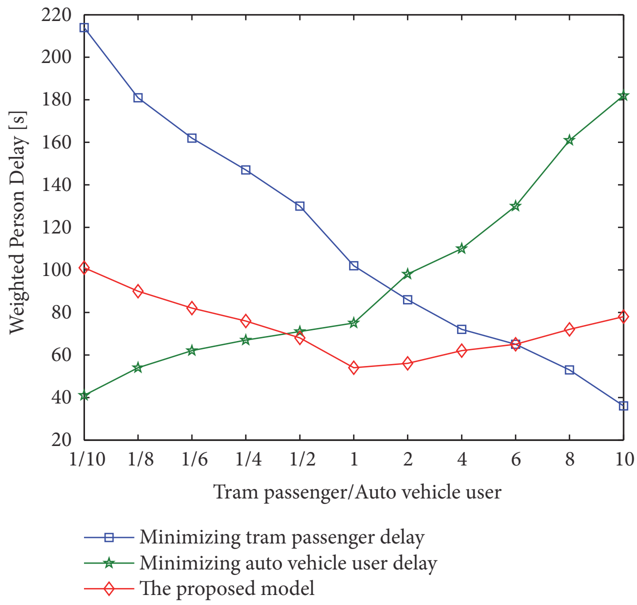

FIGURE 9: Performance on different ratio of tram passenger to auto vehicle user with different objectives.

whole system. This leads to person delay of the whole system which is relatively high due to the high auto vehicle user delay. When only minimizing auto vehicle user delay, the interests of auto vehicle passengers will be ensured by less TSP activated for trams. Thus trams passenger delay increase, which reduced the attraction of public transportation. Considering optimizing tram passengers and auto vehicle users that separately reduced the efficiency of the whole system, these two stakeholders should be optimized simultaneously.

6.2.2. Performance on Different Ratio of Tram Passenger to Auto Vehicle User. Figure 9 shows the changes in different ratio of tram passengers to auto vehicle users with different objectives. When the ratio varies, weighted person delay fluctuates greatly with the objectives of only minimizing tram passengers or only minimizing auto vehicle passengers. Neither of them can adapt to the situation when the ratio changes. However, by taking tram passengers and auto vehicle users as a whole, it can stabilize the weighted person delay and adapt to changes in different ratio.

In practice, the ratio of tram passenger to auto vehicle user varies from day to day, especially the changes between weekdays and weekends, peak hour and non-peak hour. For example, the number of auto vehicles is larger than that of trams on weekdays and the number of trams becomes larger on weekends. If a single type of person is considered for optimization, such a change cannot be adapted. Therefore, the proposed model has better applicability.

7. Conclusions

Operating in semi-exclusive ROW, trams may stop at intersections to wait red signals, which results in extra interstation run-time or even delays. To improve the tram service quality, Transit Signal Priority (TSP) has been applied at intersections by offering extra green phase for trams. However, providing extra green phase for every tram might lead to heavy delays to crossing vehicles. To address this problem, this study developed an integrated optimization model of tram schedule and signal priority which can balance the delay between trams and other vehicles to minimize the average person delay.

Due to the complexity of the problem, the GA is employed to solve the proposed model. A numerical case is conducted to testify the computing time and solution optimality of the proposed GA and the enumeration procedure. The results show that the enumeration is unable to find the optimal solution or even a near-optimal solution when the tramline covers several stations and intersections due to the huge solution space, while the GA outperforms the enumeration procedure within the restrained computing time. The case studies on the Ningbo tramline indicate that the integrated optimization reduces the average delay of passengers on both trams and auto vehicles, in comparison with only optimizing tram timetable or only applying TSP. It is also found that minimizing the average person delay of the whole system is able to adapt to the possible fluctuations in the ratio of tram passengers to auto vehicle users, compared with only minimizing tram passenger delay or auto vehicle user delay.

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.

Acknowledgments

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