

Research Article

Route-Based Signal Preemption Control of Emergency Vehicle

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Received 30 October 2017; Accepted 20 February 2018; Published 1 April 2018

Academic Editor: Ai-Guo Wu

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This paper focuses on the signal preemption control of *emergency vehicles* (EV). A signal preemption control method based on route is proposed to reduce time delay of EV at intersections. According to the time at which EV is detected and the current phase of each intersection on the travelling route of EV, the calculation methods of the earliest start time and the latest start time of green light at each intersection are given. Consequently, the effective time range of green light at each intersection is determined in theory. A multiobjective programming model, whose objectives are the minimal residence time of EV at all intersections and the maximal passing numbers of general society vehicles, is presented. Finally, a simulation calculation is carried out. Calculation results indicate that, by adopting the signal preemption method based on route, the delay of EV is reduced and the number of society vehicles passing through the whole system is increased. The signal preemption control method of EV based on route can reduce the time delay of EV and improve the evacuation efficiency of the system.

1. Introduction

Once an unexpected event has happened, an evacuation or a rescue must be carried out to help people in hazardous situations, and emergency vehicles (EV) play an important role in this process. To reduce the negative impact of unexpected events, EV is used to transferr people from dangerous areas to emergency shelters or medical assistance organizations as rapidly as possible. As is well-known to us all, the quality of the emergency service relies on the travel time that EV spends in the evacuation route [1, 2]. Therefore, EV has a greater priority than normal social vehicles, and signal preemption policy should be adopted to ensure the rapid transit of EV. However, under the condition of traffic jams or if there is no emergency lane, the queuing vehicles may prevent EV from passing through the intersection. Even if there is an emergency lane, to avoid an urgent spectacle, EV also has to wait if green traffic light for the opposite direction is going on.

To ensure that EV can pass through intersections safely and rapidly, some scholars proposed the signal preemption strategies. Paniati and Amoni [3] summarized the advantages of traffic signal preemption for EV in improving response speed, ensuring safety, saving cost, and other aspects and pointed out some of the key technologies used in traffic

signal preemption system as well as some associated responsibility institutions. Mirchandani and Lucas [4] studied control strategies by integrating transit signal priority and rail/emergency preemption within a dynamic programming-based real-time traffic adaptive signal control system. Song [5] proposed traffic signal priority control method for multiple EVs based on multiagent and obtained signal priority control strategies through the coordination of phase agent and management agent. Taking the minimum delay of EV at single intersection as control target, three signal priority strategies, namely green time extension, red time shortening, and multiphase integrated control were proposed by Yang et al. [6], and Vissim was adopted to evaluate the proposed strategies. Ma and Cui [7] studied the signal priority problem of EV that was coming from different directions and had to pass the same intersection in the certain time period and presented a signal priority control system for multiple EV based on multi-agent. Wang et al. [8] proposed a degree-of-priority based control strategy for emergency vehicle preemption operation to decrease the impacts of emergency vehicles on normal traffic, and the performance of the proposed strategy was compared with the conventional local detection based method under the microscopic simulation model. To reduce the response time and minimize the impact

of EV operation on general traffic, Qin [9] proposed two new control strategies for EV signal preemption, where the first strategy was developed to enable signal transition from normal operation to EV signal preemption and the second control strategy was used for the transition from EV signal preemption back to normal operation.

Most of the signal preemption methods adopted currently are based on isolated intersection, namely, taking single intersection as a basis, and signal preemption of this intersection will be activated after local detector has detected EV and thus form a signal priority sequence from intersection to intersection [10, 11]. This kind of signal preemption strategy, which is based on local detection and clears the intersection one by one, can start only after an EV has been detected and usually leads to inevitable intersection delay. Moreover, when multiple signal preemptions are implemented during peak period, the queue and delay of social vehicles in a given network will be significantly affected [12].

Studies have shown that implementing signal preemption from the perspective of entire route can reduce the response time of EV [13]. Although substantial progress has been made in signal preemption of isolated intersection, research of dynamic signal preemption based on entire route is rarely seen. Kwon and Kim [14] developed a route-based signal preemption strategy. They used Dijkstra's algorithm to obtain an optimal path from a given origin to a desired destination so as to ensure a minimal travel cost under current traffic conditions. The control algorithm chose a specific phase combination for each intersection on the selected route sequentially when EV arrived. But, the main purpose of this research was to ensure the safety of pedestrians passing through intersection, and real-time traffic conditions of various intersections were ignored. To reduce travel time of EV, Gedawy et al. [15] combined signal preemption with dynamic route planning and designed route of EV from the perspective of network. A signal preemption strategy, which could ensure the safe operation of an EV and maximize traffic flow passing through the intersection at the same time, was proposed. In order to provide green wave for EV, Kang et al. [16] proposed a coordinated signal control method and carried out traffic simulation taking eight intersections as example. All the methods mentioned above ensured the smooth running of EV by determining in advance the signal phase of each intersection after EV had been detected. Since green signal stayed at the designated phase, traffic flow from other signal phases lost right of way and they had to stay a long time at the intersection, which in turn increased the burden of traffic system and even caused traffic jams. Therefore, it is especially important to establish a route-based dynamic preemption strategy so as to provide efficient and safe operating environment for EV and minimize the interference on social vehicles.

So far, most of the developed preemption systems operate on a single intersection basis and require local detection of EV at each intersection to activate signal preemption sequence. Owing to the fact that these kinds of strategies depend on local detection and clear intersection one by one, and signal preemption procedure can not start until an EV is detected, inherent delays at intersections are unavoidable. The basic

method of route-based signal preemption control of EV is that, when unexpected events occur, in consideration of dynamically changing traffic situations, the route that EV can use to reach the scene of the accident in the shortest time is calculated and recommended as the evacuation route. Once an evacuation route is selected, particular signal preemption control strategy is presented to determine the activation time for preemption at each intersection on the emergency route and realize the signal preemption control of EV ultimately.

Evacuation route planning is an important component of emergency management that seeks to minimize the loss of life or harm to the public during unexpected events [17]. The aim of evacuation route planning is to minimize evacuation time under certain constraints and minimize the possibility of depth hazards to people from accident areas. Nowadays, almost all of the intersections in urban traffic network are signalized intersections. In order to realize smooth traffic under real road condition, traffic management departments usually adopt regulation measures, including no-left-turn, no-right-turn, P-turn, and U-turn, to improve the safety and efficiency of traffic. For this reason, the road network that is connected ostensibly is not connected actually, which add difficulties to the shortest path algorithms and make some classical finding methods unavailable. Many scholars have intensively studied the shortest path problems of road network with traffic restrictions [18–23]. Various techniques have been proposed to eliminate certain turning and crossing maneuvers at intersections so as to obtain evacuation routes that can provide continuous traffic flow and reduce accidents [24–30]. There also has been a considerable amount of evacuation route works that consider delay and capacity of intersections [31, 32]. The majority of the evacuation route works in the literature can be divided into three categories, namely, network flow methods, which can be further divided into linear programming and dynamic minimum cost flow problem [24, 33–38], simulation methods [39, 40], and heuristic methods, which mainly includes the well-known Capacity Constrained Route Planner (CCRP) algorithm and its improved algorithms [41–47]. The research of evacuation route planning has made substantial progress, and the development of modern detecting equipment and information technology ensures the enforceability of real-time traffic flow detection and information exchange among different intersection controllers. These technologies make it possible to implement route-based signal preemption control of EV, but a safe and efficient manner to change the traffic signal timing plan, namely, control mechanism, has not been well studied.

In this paper, we will study the problem of dynamic signal preemption control of EV based on entire route. We limit the scope of this paper to signal preemption control of EVs under the assumption that the evacuation route has been determined, and the problem of evacuation route calculation will not be discussed further. The objectives of research reported here were to (1) propose a route-based signal preemption strategy to provide efficient and safe operating environment for EV and minimize the impact on social vehicles in traffic network as far as possible, (2) develop a multiobjective optimization model to minimize the residence time of EV at

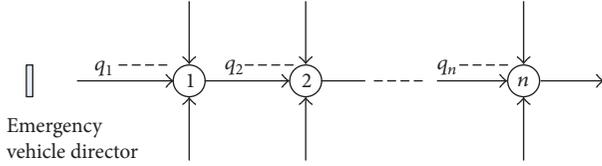


FIGURE 1: Diagram of intersection.

all intersections and maximize the number of social vehicles passing through all intersections, and (3) design a solving algorithm for the presented optimization model and verify the efficiency of the proposed signal preemption strategy.

First, on the premise of having selected a concrete evacuation route, taking isolated intersection as objective and considering the distance between EV detector and each intersection, the operating speed of EV and the number of queued vehicles at each intersection, the earliest-possible start time, and the latest-possible start time of green light at each intersection in the route are given. And then, in order to establish a real-time signal control strategy to ensure that EV can pass through intersection with operating speed or without stopping and minimize the impact of EV on social vehicles, a multiobjective programming model is presented and a particle swarm algorithm is designed to find the Pareto optimal solution set of this model. Finally, a simulation analysis is carried out.

2. Calculation of Intersection Time Parameters

After the optimal evacuation route of EV has been given, to ensure that the delay of EV is much smaller and the social vehicles passing through the whole system are much larger, we need to determine the most suitable time of opening the green light for EV of each intersection in the given route. Suppose that there are n intersections in the evacuation route except the given origin and the desired destination, and the evacuation direction is from west to east as shown in Figure 1. What needs to be stressed here is that we just take Figure 1 as an example to introduce the following concepts and calculation methods of intersection parameters. In fact, an EV may turn left or right at some of the intersections on the given evacuation route, and the following methods are also applicable to this kind of route. We assume that EV is detected at time t_0 , and q_i , $i = 1, 2, \dots, n$ denotes vehicles waiting to pass through intersection i in front of EV along the direction of evacuation at time t_0 ; q_{iN} , q_{iS} , q_{iW} , q_{iE} , $i = 1, 2, \dots, n$ denotes vehicles waiting to pass through intersection i in north-southward direction, south-northward direction, west-eastward direction, and east-westward direction at time t_0 , respectively. Suppose that all the intersections are two-phase control intersections and have fixed signal cycle, as shown in Figure 2. Each intersection i corresponds to a time window sequences $WL(i) = (ws_i, w_{i1}, w_{i2})$, where ws_i denotes the start time of the first time window, and w_{ik} , $k = 1, 2$ denotes the k th time window of intersection i .

The time parameters mentioned in this paper include the earliest-possible start time and the latest-possible start time of green light at each intersection.

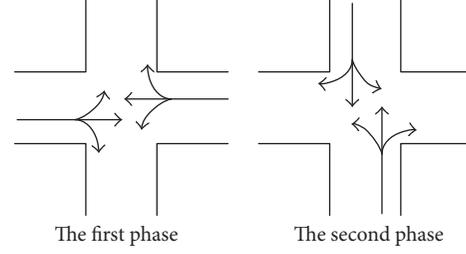


FIGURE 2: Phase diagram of traffic signal.

Definition 1. The earliest-possible start time is defined as the earliest time that traffic light of EV direction can be changed to green from the time the EV is detected and on the premise of ensuring the efficiency of the whole system.

Definition 2. The latest-possible start time is defined as the latest time that traffic light of EV direction must be changed to green so as to ensure that EV can pass through the intersection without reducing speed or without stopping.

2.1. Calculation of Time Parameters of Intersection 1. We employ d_{ij} and t_0 to denote the duration time of phase j at intersection i and the time that EV is detected. If the starting time of the first time window of intersection 1, denoted by ws_1 , is determined and the duration time of the two phases denoted by d_{11} and d_{12} is also determined, then the current phase of intersection 1 and the elapsed green time of this phase can be calculated correspondingly.

Provided that C_i denotes the cycle length of intersection i and $D_{i,j}$ denotes the elapsed green time of intersection i after j phases, the elapsed number of cycles in period $t_0 - ws_1$ is denoted as a , and the remaining time after a cycles in period $t_0 - ws_1$ is denoted as b . Then we have

$$\begin{aligned} D_{1,0} &= 0, \\ D_{1,j} &= \sum_{p=1}^j d_{1,p}, \quad j = 1, 2. \end{aligned} \quad (1)$$

Let

$$\begin{aligned} a &= \frac{(t_0 - ws_1)}{C_i}, \\ b &= (t_0 - ws_1) \bmod C_i; \end{aligned} \quad (2)$$

then the current phase is i if it satisfies that $D_{u,i-1} \leq b < D_{u,i}$, and the elapsed green time of phase i is $t_0 - ws_1 - a \times C_i - \sum_{p=0}^{j-1} D_{1,p}$.

Let G_{\min}^j , G_{\max}^j , G_{ela}^j , and G_{real}^j denote the minimal green time, the maximal green time, the elapsed green time, and the real green time of phase j , respectively; L_{EV-i} denotes the distance between EV detection and intersection i ; v_{EV} , v_{reg} denote the speed of EV and mean speed of general traffic, respectively; t_{switch} denotes the time needed to switch green indication from one phase to another phase; t_{safe} is the safety time interval that must be kept between the last vehicle in

the queue on the EV approach and the EV so as to avoid collision between EV and social vehicles. It is an important factor to ensure the safe operation of emergency vehicles and can be provided by an appropriate advance notice of the approaching of EV and a real-time traffic queue control strategy; B is the average effective length of each vehicle when parking, which is equal to the sum of the length of vehicle itself and the distance between adjacent vehicles. Let $t_E(i)$ and $t_L(i)$ $i = 1, 2, \dots, n$ denote the earliest-possible start time and the latest-possible start time of phase i in EV approach; then we will illustrate the calculation method of $t_E(i)$ and $t_L(i)$ $i = 1, 2, \dots, n$ beginning from the first intersection.

2.1.1. The Calculation of $t_E(1)$

(1) *Phase 1 is the Current Phase of Intersection 1 at Time t_0 .* If the elapsed green time is G_{ela}^1 and satisfies $L_{\text{EV-1}}/v_{\text{EV}} + G_{\text{ela}}^1 \leq G_{\text{max}}^1$, then $t_E(1) = t_0$ and the real start time of green signal at intersection 1 is t_0 . Otherwise, if $L_{\text{EV-1}}/v_{\text{EV}} + G_{\text{ela}}^1 > G_{\text{max}}^1$, then we have to determine whether $G_{\text{ela}}^1 \geq G_{\text{min}}^1$ is met at time t_0 . If it is met, the green indication of phase 1 is ended and starts again after the minimal green time of phase 2 is finished. Before this, we have to check, after phase 1 regains the green indication, whether the queuing vehicles at the intersection can be cleared before EV arrives and can maintain a certain safety interval between EV and social vehicles. If we have

$$t_{\text{switch}} + G_{\text{min}}^2 + t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \leq \frac{L_{\text{EV-1}}}{v_{\text{EV}}} \quad (3)$$

then $t_E(1) = t_0 + 2t_{\text{switch}} + G_{\text{min}}^2$. If $G_{\text{ela}}^1 < G_{\text{min}}^1$ is met, then the green indication of phase 1 will remain $G_{\text{min}}^1 - G_{\text{ela}}^1$ seconds. After $G_{\text{min}}^1 - G_{\text{ela}}^1$ seconds, the signal transformation mentioned above will be carried out on the basis of satisfying

$$\begin{aligned} G_{\text{min}}^1 - G_{\text{ela}}^1 + t_{\text{switch}} + G_{\text{min}}^2 + t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \\ \leq \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \end{aligned} \quad (4)$$

It can be seen from (3) and (4) that, when $G_{\text{ela}}^1 < G_{\text{min}}^1$, if (4) is satisfied then (3) is sure to be satisfied. Let G_{low}^1 denote the allowed lower bound of green light time that is smaller than G_{min}^1 , and G_{short}^j denote the shortened green light time of phase j . If (3) is satisfied while (4) is not satisfied, then G_{low}^1 is given. If $G_{\text{ela}}^1 \geq G_{\text{low}}^1$, then $t_E(1) = t_0 + G_{\text{min}}^2 + 2t_{\text{switch}}$. If (3) is also not satisfied, then the green light time of phase 2 will be shortened to G_{short}^2 to satisfy the following equation:

$$t_{\text{switch}} + G_{\text{short}}^2 + t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} = \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \quad (5)$$

Thus we have

$$G_{\text{short}}^2 = \frac{L_{\text{EV-1}}}{v_{\text{EV}}} - \left(2t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \right). \quad (6)$$

If $G_{\text{short}}^2 < G_{\text{low}}^1$, it shows that the green light time of phase 2 is very short and has little effect on alleviating traffic pressure and can lead to security problems. Therefore, $t_E(1) = t_0$ under this condition. Otherwise, the green light time of phase 2 is equal to G_{short}^2 , and $t_E(1)$ is equal to $t_0 + G_{\text{short}}^2 + t_{\text{switch}}$. The real start time of green signal is $t_E(1)$.

(2) *Phase 2 is the Current Phase of Intersection 1 at Time t_0 .* Calculate G_{ela}^2 firstly. If $G_{\text{ela}}^2 \leq G_{\text{min}}^2$, it should be guaranteed generally that the green duration of phase 2 is G_{min}^2 seconds and then changed to phase 1 after fixed yellow and red duration. However, it should be guaranteed that

$$G_{\text{min}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \leq \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \quad (7)$$

Now, $t_E(1)$ is equal to $t_0 + G_{\text{min}}^2 - G_{\text{ela}}^2 + t_{\text{switch}}$. Otherwise, we have to check whether the following equation is satisfied:

$$G_{\text{low}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \leq \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \quad (8)$$

If it is satisfied, then $t_E(1)$ is equal to $t_0 + G_{\text{low}}^2 - G_{\text{ela}}^2 + t_{\text{switch}}$.

If $G_{\text{ela}}^2 > G_{\text{min}}^2$, then determine whether the following equation is satisfied:

$$t_{\text{switch}} + \frac{q_1 \times B}{v_{\text{reg}}} + t_{\text{safe}} \leq \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \quad (9)$$

If it is satisfied, then $t_E(1)$ is equal to $t_0 + t_{\text{switch}}$.

2.1.2. *The Calculation of $t_L(1)$.* Assume that t_{arr}^i denotes the time that EV arrive at intersection i without reducing its speed; then we have

$$t_{\text{arr}}^1 = t_0 + \frac{L_{\text{EV-1}}}{v_{\text{EV}}}. \quad (10)$$

Let t_{clear}^i denote the time needed to clear the queues at intersection i before EV arrives, then we have

$$t_{\text{clear}}^1 = \frac{q_1 \times B}{v_{\text{reg}}}. \quad (11)$$

The value of $t_L(1)$ can be described by the following equation:

$$t_L(1) = t_0 + \frac{L_{\text{EV-1}}}{v_{\text{EV}}} - \frac{q_1 \times B}{v_{\text{reg}}} - t_{\text{safe}}. \quad (12)$$

If the distance between EV detector and intersection 1 is far enough and queued vehicles are not too much, $t_L(1)$ is sure greater than or equal to $t_E(1)$. However, if the traffic is rather heavy and clearing queued vehicles takes a long time, $t_L(1)$ may be less than $t_E(1)$ at phase 2. Under this condition, to ensure the smooth and safe passing of EV, the green time of phase 2 has to be sacrificed; namely, the green signal is converted to phase 1 after phase 2 has executed a short green time that is less than the minimum green time. Now, the value of $t_E(1)$ is $t_0 + t_{\text{switch}}$. If $t_L(1)$ is still less than $t_E(1)$, then let $t_L(1)$ and $t_E(1)$ have the same value, say, $t_0 + t_{\text{switch}}$. Now, it is unable to meet the requirement of EV's passing through the intersection without deceleration and stopping, and all that we can do is to minimize the waiting time of EV at intersection 1.

2.2. Calculation of Time Parameters at Other Intersections

2.2.1. *The Calculation of $t_L(2)$.* Let t_{pass} be the time EV needs to pass through the intersection, t_{arr}^2 the time EV needs to arrive at the parking line of intersection 2 after passing through intersection 1 without stopping, t_{start}^i the real start time of green signal of intersection i along the evacuation direction of EV, and Q_i and D_i the number of vehicles arriving at intersection $i+1$ from intersection i and vehicles departing from intersection i in t_0 to t_{start}^i time period, respectively. Then we have

$$t_{\text{arr}}^2 = t_0 + \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}}. \quad (13)$$

And the queuing vehicles q_2' at intersection 2 can be described as

$$q_2' = q_2 + Q_1 - D_2, \quad (14)$$

where Q_i and D_i are calculated according to the situation that the green light of intersection 1 starts at the latest-possible start time. Let t_{clear}^2 be the time needed for clearing q_2' before EV arrives; then we have

$$t_{\text{clear}}^2 = \frac{q_2' \times B}{v_{\text{reg}}} = \frac{(q_2 + Q_1 - D_2) \times B}{v_{\text{reg}}}. \quad (15)$$

We have the following equation to determine the latest start time of green signal at intersection 2:

$$\begin{aligned} t_L(2) &= t_{\text{arr}}^2 - t_{\text{clear}}^2 - t_{\text{safe}} \\ &= t_0 + \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}} - \frac{(q_2 + Q_1 - D_2) \times B}{v_{\text{reg}}} \\ &\quad - t_{\text{safe}}. \end{aligned} \quad (16)$$

2.2.2. The Calculation of $t_E(2)$

(1) *Phase 1 is the Current Phase of Intersection 2 at Time t_0 .* If the elapsed green time of phase 1 is G_{ela}^1 , $G_{\text{ela}}^1 + L_{\text{EV-2}}/v_{\text{EV}} + t_{\text{pass}}$ is the sum of the elapsed green time of phase 1 and the time EV spent before reaching intersection 2. We can discuss the calculation of $t_E(2)$ in the following three cases.

Case 1.

$$G_{\text{ela}}^1 + \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}} \leq G_{\text{real}}^1. \quad (17)$$

Case 2.

$$G_{\text{real}}^1 < G_{\text{ela}}^1 + \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}} \leq G_{\text{max}}^1. \quad (18)$$

Case 3.

$$G_{\text{ela}}^1 + \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}} > G_{\text{max}}^1. \quad (19)$$

In Case 1, there is no need to perform signal preemption at intersection 2, and both $t_E(2)$ and the real start time of green signal are equal to t_0 .

In Case 2, after both phase 1 and phase 2 have executed the minimum green time and then green indication goes back to phase 1, we should check whether the following equation is satisfied:

$$\begin{aligned} (G_{\text{min}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{min}}^2 + \frac{q_2' \times B}{v_{\text{reg}}} + t_{\text{safe}} \\ \leq \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}}, \end{aligned} \quad (20)$$

where q_2' is the queue length of intersection 2 at time $(G_{\text{min}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{min}}^2$ and is calculated according to (14). In (14), Q_1 is calculated according to the situation that the green light of intersection 1 starts at the earliest-possible start time; D_2 is the number of vehicles passing through intersection 2 in the effective green duration of phase 1 in the period of t_0 to $t_E(2)$. If (20) is satisfied, then $t_E(2)$ is equal to $t_0 + (G_{\text{min}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{min}}^2$; otherwise, $t_E(2)$ is equal to t_0 .

In Case 3, we need to consider the restriction of the maximum green time. Let both phase 1 and phase 2 execute the maximum green time, and then let green indication go back to phase 1. But we should check whether q_2' can be cleared before EV arrives, namely, whether the following equation is satisfied:

$$\begin{aligned} (G_{\text{max}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{max}}^2 + \frac{q_2' \times B}{v_{\text{reg}}} + t_{\text{safe}} \\ \leq \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}}. \end{aligned} \quad (21)$$

The calculation of q_2' is similar to Case 2. If (21) is satisfied, $t_E(2)$ is equal to $t_0 + (G_{\text{max}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{max}}^2$. Otherwise, let phase 1 and phase 2 execute the minimum green time and the maximum green time, respectively, and then let green indication go back to phase 1. But the following equation should be satisfied:

$$\begin{aligned} (G_{\text{min}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{max}}^2 + \frac{q_2' \times B}{v_{\text{reg}}} + t_{\text{safe}} \\ \leq \frac{L_{\text{EV-2}}}{v_{\text{EV}}} + t_{\text{pass}}. \end{aligned} \quad (22)$$

Now, $t_E(2)$ is equal to $t_0 + (G_{\text{min}}^1 - G_{\text{ela}}^1) + 2t_{\text{switch}} + G_{\text{max}}^2$.

If (22) is not satisfied, then both phase 1 and phase 2 will execute the minimum green time, and then green indication will go back to phase 1. Let the cycle length be C_{max} when all of the two phases execute the maximum green time and C_{min} when all of the two phases execute the minimum green time.

(2) *Phase 2 Is the Current Phase of Intersection 2 at Time t_0 .* If the elapsed green time of phase 2 is G_{ela}^2 , we can discuss the calculation of $t_E(2)$ in the following four cases.

Case 1.

$$G_{\text{real}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}} \leq \frac{L_{\text{EV}-2}}{v_{\text{EV}}} + t_{\text{pass}}. \quad (23)$$

Case 2.

$$G_{\text{min}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}} \leq \frac{L_{\text{EV}-2}}{v_{\text{EV}}} + t_{\text{pass}} \\ < G_{\text{real}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}}. \quad (24)$$

Case 3.

$$G_{\text{low}} - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}} \leq \frac{L_{\text{EV}-2}}{v_{\text{EV}}} + t_{\text{pass}} \\ < G_{\text{min}}^2 - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}}. \quad (25)$$

Case 4.

$$\frac{L_{\text{EV}-2}}{v_{\text{EV}}} + t_{\text{pass}} < G_{\text{low}} - G_{\text{ela}}^2 + t_{\text{switch}} + t_{\text{clear}}^2 + t_{\text{safe}}. \quad (26)$$

Case 1 corresponds to the situation that the time needed by green light of phase 1 turning green after the normal green duration of phase 2 and clearing the queue length of phase 1 is no more than the time spent by EV for arriving at intersection 2; then there is no need to perform signal preemption at intersection 2 and $t_E(2)$ is equal to $t_0 + G_{\text{real}}^2 - G_{\text{ela}}^2 + t_{\text{switch}}$. Case 2 corresponds to the situation that the time needed by phase 1 turning green after the minimum green duration of phase 2 and clearing the queue length of phase 1 is no more than the time spent by EV for arriving at intersection 2; then signal preemption is necessary and $t_E(2)$ is equal to $t_0 + G_{\text{min}}^2 - G_{\text{ela}}^2 + t_{\text{switch}}$. In Case 3, green light of phase 1 turns green after phase 2 has passed G_{low} time, and now $t_E(2)$ is equal to $t_0 + G_{\text{low}} - G_{\text{ela}}^2 + t_{\text{switch}}$. In Case 4, signal preemption is necessary at intersection 2, and the green duration of phase 2 has to be sacrificed; namely, the green signal has to turn to phase 1 immediately after detecting EV, and now $t_E(2)$ is equal to $t_0 + G_{\text{ela}}^2 + t_{\text{switch}}$.

The time parameters of the other intersections on the line are similar to those of intersection 2, which is no longer introduced here.

3. Multi-Objective Optimization Model

Let n be the number of intersections on the evacuation route, m the number of entrance sections on the cross road of evacuation route; t_{dep}^i the time instant EV departing from intersection i ; $g_{\text{eff}}^{i,j}$, $s_{i,j}^{y-z}$, and $S_{i,j}$ the effective green time of phase j at intersection i , the average departure rate of vehicles from y to z directions on the entrance sections, and the saturation flow rate of all lanes on the entrance sections, respectively; and $A_{\text{thr}}^{i,j}$, $A_{\text{left}}^{i,j}$, and $A_{\text{right}}^{i,j}$ the ratio of straight, left turn and right turn of phase j at intersection i ,

respectively. The multiobjective optimization model for EV signal preemption control based on route is

$$\min f_1 = \sum_{i=1}^n (t_{\text{start}}^i + t_{\text{clear}}^i + t_{\text{safe}} - t_{\text{arr}}^i) \times \delta_i, \quad (27)$$

$$\max f_2 \\ = \sum_{i=1}^n g_{\text{eff}}^{i,2} \quad (28)$$

$$\times \left[(s_{i,2}^{N-S} + s_{i,2}^{S-N}) \times A_{\text{thr}}^{i,2} + s_{i,2}^{N-S} A_{\text{left}}^{i,2} + s_{i,2}^{S-N} A_{\text{right}}^{i,2} \right],$$

$$\text{s.t. } t_E(i) \leq t_{\text{start}}^i \leq t_L(i) \quad i = 1, 2, \dots, n, \quad (29)$$

$$t_{\text{arr}}^i = \frac{L_{\text{EV}-i}}{v_{\text{EV}}} \quad i = 1, 2, \dots, n, \quad (30)$$

$$t_{\text{clear}}^i = \frac{q_i' \times B}{v_{\text{reg}}} \quad i = 2, \dots, n, \quad (31)$$

$$q_i' \\ = q_i + \min \{ q_{i-1}' \times A_{\text{thr}}^{i-1,1}, g_{\text{eff}}^{i-1,1} \times S_{i-1,j} \times A_{\text{thr}}^{i-1,1} \} \\ + g_{\text{eff}}^{i-1,2} (s_{i,2}^{N-S} A_{\text{left}}^{i,2} + s_{i,2}^{S-N} A_{\text{right}}^{i,2}) \quad (32)$$

$$- \sum_{e=1}^l \min \{ q_e'', g_{\text{eff}}^{e,1} \times A_{\text{thr}}^{e,1} \},$$

$$\delta_i = \begin{cases} 0 & t_{\text{start}}^i + t_{\text{clear}}^i + t_{\text{safe}} \leq t_{\text{arr}}^i \\ 1 & \text{otherwise} \end{cases} \quad i = 2, \dots, n, \quad (33)$$

$$t_{\text{safe}} \geq 2, \quad (34)$$

$$t_E(i) \geq t_0 \quad i = 1, 2, \dots, n, \quad (35)$$

$$t_L(i) \geq t_0 \quad i = 1, 2, \dots, n, \quad (36)$$

where (27) and (28) are objective functions and represent minimizing the residence time of EV at all intersections and maximizing the number of social vehicles passing through all intersections of the evacuation route, respectively. The number of social vehicles includes the vehicles entering in the system from the cross road of evacuation route and passing through intersections and the vehicles passing through intersections in the direction of the evacuation route of EV. Equation (29) ensures that the real start time of green signal of intersection i is between $t_E(i)$ and $t_L(i)$; (30) represents the arrival time of EV at intersection i ; (31) represents the time needed to clear the queued vehicles before EV arrives; (32) denotes the calculation method of the queued vehicles at intersection i at the moment the green signal is starting, and q_e'' , $e = 1, 2, \dots, l$ represents the number of queued vehicles of phase 1 at the moment the green signal is starting in each signal cycle of intersection i before t_{start}^i , and l denotes the number of passed signal cycles; (33) represents the 0-1 variable of intersection i , which means that the waiting time of EV at intersection i is 0 if the green signal is on at intersection i , and the queued vehicles have been cleared and security interval is satisfied, namely, $t_{\text{start}}^i + t_{\text{clear}}^i + t_{\text{safe}} \leq t_{\text{arr}}^i$. Otherwise, the EV has to wait in line, and the waiting

time is equal to $t_{\text{start}}^i + t_{\text{clear}}^i + t_{\text{safe}} - t_{\text{arr}}^i$; (34) shows the lower limit of the value of t_{safe}^i ; (35) and (36) represent the relationship between $t_E(i)$, $t_L(i)$, and t_0 . Variable $g_{\text{eff}}^{i,2}$ will take different values according to different t_0 and t_{start}^i . The value of $g_{\text{eff}}^{1,2}$ and $g_{\text{eff}}^{2,2}$ can be calculated by (3)–(9) and (10)–(16) and (20)–(22), respectively, and the calculation method of $g_{\text{eff}}^{i,2}$, $i = 3, 4, \dots, n$ is similar to $g_{\text{eff}}^{2,2}$.

4. Design of Solving Algorithm

At present, the evolutionary algorithm is the main algorithm for solving multiobjective programming problems. Owing to the advantages of fast convergence speed and easy implementation, the particle swarm algorithm (PSO) has been successfully applied in many optimization problems [48–52]. In this paper, PSO is adopted to solve the given model.

4.1. Encoding and Particle Swarm Generation. Generate particle swarm P with N_1 particles randomly, and each particle can be represented as $X = (x_1, x_2, \dots, x_n)$, where x_i , $i = 1, 2, \dots, n$ denotes t_{start}^i of intersection i and $x_i \in [t_E(i), t_L(i)]$. If $\text{rand}()$ represents a random number between 0 and 1, then the specific method of producing x_i , $i = 1, 2, \dots, n$ is defined as follows:

$$x_i = \text{int} [t_E(i) + (t_L(i) - t_E(i)) \times \text{rand}()]. \quad (37)$$

4.2. Density of Solutions. Since the density of nondominated solutions is inversely proportional to their diversity [48], to obtain uniformly distributed Pareto frontier, the diversity of solutions should be guaranteed; that is, the sparse solutions should be retained as many as possible. For this reason, the solution density is introduced in this paper. Suppose that there are p objectives and there are S solutions in dominant population E . If the solutions in E are sorted in ascending order according to their fitness values and $f_j(i)$, $j = 1, 2, \dots, p$; $i = 1, 2, \dots, S$ represents the i th solution when sorting by the j th objective, then the solution density is defined as follows:

$$\begin{aligned} & \sum_{j=1}^p [f_j(i+1) - f_j(i-1)] + \sum_{j=1}^p [f_j(i) - f_j(i-1)] \\ & = \sum_{j=1}^p f_j(i+1) + \sum_{j=1}^p f_j(i) - 2 \sum_{j=1}^p f_j(i-1). \end{aligned} \quad (38)$$

4.3. Updating of Location and Velocity. In standard multiobjective PSO algorithm, location updating requires the inertia factor w and learning factors c_1 and c_2 . Since a larger w is suitable for a wide range exploration of solution space, while a smaller w is suitable for detailed search on the target, the learning factors are adopted to balance the cognitive abilities of individuals and groups. To achieve better search and balance, some scholars put forward the idea that inertia factor and learning factors can change dynamically [49]. In this paper, inertia factor and learning factors are changed as follows:

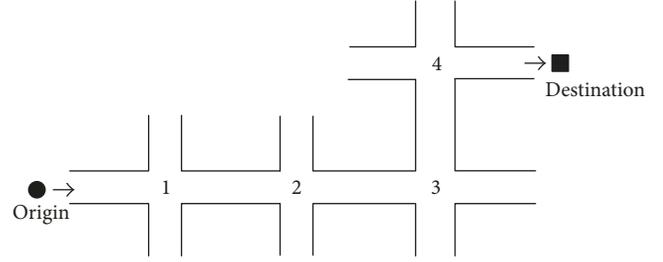


FIGURE 3: Intersections on evacuation route.

$$\begin{aligned} w(k) &= (w_f - w_s) \times \frac{\text{Max} - k}{\text{Max}} + w_s, \\ c_1(k) &= (c_{1f} - c_{1s}) \times \frac{\text{Max} - k}{\text{Max}} + c_{1s}, \\ c_2(k) &= (c_{2f} - c_{2s}) \times \frac{\text{Max} - k}{\text{Max}} + c_{2s}, \end{aligned} \quad (39)$$

where k , Max , w_s , and w_f represent current iterations, maximum iterations, the initial value of inertia weight, and the final value of inertia weight, respectively; c_{1s} , c_{2s} represent the initial value of c_1 and c_2 , respectively; c_{1f} , c_{2f} represent the final value of c_1 and c_2 , respectively.

4.4. Mutation. In order to prevent the algorithm from falling into local optimum, mutation operator is introduced. Let O be the mutation probability; if $k < \text{Max} \times O$, then $\text{Max} \times O - k$ particles are selected from P and mutate according to the following equation:

$$x(i) = x(i) + \text{rand}() \times \text{int} \left(\frac{t_L(i) - t_E(i)}{2} - \frac{x(i)}{2} \right). \quad (40)$$

This will not only ensure the diversification of particles but also ensure the feasibility of particles after mutation.

5. Simulation Analysis

Assume that the evacuation route is composed of 4 intersections, as shown in Figure 3. The evacuation direction of EV is from west to east. It will pass through intersection 1 and intersection 2 straight ahead, turn left at intersection 3, and turn right at intersection 4, and $L_{\text{EV}-1} = 400$ m, $L_{\text{EV}-2} = 850$ m, $L_{\text{EV}-3} = 1350$ m, $L_{\text{EV}-4} = 1850$ m, $v_{\text{EV}} = 45$ km/h, $v_{\text{reg}} = 45$ km/h; $d_{i1} = d_{i2} = 28$ s, $C_i = 56$ s, $i = 1, 2, 3, 4$, $C_{\text{max}} = 120$ s, $C_{\text{min}} = 30$ s; $ws_1 = 0$ s, $ws_2 = 30$ s, $ws_3 = 60$ s, $ws_4 = 90$ s; $t_{\text{switch}} = 3$ s, $t_{\text{pass}} = 2$ s, $B = 7$ m; $G_{\text{min}}^1 = G_{\text{min}}^2 = 15$ s, $G_{\text{max}}^1 = G_{\text{max}}^2 = 60$ s, $G_{\text{real}}^1 = G_{\text{real}}^2 = 25$ s, $G_{\text{low}} = 10$ s, $G_{\text{short}}^j = 10$ s.

In south-northward direction and west-eastward direction, the ratio of straight, right turn, and left turn is 0.7, 0.2, and 0.1, respectively. And it is 0.6, 0.3, and 0.1 respectively, in north-southward direction. In the particle swarm algorithm, $N_1 = 100$, $\text{Max} = 1000$, and $O = 0.1$. The size of external dominance population is 100, and $w_s = 0.4$, $w_f = 0.9$, $c_{1f} = 1$, $c_{2f} = 2$, $c_{1s} = 2$, $c_{2s} = 1$.

TABLE 1: The Pareto solution set of of EV when t_0 is 9 o'clock.

Number	The real start time of green signal(s)				f_1 (s)	f_2 (pcu)
	Intersection 1	Intersection 2	Intersection 3	Intersection 4		
(1)	10	33	53	81	0	112.1
(2)	10	34	54	81	2.3	113.6
(3)	10	34	55	82	2.4	114.8
(4)	11	34	55	83	3.9	116.6
(5)	12	34	56	83	4.7	118.7
(6)	13	34	58	84	4.8	120.4

TABLE 2: The Pareto solution set of EV when t_0 is 10 o'clock.

Number	The real start time of green signal(s)				f_1 (s)	f_2 (pcu)
	Intersection 1	Intersection 2	Intersection 3	Intersection 4		
(1)	10	31	56	82	0	119.7
(2)	11	33	58	83	2.9	119.9
(3)	11	34	57	83	3.2	122.4
(4)	12	34	58	83	4.9	122.7
(5)	13	34	57	83	5.5	123.5

Assume that the number of vehicles waiting to pass through each intersection at time t_0 is $q_1 = 10$, $q_2 = 5$, $q_3 = 6$, and $q_4 = 8$, respectively, and $q_{iN} = q_{iS} = 10$, $i = 1, 2$, $q_{3S} = q_{3E} = 10$, and $q_{4N} = q_{4W} = 10$. At each intersection, the arrival rate from south to north is 1080–1440 pcu/h and the average departure rate is 1440 pcu/h, the arrival rate from east to west is 1440–1800 pcu/h, and the saturation flow rate is 1800 pcu/h. Assume that t_0 is 9 o'clock and 10 o'clock, respectively. The Pareto solution set obtained by using C# for simulation calculation is shown in Tables 1 and 2. The data corresponding to each intersection indicates how many seconds after 9 o'clock or 10 o'clock will each intersection start the green signal; f_1 and f_2 are the residence time of EV at all the intersections and the number of vehicles passing through the system, respectively.

Assume that the number of vehicles waiting to pass through each intersection at time t_0 is $q_i = 20$, $i = 1, 2, 3, 4$, and $q_{iN} = q_{iS} = 10$, $i = 1, 2$, $q_{3S} = q_{3E} = 10$, $q_{4N} = q_{4W} = 10$. Traffic flow from north to south and from west to east is the key traffic flow. At each intersection, the arrival rate from north to south is 1400–1600 pcu/h and the average departure rate is 1440 pcu/h; the arrival rate from west to east is 1800–1900 pcu/h and the saturation flow rate is 1800 pcu/h; the arrival rate in other directions remain unchanged. If t_0 is 9 o'clock and 10 o'clock, respectively, the Pareto solution set is shown in Tables 3 and 4.

To verify the control effect of the signal preemption control method presented in this paper under the condition of much larger traffic volume, for example, in the morning peak or the evening peak period, we assume that t_0 is 8 o'clock, namely, in the morning peak period, and $q_i = 20$, $i = 1, 2, 3, 4$, $q_{iN} = q_{iS} = 15$, $i = 1, 2$, $q_{3S} = q_{3E} = 15$, $q_{4N} = q_{4W} = 15$. At each intersection, the arrival rate from north to south and from west to east is 1800–1900 pcu/h and 2200–2400 pcu/h, respectively. The saturation flow rate is 1800 pcu/h and the

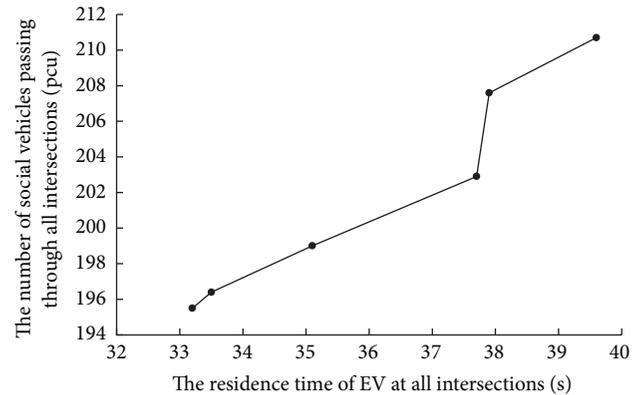


FIGURE 4: The Pareto optimal set.

arrival rate in other directions remain unchanged. The Pareto optimal set is shown in Figure 4.

We can see from the simulation results shown in Tables 1 and 2 that, for each solution in the Pareto solution set, the variation law of the two optimization objectives is that with the reduction of one objective; the other objective is reduced simultaneously, which implies that the decrease in the residence time of EV at intersections is at the expense of the reduction of the number of vehicles passing through the system. It also can be seen from the simulation results shown in Tables 3 and 4 that, at the moment the EV is detected, if there are many queued vehicles at each intersections and the traffic volume of key traffic flow exceeds the amount of traffic that the system can release, the control method can still guarantee the EV to pass through the intersection at a faster speed, and more social vehicles can pass through the system. The results shown in Figure 4 also indicate that the signal preemption control method is effective when the

TABLE 3: The Pareto solution set for an increasing arrival rate when t_0 is 9 o'clock.

Number	The real start time of green signal(s)				f_1 (s)	f_2 (pcu)
	Intersection 1	Intersection 2	Intersection 3	Intersection 4		
(1)	2	46	73	108	29.4	165.7
(2)	2	45	75	108	29.5	167.1
(3)	0	45	76	114	33.2	171.2
(4)	1	43	76	111	36.7	175.4
(5)	1	44	80	116	37.9	183.5
(6)	4	44	80	111	38.4	184.4
(7)	7	43	82	123	38.4	186.9
(8)	4	43	80	117	39.3	189.1
(9)	7	43	84	119	39.9	193.6

TABLE 4: The Pareto solution set for an increasing arrival rate when t_0 is 10 o'clock.

Number	The real start time of green signal(s)				f_1 (s)	f_2 (pcu)
	Intersection 1	Intersection 2	Intersection 3	Intersection 4		
(1)	11	43	79	110	27.2	169.9
(2)	10	45	80	108	29.4	174.7
(3)	4	33	76	106	29.7	180.2
(4)	2	34	73	111	30.1	183.8
(5)	6	46	79	116	31.8	185.7
(6)	4	35	71	107	36.6	187.0
(7)	12	43	77	108	38.3	189.2

arrival rate are much larger in the morning peak period. Simulation results under different traffic states show that the signal preemption control method presented in this paper can reduce the delay of EV at intersections and lessen the impact of EV on social vehicles.

When multiple EVs arrive at the same time, the signal priority control method proposed in this paper is also applicable. If the arrival interval of adjacent EV is relatively long, it should be regarded as two signal priority processes. Now, after the front EV has passed through the intersection, we must consider signal transition from priority signal to normal signal firstly and then adopt the method mentioned above to control the following EV.

6. Conclusion

In order to overcome the disadvantages of signal preemption control method from intersection to intersection, we study the dynamic signal preemption control method based on route for EV in this paper. Firstly, a single intersection is taken as the research object to determine the earliest-possible start time and the latest-possible start time of each intersection in evacuation direction of EV on the selected route. Then, considering the delay of EV at intersections and the effect of EV to social vehicles comprehensively, to ensure that EV can pass through the intersections without reducing speed and without stopping as far as possible and the impact on social vehicles can be minimal, a multiobjective programming model is established and the solving algorithm is designed. Simulation calculations, considering EV is detected

at different times and different traffic states, are carried out, and the corresponding Pareto sets are given. The result shows that, by adopting this method, we can get more reasonable start time of green light at each intersection, reduce the delay of EV at intersections, and improve the efficiency of evacuation. Determine how the signal should be converted to the normal signal when signal preemption has been finished according to the signal timing, the traffic flow characteristics, and other parameters; namely, the signal transition strategy is the next focus of the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research is supported by National Nature Science Foundation of China (nos. 61563029, 71671079, 71361018, and 71571090).

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