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Research Article

Signal Preemption Control of Emergency Vehicles Based on Timed Colored Petri Nets

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This paper focuses on the use of timed colored Petri nets (TCPN) to study emergency vehicle (EV) preemption control problem. TCPN is adopted to establish an urban traffic network model composed of three submodels, namely, traffic flow model, traffic signal display and phase switch model, and traffic signal switch control model. An EV preemption optimization control system, consisting of monitoring subsystem, phase time determination subsystem, and phase switching control subsystem, is designed. The calculation method of the travelling speed of EV on road sections is presented, and the methods of determining the actual green time of current phase and the other phase are given. Some computational comparisons are performed to verify the signal preemption control strategies, and simulation results indicate that the proposed approach can provide efficient and safe running environments for emergency vehicles and minimize EV's interference to social vehicles simultaneously.

1. Introduction

With the continuous increase of traffic volume, traffic congestion and transportation delay on urban roads become more and more serious. Improving transportation safety and efficiency becomes a problem to be solved urgently [1]. Traffic signal control is an effective way to solve this problem. Signal timing and signal coordination control can save energy, reduce vehicle delay, improve transportation efficiency, and ensure transportation safety [2]. In addition, as an important step to cope with urban emergent events, emergency evacuation is viewed as an important measure to decrease the loss of emergent events. The people in impacted areas may suffer from some further injures, even death, if they stay for too long at the accident area. Therefore, one of the core problems of emergency evacuation is to transfer people in impacted areas to emergency shelters or medical assistance organizations as rapidly as possible [3], and emergency vehicles (EV) have larger priority than social vehicles in the case of emergencies. To ensure that EV can pass through intersections safely and rapidly, some scholars proposed signal preemption control strategy, and many methods and technologies of EV preemption have been employed today.

It was in [4] that bus preemption and EV preemption were integrated to study the signal preemption control strategy based on dynamic programming technology, and traffic flow in the network was controlled by the signal phase. To shorten the response time of EV, two kinds of signal preemption control strategies, namely, the real-time control strategy from general signal to EV preemption and the control strategy from EV preemption to general signal, were presented by Qin and Khan [5]. Wang et al. [6] proposed a priority level based EV preemption control strategy, and a travel time estimation model and an optimal route determination model were established for different levels of EV to minimize evacuation time and reduce the adverse effects on normal traffic. Ma and Cui [7] proposed a multiagent based EV preemption control system to study the coordinated control problem of multiple EVs in different import directions that pass through the same signalized intersection during the same period. In addition, the mechanism of centralized server and national transportation communications for ITS Protocol have also been used in EV preemption control field [8, 9].

Although there are many methods based on different traffic control strategies, all of them are mainly based on advanced communication, information, and electronic technologies to solve the EV preemption problem. While in

practice, the collection of information needed for wireless communication is very difficult.

Petri net (PN) is a powerful modeling and analysis tool, and it has been proved to be a powerful modeling tool for various kinds of discrete event systems [10]. Its formal expression can clearly reflect traffic signal control logic. Urban traffic system is highly concurrent and asynchronous. At the same time, since vehicles have to share traffic facilities and compete for lanes, green light phases, and other resources, resource sharing and conflict are also characteristics of urban traffic system. Since PNs have incomparable advantages in describing concurrency, asynchronization, parallelism, and conflict, they can be adopted to describe the characteristics of traffic signal control and reflect the characteristics of road traffic flow clearly. Therefore, PNs are suitable for describing urban traffic system and performing simulation. Urban traffic system models based on PNs have been proved to be effective tools for analyzing system performance, assisting intelligence, and optimizing traffic control.

It was in 1994 that PN was first applied to solve traffic signal control problem [11]. Afterwards, some experts and scholars began to use various types of PN models, such as timed Petri nets [12–16], continuous Petri nets [17, 18], hybrid Petri nets [19, 20], and colored Petri nets (CPN) [21–23] to establish simulation models of traffic in smart cities and to study urban traffic signal control problems. These papers mentioned above are aimed at general urban traffic network without EV. Some scholars adopted PNs to study traffic signal control problem under unexpected events when EVs were used for emergency evacuation or rescue. Huang et al. [24, 25] adopted timed Petri net to model the preemption of emergency vehicle systems and proposed a new EV preemption policy to ensure the safety and speed of EVs that passing through intersections. Huang and Weng [26] applied synchronized timed Petri net to design and analyze an urban emergency vehicle preemption control system. Qi et al. [27] employed timed Petri nets and synchronized Petri nets to design a real-time traffic control system for intersections facing accidents so as to provide secondary accident prevention and prevent additional accidents. Zhong et al. [28] studied the performance of China typical Urban Emergency Response System (UERS) and established its PN model, and the performance of UERS was analyzed through the Markov chain of the established model.

However, we can see from the methods adopted by existing research on EV preemption based on PN that traffic signal will change immediately from the current phase to the phase of EV as soon as EV is detected to ensure the smooth passage of EV. Since traffic signal stays in the designated phase for a long time, the right of way of traffic flow in other directions is derived, the delay of vehicles is increased, and traffic jams might be caused. It is very important to establish dynamic preemption strategy in urban traffic management to provide efficient and safe operation environment for emergency vehicles and minimize interference to social vehicles.

In this paper, an urban traffic network model based on timed colored Petri nets (TCPN) is presented, and an EV preemption optimization control system consisting of monitoring, phase time determination, and phase switching control is designed. For convenience and without loss of generality, four-phase lights are modeled with a fixed number of discrete time intervals by TCPN. The TCPN based urban traffic network model consists of three parts. The first part is traffic flow model for road section and intersection. In the traffic flow model of road section, space discretization method is adopted to divide the area between two intersections into three parts, namely, subsection 1, subsection 2, and detection area. Vehicles coming from gas stations, maintenance stations, and other places on the roadside and entering the road sections can be described by this model. The second part is signal display and phase switch model. Under normal circumstances, traffic signal at each intersection is switched orderly. When an EV is detected, in the premise of minimizing the interference to social vehicles, traffic signal can be switched to the phase of EV as soon as possible. The third part is traffic signal switch control model. It ensures that traffic signal can change from EV phase to the next phase after EV has passed through the intersection. The traffic signal optimization system can provide EVs with no or less delay and minimize their interference to social vehicles.

The remainder of the paper is organized as follows. Section 2 provides the definitions of TCPN in a compact way. Section 3 explains the TCPN representation and its signal control logic. Analysis of the EV preemption optimization control system is explained in Section 4. Simulation is carried out in Section 5 and conclusions are presented in Section 6.

2. Basic Concepts of TCPN

CPN is a high-level modeling formalism which has been widely used to model and verify systems. TCPN is obtained by extending the concept of time on the basis of CPN. This extension is made by introducing a global clock for the model and time stamps for the entities [29]. The global clock represents the model time while the time stamps describe the earliest model time at which the entities of the model can be used for the transition evaluation process [30, 31]. If the time stamp of a token is not larger than the current model time, then the token can be used. Otherwise the token is not ready and cannot be used in the transition enabling procedure.

TCPN is a tuple TCPN= $(\sum, P, T, A, N, C, G, E, I, R, r_0)$, where

(i) $\sum$ is a finite set of non-empty color sets;

(ii) P is a finite set of places;

(iii) T is a finite set of transitions;

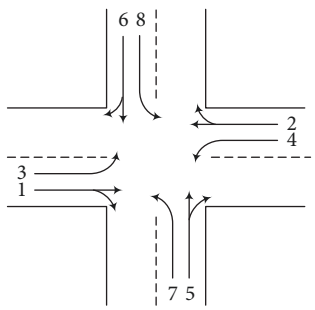
(iv) A is a finite set of directed arcs such that $P \cap T = P \cap A = T \cap A = \Phi$;

(v) N is a node function that satisfies $N(A) = P \times T \cup T \times P$;

(vi) $C: C(P) \longrightarrow \sum$ is a color function which assigns a set of color sets for each place;

(vii) G is a guard function. It is defined from T into expressions such that

$$\forall t \in T, \quad \text{Tpye}(G(t)) = B \wedge \text{Tpye}(\text{var}(G(t))) \subseteq \sum \tag{1}$$



(a) Traffic flow

Phase	Direction
1	1, 2
2	3, 4
3	5, 6
4	7, 8

(b) Phases

Figure 1: Traffic flow and phases of signalized intersection.

where Tpye($G(t)$)is the type of $G(t)$, B represents Boolean type, var($G(t)$) is variable set of function $G(t)$, and Type$[v] \in \sum$ for all variables $v \in V$;

(viii) E is an arc expression function. It is defined from A into timed or untimed expressions such that

$$\forall a \in A, \quad \text{Tpye}(E(a)) = C(p(a))_{MS} \wedge \text{Tpye}(\text{var}(E(a))) \subseteq \sum \tag{2}$$

where $C(p(a))_{MS}$ is the multiset of $C(p(a))$;

(ix) I is an initialization function. It is defined from P into timed or untimed closed expressions such that $\forall p \in P$, Tpye$(I(p)) = C(p)_{MS}$;

(x) R is a set of time values, also called time stamps. It is a subset of R closed under + and containing 0;

(xi) r_0 is an element of R, called the start time.

Marking is represented by the number of tokens inside a place. For $\forall p_i \in P$, $m_0(p_i)$ is the initial marking of place p_i, and the marking of p_i under other state is denoted as $m(p_i)$. There are two kinds of markings in a TCPN model, namely, the timed marking and the untimed marking.

3. Urban Traffic Network Model Based on TCPN

3.1. Traffic Flow Models of Road Section and Intersection. Consider a signalized intersection shown in Figure 1(a). The traffic flow of each direction is composed of left-turn, straight, and right-turn vehicles. Two magnetic induction coils buried in the corresponding position of each lane are used to obtain the traffic flow information that enters or exits the intersection, and the range between the two magnetic induction coils is detection area [32]. Vehicles with labels 1, 2, 5, and 6 are combinations of straight and right-turn vehicles, while the ones with labels 3, 4, 7, and 8 are left-turn vehicles. The 4-phase signal control scheme is shown in Figure 1(b). In phase i, vehicles with label $2i - 1$ and $2i$ are permitted to pass through the intersection and right-turn vehicles are not restricted by traffic light.

For convenience of description, the directions of traffic flow heading eastward, westward, northward, and southward are symbolized by the notations WE, EW, SN, and NS, respectively.

3.1.1. Traffic Flow Model of Road Section. Traffic flow is continuous on road section and discrete at intersection. The change rule of traffic flow is very complex because it is affected by random factors. For example, vehicles from gas stations, car repair stations, and other places on both sides of the road may pull into the road and exert an impact on the original traffic flow. To reflect the main characteristics of road traffic flow and take full account of the influence of vehicles entering from the roadside to road, the spatial discretization method is adopted in this paper. The region between two intersections is divided into three parts, namely, subsection 1, subsection 2, and intersection region (detection area). Subsection 1, subsection 2, and intersection region are used to reflect the condition of traffic flow that entered road section after leaving from the upstream intersection, the running condition of traffic flow at road section, and the condition of traffic flow that deviated from the road section and entered the downstream intersection, respectively. In addition, subsection 1 and subsection 2 can describe the vehicles that pulled into the road from roadside. Taking traffic flow that enters road section after leaving the first intersection from west to east as an example, we can give the model of traffic flow at road section as shown in Figure 2.

In Figure 2, the region between transition t_{s0} and t_{s1} is subsection 1, the region between transitions t_{s1} and t_{s2} is subsection 2, and the region on the right side of t_{s2} is the intersection region. The model of vehicle flow at intersection region will be discussed later in Figure 3. The marking of places p_1 and p_2, p_{1u} and p_{2u}, p_{1e} and p_{2e}, and p_{1r} and p_{2r} represents the residual position number of the two subsections, the vehicles waiting to pull into subsection 1 and subsection 2 from roadside, vehicles on the two subsections, and vehicles that are leaving subsection 1 and subsection 2, respectively. The firing of transitions t_{s0}, t_{s1}, and t_{s2} represents vehicles having entered subsection 1, subsection 2, and intersection area, respectively. The firing of transitions t_{1m} and t_{2m}, t_{1u} and t_{2u}, and t_{1a} andt_{3a} represents the fact that vehicles are running in subsection 1 and subsection 2, vehicles from the roadside have pulled into subsection 1 and subsection 2, and vehicles have entered the intersection area. Place p_1 is the input place of transitions t_{s0} andt_{1u}, which indicates that vehicles running

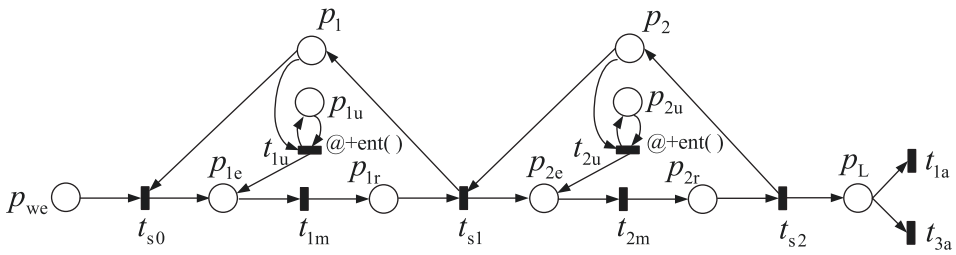


Figure 2: TCPN model of traffic flow on road section.

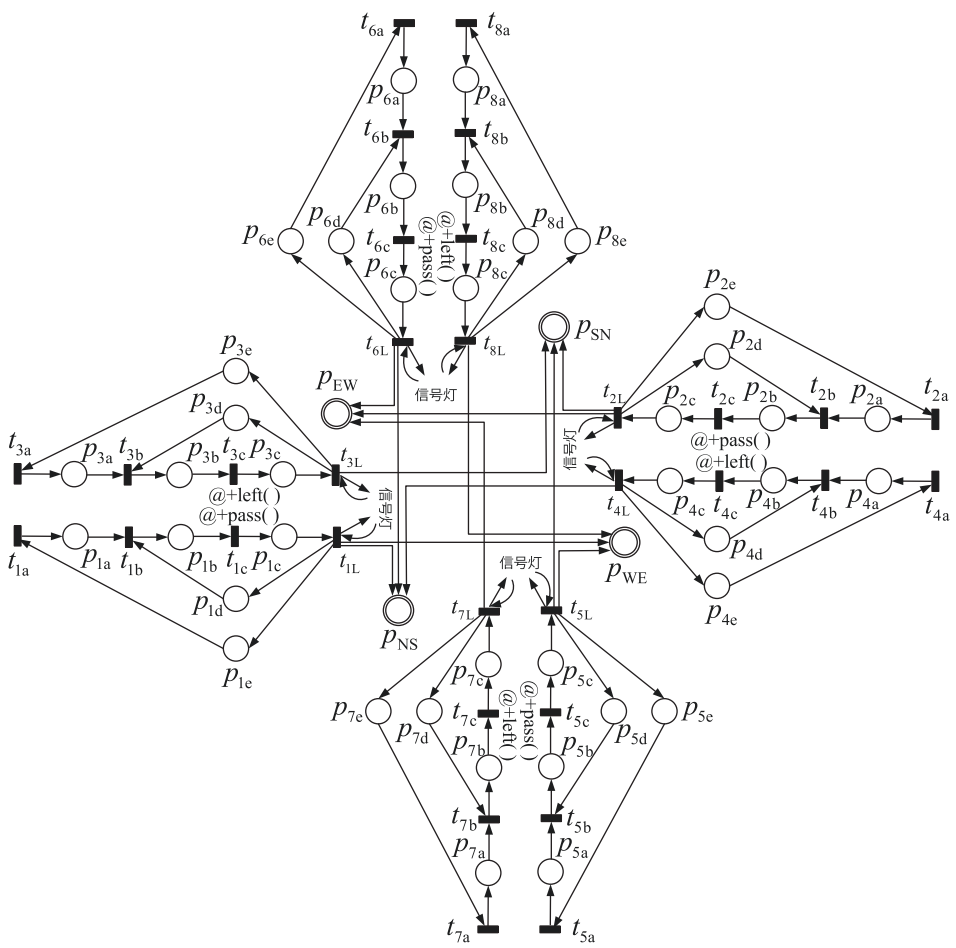


Figure 3: TCPN model of traffic flow at intersection.

on the road and vehicles pulling into the road from roadside are all limited by the capacity of subsection 1. Once transition t_{s1} is fired, namely, a vehicle has left subsection 1, the marking of place p_1 will change from $m(p_1)$ to $m(p_1)+1$ and then one vehicle is permitted to enter sub section 1.

The firing time of transitions t_{1m} and t_{2m} represents the travel time of vehicles on subsection 1 and subsection 2, respectively. The firing time of transitions t_{1u} and t_{2u} represents the time interval between two adjacent vehicles entering subsection 1 and subsection 2 from roadside, respectively. The time delay expression @ + Ent() is the time delay of firing corresponding transition. The function Ent takes a unit (( )) as argument and is defined as follows:

$$\text{fun Ent}() = \text{discrete}(d_1, d_2).$$

The function discrete is a predefined function providing a discrete uniform distribution over the closed interval specified by its arguments [33]. This means that a call Ent( ) returns an integer from the interval $[d_1, d_2]$ $(d_1 < d_2)$ and that all numbers in the interval have the same probability of being chosen.

3.1.2. Traffic Flow Model of Signalized Intersection. Based on the 4 phases signal control scheme as shown in Figure 1(b), the TCPN model of traffic flow at signalized intersection is established as shown in Figure 3. The marking of places p_{ia}, p_{ib}, and p_{ic}, $i = 1, 2, ..., 8$ represents traffic flow of direction i that is waiting to enter the intersection, in intersection area,

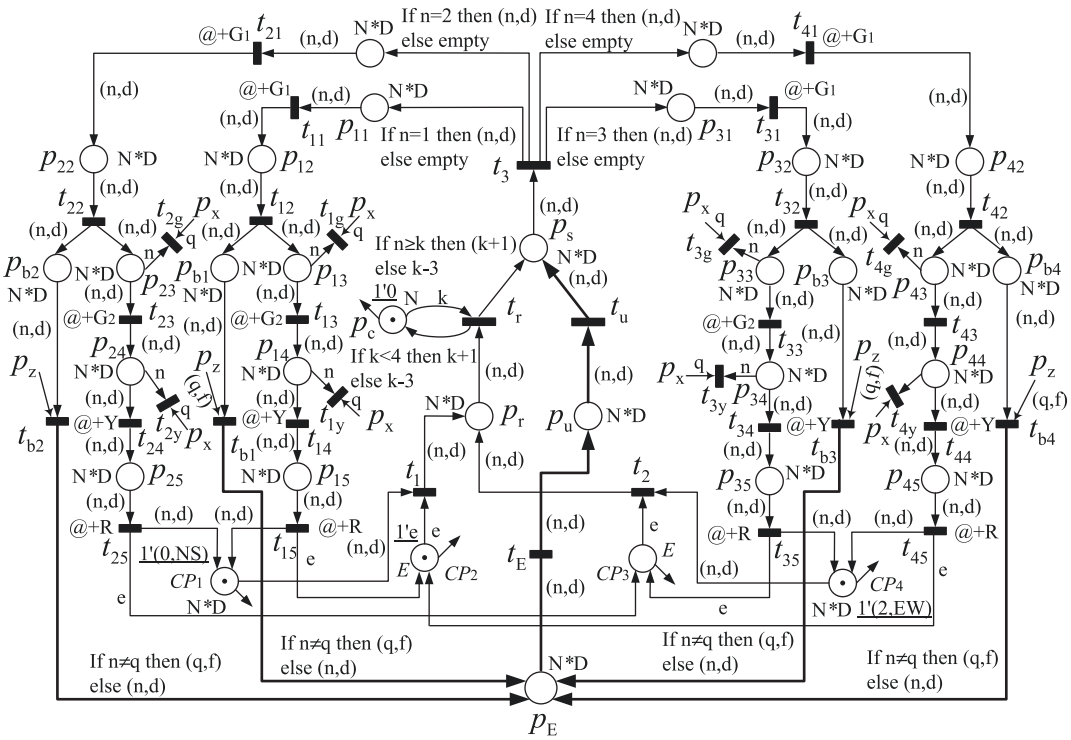


Figure 4: TCPN model of signal display and phase switch.

and passing through the intersection area, respectively. The capacity of place p_{id} is 1, $i = 1, 2, ..., 8$, which represents that only one vehicle can pass through the intersection at the same time in direction i. The marking of place p_{ie},$i = 1, 2, ..., 8$ represents the residual position number of the intersection area. For vehicles from direction i, arriving, entering intersection area, passing through intersection area, and leaving from the intersection are represented by the firing of transition t_{ia}, t_{ib}, t_{ic} and t_{iL}, $i = 1, 2, ..., 8$, respectively. In Figure 3, places represented by double circles are macro places, and a macro place is composed of a series of places and transitions. For example, places p_{WE}, p_{EW}, p_{NS}, and p_{SN} are macro place and represent traffic flow on the road from west to east, from east to west, from north to south, and from south to north, respectively. An expanded view of the macro place is a traffic flow model shown in Figure 2. The firing time of transition t_{ic},$i = 1, 2, ..., 8$ represents the time taken by a vehicle to pass through the detection area.

3.2. TCPN Model of Traffic Signal Display and Phase Switch. Under normal circumstances, traffic signals at signalized intersection are switched in accordance with the four-phase sequence as shown in Figure 1(b). When unexpected event happens and EVs are used to evacuate and rescue, traffic signal should be switched to the phase of EV as soon as possible in the premise of minimizing the disturbance to social vehicles. The TCPN model shown in Figure 4 can reflect the two situations mentioned above. The normal lines reflect normal signal switch process and the black lines indicate signal switch process when there are EVs.

The TCPN model shown in Figure 4 can display the change process of green, yellow, and red signals. According to the definition of TCPN, token is defined as a 2-tuple (n, d). The first element n represents four phases, $n \in \{1, 2, 3, 4\}$. The second element d represents the direction of vehicles, $d \in \{\mathrm{NS}, \mathrm{EW}\}$, and color k represents four phases, $k \in \{1, 2, 3, 4\}$. Once places p_{i1}, p_{i3}, p_{i4}, and p_{i5}, $i = 1, 2, 3, 4$ get a token, this means that the traffic light of phase i is at the stage of the minimum green time, the remaining green time, yellow time, and red time, respectively. The token in place p_{i2}, $i = 1, 2, 3, 4$ represents the end of the minimum green time. p_x and p_z are places in signal transition control system. When an EV is detected, the token in places p_x, p_z, and p_{bi}, $i = 1, 2, 3, 4$ ensures that the normal signal will be ended and the emergency signal will be started. The specific phase that emergency signal should switch to is determined by q, namely, the color of token in place p_z. The token in place CP_i, $i = 1, 2, 3, 4$ controls the switch of traffic signal from phase 1 to phase 4.

The firing time of transitions t_{i1}, t_{i3}, t_{i4}, and t_{i5} is G_1, G_2, Y, and R, respectively, and G_1, G_2, Y, and R represent the minimum green time, the difference between the actual green time and the minimum green time, the yellow time, and the red time, respectively. In this paper, G_1, Y, and R are fixed values, which are 10 s, 3 s, and 2 s, respectively. G_2 is a fixed value if there is no EV. Once the EV is detected, G_2 is determined by the method mentioned in Section 3.3.

Taking the first phase as an example, we will illustrate the changes of traffic light and phase switch. Transitions that stand for traffic light are fired by tokens in input places.

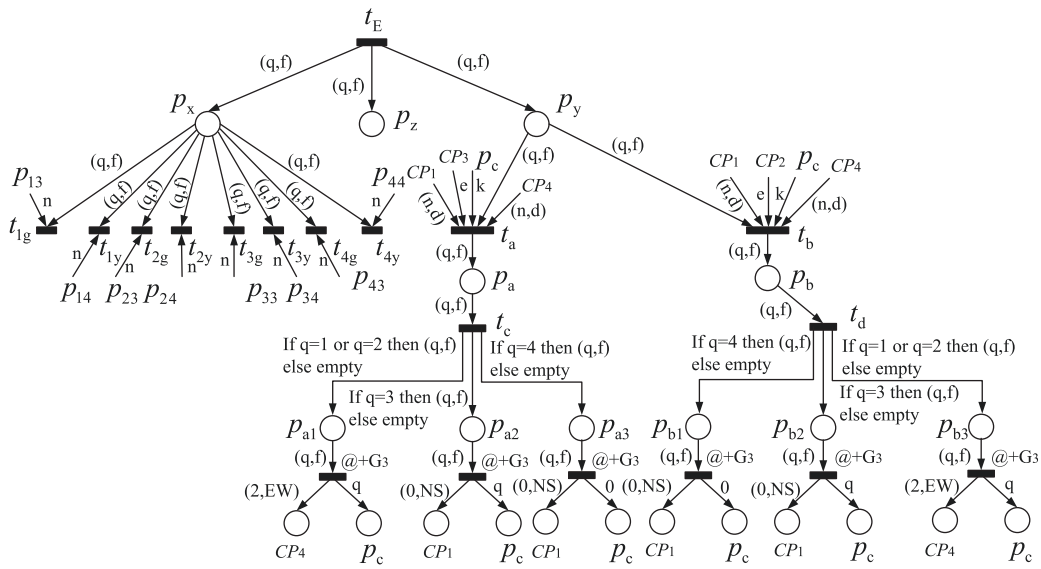


Figure 5: Traffic signal switch control model.

Initially, there is a token in places CP_1, CP_2, and CP_4 and the time stamp of the initial marking is 0. There is also a token in place p_c with color 0. If both CP_1 and CP_2 get a token, transition $t_1$is fired promptly, which in turn makes CP_1 and CP_2 lose their token and p_r receive a token, and the color of token in p_r is (0, NS). Transition t_r will be fired if both p_r and p_2 have got a token. According to the arc expressions between t_r and p_2 and between t_r and p_s, the marking of p_c and p_s changes to $1'1$ and $1'(1, \mathrm{NS})$, respectively, after t_r has been fired. Since $n = 1$ at this time, after t_3 has been fired, p_{11} gets a token with color$1'(1, \mathrm{NS})$, which means that the traffic light is green for phase 1 and it is still red for the other phases. After the minimum green light time G_1, the marking of p_{12} changes to $1'(1, \mathrm{NS})$, which in turn makes transition t_{12} fired, and the marking of p_{b1} and p_{13} changes to $1'(1, \mathrm{NS})$.

In the absence of EVs, both p_x and p_z are not marked and neither transition t_{b1} nor transition t_{1g} can be fired. After the residual green time G_2, the marking of p_{14} changes to $1\prime(1, \mathrm{NS})$, and both CP_1 and CP_2 will get a token again after a yellow time and a red time. But now, the marking of CP_1 will change from$1'(0, \mathrm{NS})$ to $1'(1, \mathrm{NS})$. After t_r has been fired according to the similar process as described above, the marking of p_c changes to$1'2$ and the marking of p_s changes to $1'(2, \mathrm{NS})$, and thus the signal is transferred into phase 2.

On the contrary, when an EV is detected, the signal optimization control system will control the signal to switch to the part described by thick lines as shown in Figure 4, and finally the signal of EV direction will change to green.

Now, we will illustrate it under the condition that phase 1 is the current green phase and the EV will pass through the intersection at another phase. Without loss of generality, we assume that it is phase 3. If an EV is detected when the elapsed green time of phase 1 is less than the minimum green time, phase transition will not be performed until the end of the minimum green time of phase 1 so as to ensure the safety of the vehicles. At this moment, both p_{b1} and p_{13} get a token. Once an EV is detected and its phase 3 is determined, the signal optimization control system puts a token with color $(3, \mathrm{EW})$ to p_x and p_z, respectively. And then both t_{1g} and t_{b1} will be fired, which in turn makes p_{13} and p_{b1} lose their token simultaneously. The absence of token in p_{13} makes phase 1 end early, and p_E gets a token when p_{b1} loses its token. And then, transitions t_E and t_u are fired successively, which makes p_s get a token with color $(3, \mathrm{EW})$ and finally transition t_3 is fired and phase 3 changes to the green phase. If an EV is detected when the signal of current phase is yellow, then there is a token in both p_{b1} and p_{14} and the following process is identical to the process mentioned above. The other phase switch process from one phase to another EV phase is similar to what we have given, and we will not give unnecessary details here.

3.3. TCPN Model of Traffic Signal Switch Control. The traffic signal switch control model based on TCPN is shown in Figure 5. Places p_c, p_{i3}, p_{i4}, and CP_i, $i = 1, 2, 3, 4$, in Figure 5 are the same name places in Figure 4. Transition t_E will be fired by the EV preemption optimization control system while an EV is detected, and p_x, p_y, and $p_z$will get a token with color (q, f), respectively. The token in p_x will prevent the phase from switching in normal order, the token in p_z will fire transition $t_{bi}, i = 1, 2, 3, 4$, and realize switch from current phase i to EV phase, and the token in p_y will control the signal to transfer to the next phase of EV after EV has passed through the intersection. The control of p_x and p_z to traffic signal from normal signal to EV preemption has been described earlier in this section, and we will focus on how the token in p_y will control the signal to transfer from EV phase to its next phase.

If an EV is detected when the signal of current phase is green or yellow, after the signal has switched to EV phase and executed corresponding green time (calculated by the EV preemption optimization control system), the signal can

transfer to the next phase of EV smoothly according to the marking changes of places and the arc expressions. Traffic signal switch control model is needed when one phase is finished and is ready to switch to another. Now, we will illustrate the details of phase switch under this condition. If the current phase is finished and traffic light is ready to switch to the next phase while an EV is detected, then there are tokens in either CP_1, CP_2, and CP_4 or in CP_1, CP_3, and CP_4 in Figure 4. When phase 1 (phase 4) is finished and traffic light is ready to turn to phase 2 (phase 1), there are tokens in CP_1, CP_2, and CP_4 and there are tokens in CP_1, CP_3, and CP_4 in the other two cases.

Suppose that phase 1 is finished and the traffic light is ready to transfer to phase 2 at present and an EV is detected just right. Now, the tokens in all the input places of transition t_b, namely, places p_y, CP_1, CP_2, CP_4, and p_c, make transition t_b fire. The firing of t_b makes all of its input places lose their tokens—thus the normal phase switch is prohibited—and makes the output place p_b of t_b get a token simultaneously. Assume that the EV phase is phase 4; that is, the value of color q is 4. We can see from Figure 4 that both CP_2 and CP_4 will get a token after phase q has been finished and CP_1 and p_c in Figure 5 will finally get a token with color (0, NS) and 4, respectively. At this time, the token in CP_1 and CP_2 fires t_1 in Figure 4 and makes p_r get a token with color (0, NS). Since now $n = 0$ and $k = 4$, according to arc expression "If n≥k then (k+1) else k-3", p_s gets a token with color (1, NS) and then phase 1 is started immediately. Thereby it can be ensured that the next phase of EV phase can be started after EV passed through the intersection. We will no longer describe the conversion process between other phases which is similar to the one mentioned above.

4. EV Preemption Optimization Control System

An EV preemption optimization control system composed of 3 subsystems, namely, monitoring, phase time determination, and phase switching control, is designed. Monitoring system is responsible for monitoring phase and elapsed green time of current phase, and phase time determination system is adopted to determine the actual green time of each phase and decide the next phase. The best time for signal to switch to EV phase, say, the time to fire transition t_E and give tokens to place p_x and p_z in Figure 5, is decided by phase switching control system. The concrete control steps of the optimization control system are described as follows:

Step 1. At the moment an EV is detected, monitoring system determines the current phase n and the EV phase q and calculates the elapsed green time of current phase.

Step 2. According to the relationship between n and q, phase time determination system determines the actual green time of each phase, namely, the value of $G_1 + G_2$ in Figure 4, and decides the time for signal to switch to phase q.

Step 3. At the moment the signal should switch to phase q, phase switching control system gives tokens to places p_x and p_z in Figure 5 and makes signal control process execute in accordance with the black line part of Figure 4; that is, the traffic signal switches to the EV phase.

Step 4. After the EV has passed through its downstream intersection, phase switching control system ensures that traffic signal can switch to the next phase of EV according to the control logic of traffic signal switch control model shown in Figure 5.

4.1. The Method of Judging the Current Phase. The method for the monitoring system to judge the current phase and calculate the elapsed green time of current phase is as follows. Let d_{ij} be the duration time of phase j at intersection i and t_0 the time that an EV is detected. Suppose that all the intersections are four-phase control intersections and have fixed signal cycle as shown in Figure 1. If the starting time of the first phase of intersection$i$, denoted by ws_1, is determined and the duration time of the four phases denoted by d_{i1}, d_{i2}, d_{i3}, and d_{i4} is also determined, then the current phase of intersection i and the elapsed green time of this phase can be calculated correspondingly. Provided that C denotes the cycle length of intersection i and D_{ij} denotes the elapsed green time of intersection i after j phases, then we have

$$D_{i,0} = 0,$$
$$D_{i,j} = \sum_{k=1}^{j} d_{ik}, \quad j = 1, 2, 3, 4 \tag{3}$$

If the elapsed number of cycles in time duration $t_0 - ws_1$is denoted as a and the remaining time after a cycles in time duration $t_0 - ws_1$ is denoted as b, then we have

$$a = \frac{(t_0 - ws_1)}{C},$$
$$b = (t_0 - ws_1) \bmod C \tag{4}$$

Then the current phase is i if it satisfies $D_{i,j-1} \le b < D_{i,j}$ and the elapsed green time of phase i is $t_0 - ws_1 - a \times C - \sum_{k=0}^{j-1} D_{i,k}$.

4.2. The Travelling Speed of EV on Road Sections. Let $G^j_{\min}$, $G^j_{\max}$, G^j_{ela}, and G^j_{real} denote the minimal green time, the maximal green time, the elapsed green time, and the actual green time of phase j, respectively, $j = 1, 2, 3, 4$; $L_{\text{EV}-i}$ denotes the distance between EV detection and intersection i; D is equivalent car length and it is equal to the sum of the length of vehicle itself and the distance between adjacent vehicles. According to the regulations of China on road transport, the variation range of vehicle's average travelling speed is set as 0 to 60 km·h^{-1}.

The travelling speed of vehicles is closely related to the traffic flow on road section, and the traffic flow on road section varies with time constantly. According to the division method shown in Figure 2, the travelling speed of vehicles at subsection 1 and subsection 2 will be determined separately. Let L_i, K_i, V^i_E, and v^i_E stand for the length, the traffic density, the maximal travelling speed of EV, and the average travelling

speed of EV at subsection i, $i = 1, 2$, respectively, and K_s stand for the jam density. If an EV enters subsection 1 and subsection 2 at time instants τ_1 and τ_2 respectively, and the number of vehicles in the two subsections is $m(p_{1e})(\tau_1)$ and $m(p_{2e})(\tau_2)$ respectively, then the traffic density of the two subsections can be described as

$$K_1 = \frac{m(p_{1e})(\tau_1)}{L_1} \tag{5}$$

$$K_2 = \frac{m(p_{2e})(\tau_2)}{L_2} \tag{6}$$

where $m(p_{1e})(\tau_1)$ and $m(p_{2e})(\tau_2)$can be obtained by the marking changing rule of PN.

According to the relationship between velocity and density, we have

$$v_{EV}^1 = V_E\left(1 - \frac{K_1}{K_s}\right) \tag{7}$$

$$v_{EV}^2 = V_E\left(1 - \frac{K_2}{K_s}\right) \tag{8}$$

4.3. The Determination of the Actual Green Time of Current Phase. Suppose that the phase of EV is q, the current phase is n, and the difference between q and n is k; then we have

$$k = \begin{cases} q - n & q \geq n \\ 4 + q - n & q < n \end{cases} \tag{9}$$

We employ T_1, T_2, and l_q to denote the time duration needed for EV to reach the intersection, the time duration needed to clear the vehicles before EV, and the number of vehicles before EV. Then we have

$$T_1 = \frac{L_{EV}}{v_{EV}}, \qquad T_2 = \frac{l_q \times D}{v_{reg}} \tag{10}$$

Next, the actual green time of the current phase will be discussed according to the value of k. In order to facilitate the description, we employ d_j to denote the duration time of phase j under normal condition (without EVs), $j = 1, 2, 3, 4$.

(1) $k = 0$, namely, $q = n$

In this scenario, if $G_{ela}^n + T_1 \leq d_n$, namely, the sum of the elapsed green time of current phase and the time duration needed for EV to reach the intersection, does not exceed the time duration of phase n, then G_{real}^n, the actual green time of current phase, equals d_n. If $G_{ela}^n + T_1 > d_n$, G_{real}^nshould be extended to $G_{ela}^n + T_1$.

(2) $k = 1$; namely, q is the next phase of n.

In this scenario, we should check whether the following formula is satisfied:

$$d_n - G_{ela}^n + Y + R + T_2 \leq T_1 \tag{11}$$

If it is satisfied, G_{real}^n equals d_n and the traffic signal will switch to phase q after G_{real}^n. Otherwise, let

$$G' = T_1 - (Y + R + T_2) \tag{12}$$

If $G' > G_{min}^n$ then G_{real}^n equals $G\prime$. Otherwise, G_{real}^n equals G_{min}^n. The traffic signal will switch to phase q after G_{real}^n in the two cases.

(3) $k = 2$; namely, there is a phase between$q$and n

Suppose that the phase between q and n is phase b; then we have

$$b = \begin{cases} n + 1 & q > n \\ q + 1 & q < n \end{cases} \tag{13}$$

Now, we will judge whether the following formula is satisfied:

$$d_n - G_{ela}^n + Y + R + d_b + Y + R + T_2 \leq T_1 \tag{14}$$

If formula (14) is satisfied, then the actual green time of current phase n and the next phase b is d_n and d_b, respectively, and then the traffic signal will switch to phase q. Otherwise, we judge whether the following formula is satisfied:

$$d_n - G_{ela}^n + Y + R + G_{min}^b + Y + R + T_2 \leq T_1 \tag{15}$$

If formula (15) is satisfied, then the actual green time of current phase n and the next phase b is d_n and G_{min}^b, respectively, and then the traffic signal will switch to phase q. Otherwise, we will judge whether formula (11) is satisfied. If it is satisfied, the traffic light will skip phase b and switch to phase q directly after the current phase n has executed green time d_n. If formula (11) is also not satisfied, we will calculate $G\prime$ according to formula (12). The actual green time of current phase n is $\max\{G\prime, G_{min}^n\}$, and then the traffic light will skip phase b and switch to phase q directly.

(4) $k = 3$; namely, there are two phases between q and n.

Let b_1 and b_2 be the two phases between q and n; then we have

$$b_j = \begin{cases} n + j & n + j < 4 \\ n + j - 4 & n + j > 4 \end{cases} \quad j = 1, 2 \tag{16}$$

In this case, the actual green time of current phase n will be calculated according to the method of$k = 1$, and then the traffic signal will switch to phase q.

After the traffic light has switched to phase q, the green time of phase q is T_1 seconds if $T_1 \geq G_{min}^q$; otherwise the green time of phase q is G_{min}^q. Then, the traffic light will switch to the next phase of phase q according to the TCPN model shown in Figure 4. The relationship between T_1 and G_{max}^n is not discussed here because no matter what relationship exists between them, it is necessary to ensure that the EV can pass through the intersection smoothly and the green time will be extended to T_1 even if $T_1 > G_{max}^n$.

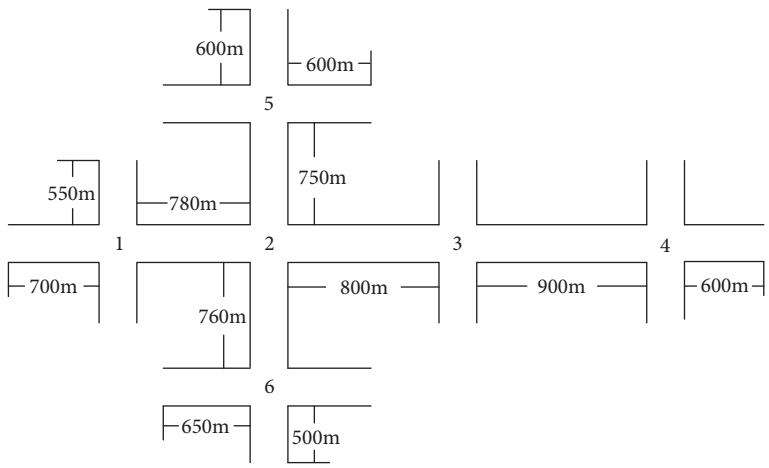


Figure 6: Schema of urban intersection group.

5. Simulation Results Analysis

To analyze the effectiveness of the method presented in this paper, taking CPN Tools and C# as the simulation tool, a computer simulation is carried out on the basis of the intersection group with 6 intersections as shown in Figure 6. The distance between intersections is shown in Figure 6. The road link between two intersections is divided into three parts: intersection region, subsection 1, and subsection 2 as mentioned above. Suppose that the length of intersection region is 100 m and half of the residual length calculated by subtracting the length of intersection region from the length between two intersections is the length of each subsection. The EV detector of each road link is located at the start position of subsection 1; that is, EV can be detected as soon as it is entering subsection 1.

Assume that there are 6-lane dual carriageways in each direction and the lane from inside to outside is left-turn lane, straight lane, and straight-right mixed lane, respectively. At each intersection, for vehicles with labels 1, 2, 5, and 6, the ratio of straight traffic and right-turn traffic is 75% and 15%, respectively, and the ratio of vehicles with labels 3, 4, 7, and 8 is 10%. Let $G^j_{\min} = G_1 = 10$ s, $G^j_{\max} = 60$ s, $d_1 = d_3 = 25$ s, $d_2 = d_4 = 15$ s, $Y = 3$ s, $R = 2$ s, $V_E = 60\,\mathrm{km \cdot h^{-1}}$, $V_F = 54\,\mathrm{km \cdot h^{-1}}$, $D = 5$ m, and $K_s = 0.2\,\mathrm{pcu \cdot m^{-1}}$. Suppose that the speed of straight and right-turn vehicles is 36 km·h^{-1} while passing through the intersection and the speed of left-turn vehicles is 30 km·h^{-1} while passing through the intersection. We assume that the arrival rate of vehicles from east to west and from west to east is 1260-1440 pcu·h^{-1} and it is 1080-1260 pcu·h^{-1} from north to south and from south to north. The saturation flow rate is 1800 pcu·h^{-1}.

In this paper, a path is represented by intersections that EV passing through successively in the intersection group, and adjacent intersection is connected by "-". E, W, S, and N are adopted to represent the fact that vehicles have entered or left the intersection from east, from west, from south, and from north, respectively. For example, if an EV enters the intersection group from the west side of intersection 1 and leaves the intersection group through intersections 4, 5, and 6 by means of going straight, then the path can be described by W1-2-3-4E, W1-2-5 N, and W1-2-6S, respectively. Similarly, other paths can be obtained. Assume that the starting time of the first phase of each intersection is 0, namely, $ws_1 = 0$. At time t_0, $m(p_{1b}) = m(p_{3b}) = 10$ and $m(p_{2b}) = m(p_{4b}) = 4$, and $m(p_{5b})$ to $m(p_{8b})$ are all 5. For each intersection, $m(p_{1e})$ and $m(p_{2e})$ take random numbers from 8 to 12 on the road link from east to west and from west to east, and they are random numbers from 6 to 10 on the road link from north to south and from south to north.

Assume that an EV enters the intersection group from the upstream section of intersection 1 at 9 o'clock, 10 o'clock, 11 o'clock, and 12 o'clock, respectively, and leaves the intersection group at intersection 4; namely, the path of EV is W1-2-3-4E. Let i, n, p, q, and r_i denote the intersection, the current phase, the next phase, the phase of EV, and the residence time of EV at intersection i, respectively. Simulation calculation is carried out and the simulation results are shown in Table 1.

We can see from Table 1 that, for the given route, if an EV is detected at different time, the current phase and the elapsed green time of the same intersection are different. Similarly, if an EV is detected at the same time, the current phase and the elapsed green time of different intersections are also not entirely the same. We can also see that the green time of the next phase equals 0 under some conditions, and all the cases that there exists EV residence time at certain intersections appear in these conditions. This implies that the EV will arrive at the intersection in a short time and the traffic light has to skip the next phase and switch to the EV phase directly after the current phase has executed correspondingly green time, which can be calculated by the method presented in Section 4.3.

Assume that the time of an EV entering the intersection group is generated randomly and the method presented in this paper is compared with the method of turning the signal of EV phase to green immediately after EV is detected. Taking the travel time of EV in the intersection group and

Table 1: Simulation results of EV arriving at different time.

t_0	i	n	G^n_{ela}	p	G^p_{real}	q	G^q_{real}	r_i
9:00	1	1	15	2	15	1	30	0
	2	2	5	3	0	1	15	0
	3	3	25	4	0	1	28	0
	4	2	7	3	0	1	17	0
10:00	1	1	25	2	15	1	43	0
	2	3	1	4	0	1	28	2.7
	3	4	13	1	25	1	25	0
	4	3	9	4	0	1	30	2.0
11:00	1	2	12	3	0	1	25	0
	2	3	15	4	0	1	29	3.2
	3	1	10	2	15	1	30	0
	4	3	21	4	0	1	26	0
12:00	1	3	6	4	0	1	28	3.7
	2	3	25	4	0	1	26	0
	3	1	19	2	15	1	32	0
	4	3	25	4	0	1	24	0

Table 2: Comparison of simulation results.

Paths	The travel time of EV (s)		The residence time of EV at all intersections (s)	
	This method	Comparison method	This method	Comparison method
W1-2-3-4E	77.1	79.9	2.9	3.8
W 1-2-5N	50.9	52.2	1.4	2.0
W 1-2-6S	54.5	51.9	4.4	3.3
E4-3-2-5N	79.2	73.0	3.7	2.4
E4-3-2-6S	75.3	70.1	3.0	1.8
N5-2-1W	53.8	55.0	4.6	5.4
N5-2-3-4E	73.4	77.7	5.3	7.2
N5-2-6S	56.6	54.1	6.0	5.4
W6-2-1N	49.5	53.5	3.8	5.1
W6-2-3-4E	73.8	72.1	6.8	6.9

the residence time of EV at all intersections as indexes, simulation for each of the paths is executed 20 runs and the simulation results are shown in Table 2. The comparison results of average number of social vehicles passing through each intersection under different routes are shown in Table 3. The obtained results of the average number of social vehicles passing through at all intersections by the presented method are also compared with that obtained by the comparison method and are shown in Figure 7.

We can see from Table 2 that there is little difference between the two indexes obtained by the method presented in this paper and the comparison method. Sometimes the results of the given method are better, and the results of the comparison method are better in the other cases; namely, better result of each index appears irregularly. While it can be concluded from Table 3 that, for all the paths, the number of social vehicles passing through each intersection obtained by the method presented in this paper is better than that obtained by the comparison method. For all the paths, the maximal improvement rate of the number of social vehicles passing through each intersection is 24.51%, 19.83%, 32.95%, 33.06%, 32.55%, and 32.95%, respectively, and for all the intersections the maximal improvement rate of that on each path is 10.07%, 11.28%, 20.94%, 18.79%, 9.77%, 32.95%, 27.19%, 16.88%, 33.06%, and 4.95%, respectively. It can be concluded from the results of Figure 7 that the average number of social vehicles passing through all the intersections obtained by this method is also better than that obtained by the comparison method. The maximal improvement rate is 29.49%, which is produced on path N5-2-1W. For path N5-2-3-4E, the average numbers of social vehicles passing through all the intersections obtained by the two methods are close to each other, and other improvement rates are between 5.03% and 27.33%. Through analysis of the simulation results, it can be concluded that the signal preemption control method can provide efficient and safe operating environment for EV and increase the number of social vehicles passing through the intersection group.

Table 3: The number of social vehicles passing through each intersection.

Paths	This method (pcu)						Comparison method (pcu)					
	1	2	3	4	5	6	1	2	3	4	5	6
W1-2-3-4E	133.4	141.2	143.0	144.8	157.1	157.5	121.2	140.4	140.6	135.6	152.6	152.6
W 1-2-5N	88.8	87.8	112.8	115.6	89.4	112.8	79.8	85.2	103.0	104.3	85.0	101.4
W 1-2-6S	98.2	93.4	116.8	115.6	116.3	88.2	81.2	83.2	98.4	98.1	98.7	80.8
E4-3-2-5N	164.4	130.8	127.8	140.4	142.4	164.4	138.4	114.6	121.6	124.6	125.2	138.4
E4-3-2-6S	179.8	147.4	146.8	142.4	179.8	159.8	163.8	134.8	142.1	135.8	163.8	145.6
N5-2-1W	119.4	129.2	159.8	159.8	123.8	159.8	106.2	97.6	120.2	120.2	93.4	120.2
N5-2-3-4E	177.2	163.0	152.0	172.4	174.0	177.6	154.6	130.2	133.2	139.8	136.8	154.6
N5-2-6S	129.6	98.6	129.6	129.6	112.2	94.9	116.0	96.4	116.0	116.5	96.0	94.3
W6-2-1N	101.6	113.6	144.6	145.7	142.9	127.0	81.6	94.8	111.6	109.5	110.7	98.2
W6-2-3-4E	165.4	144.2	146.4	147.4	165.4	135.8	160.4	137.4	142.0	145.8	160.4	129.6

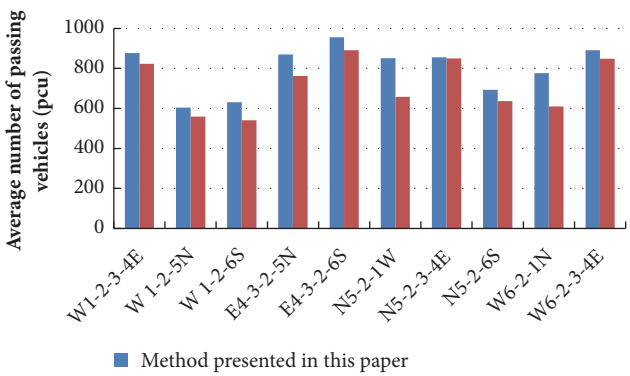


Figure 7: The average number of social vehicles passed through at all intersections.

6. Conclusions and Future Work

In this paper, signal preemption control of EVs has been studied. Taking into account the characteristics of urban traffic network and the advantages of PN in describing urban traffic network, a modeling formalism based on TCPN is adopted to represent an urban traffic network of signalized intersections. Three models, namely, traffic flow model, traffic signal display and phase switch model, and traffic signal switch control model, are put together to form the whole TCPN model. Space discretization method is adopted in the traffic flow model to describe traffic flow on road sections and reflect vehicles that come from certain places on the roadside and enter one of the two road sections. The traffic signal display and phase switch model runs in accordance with corresponding control logic, which guarantees that the traffic signal can switch orderly under normal circumstances and switch to the EV phase as soon as possible when an EV is detected and minimize the effect of EV to social vehicles at the same time. The primary task of the traffic signal switch control model is to force traffic signal to change from EV phase to its next phase after EV has passed through the intersection. An EV preemption optimization control system is also designed in this paper, and the signal preemption behavior of traffic signal display and phase switch model and traffic signal switch control model depends on the calculation and command issued by this system. To verify the control effect of the signal preemption control strategies given in this paper, some computational comparisons are performed and simulation results indicate that the signal preemption control method can provide efficient and safe operating environment for EV and increase the number of social vehicles passing through the intersection group.

Determine how the traffic signal should be converted back to the normal operation after EV signal preemption, 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.

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