Traffic Control Method Review of Signalized Intersection under Connected Vehicles Environment

Yuqing Li[a]

School of Dalian Maritime University, Dalian 116000, China

[a]lyq2020dmu@163.com

Abstract. Traffic is becoming more and more developed today, and at the same time the problem of intersection congestion is becoming more and more serious. As a key traffic scene in urban network, signalized intersection is much more important and complex than other parts. Vehicles in the connected vehicles environment can carry out data interaction with multiple platforms such as background control center, which can effectively solve the problems of traffic congestion at intersections. Therefore, for signalized intersections in the connected vehicles environment, this paper summarizes the research results of its control methods. The paper first introduces the speed guidance method and optimized signal timing method respectively, then discusses the speed and timing collaborative optimization method combining the two above, and finally introduces a new idea of future intersection zoning control. This paper summarizes the update researches and the future research direction of intersection control in the connected vehicles environment.

Keywords: intelligent transportation; connected vehicles environment; signalized intersections; signal control; intelligent vehicle infrastructure cooperatIve systems.

1. Introduction

In recent years, with the rapid development of the economy, the number of private cars is increasing, which also leads to more and more serious traffic congestion at the intersections. With Internet of Things, intelligent transportation is playing an increasingly important role in life. It can form an information interaction channel between people, cars and roads, provide a large number of real-time and accurate data, ensure vehicle safety, make driving more intelligent, and realize efficient and energy-saving green driving, so as to solve intersection traffic congestion and other problems well. For the control problem of signalized intersections in the connected vehicles environment, we first consider the speed guidance method without changing signal timing[1-6]. By planning the running speed and trajectory of vehicles, vehicles are allowed to travel at the recommended speed of the algorithm. Some of them also consider the possibility of changing lanes on multi-lanes[5-6], so as to generate smoother traffic flow. Then the method of changing the timing of signal lights is discussed[7-10]. Next, the above two methods are combined[11-13] to jointly consider vehicle speed guidance and traffic signal control to improve congestion at urban intersections. Finally, the idea of intersection traffic flow zoning control[14-15] is discussed, which changes the traffic organization mode based on signal light control, and provides a new optimization idea for signalized intersection control and has great application prospect in the future.

2. Speed Guidance Method

Some scholars adopt the speed guidance method without changing the original signal timing. Guoyuan Wu et al. studied an ecological speed control algorithm[1], which provides recommended speed for vehicles approaching or passing the signalized intersection, so that vehicles can pass the intersection as soon as possible in a more environmentally friendly manner. In this speed control strategy, vehicles at the intersection are essentially divided into the following four scenarios:

Scenario I – Cruise

A vehicle can pass a green light without accelerating or slowing down, and it maintains its original speed.

Scenario II – Speed-up

Vehicles can only pass a green light if they accelerate within a certain safe speed range, accelerate as suggested by the algorithm, cross the junction, and then slow down to their original speed.

Scenario III – Coast-down with stop

When a vehicle enters a junction during a red light, it must slow down to stop to pass the green light. The vehicle slows down under the action of power.

Scenario IV – Coast-down without stop

When a vehicle enters an intersection at a red light, it reaches a low speed. When the vehicle reaches the intersection, the red light turns green. The vehicle passes, and then accelerates to its original speed.

After receiving the traffic data of the vehicle, the algorithm first determines the available time before the next green light arrives, and then calculates the recommended speed according to the road speed limit and surrounding traffic conditions. The algorithm can also recommend the most fuel-efficient acceleration or deceleration profile. The control logic of the algorithm is shown in Figure 1, in which variables are defined as follows.

v_{limit} : the local speed limit;

d_s : safe headway distance;

t_H : safe headway time;

v_p : the velocity of the preceding vehicle;

$v_{\max}$: the maximum speed based on car following logic and local speed limit;

v_c : the current vehicle velocity;

d_0 : the distance from the vehicle to the intersection;

t_{signal} : the possible green time window for vehicle to pass the intersection;

t_{r1} : the time till the signal changes to red;

t_{g1} : the time till the signal changes to green;

t_{r2} : the time till the signal changes to red for the second time;

v_{target} : the target velocity window for vehicle to pass the intersection in green phase;

v_l, v_h : the minimum and maximum of acceptable target velocity.

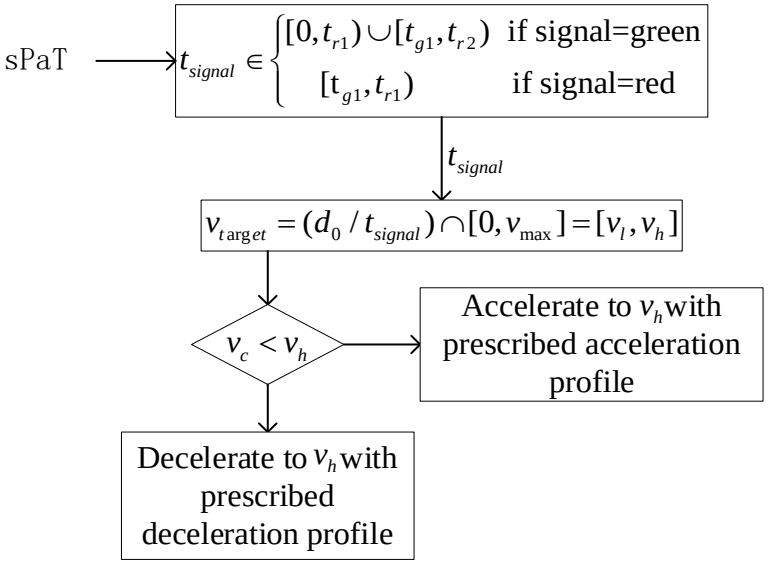


Fig. 1 Algorithm control logic diagram

Later, based on this system, Wu G et al. proposed an enhanced ecological approach and departure system[2]. Compared with the previous system, this system collected the queuing information of the intersection, considered the traffic situation in front of the target vehicle, and formatted it into the intersection delay. The calculation formula is as follows:

$$t_{delay} = nt_{slot} \tag{1}$$

t_{slot} is the fixed time occupied by each vehicle when passing through the intersection, with a reasonable approximation of 2 seconds; n is the total number of approaching vehicles within the communication range.

To evaluate the energy and emissions of this method, the MOVES(Vehicle Emission Simulator) model[3] developed by the United States Environmental Protection Agency (USEPA) is used. The index of fuel consumption and emissions is calculated as VSP, and the formula is as follows:

$$VSP = \left(\frac{A}{M}\right) \times v + \left(\frac{B}{M}\right) v^2 + \left(\frac{C}{M}\right) v^3 + (a + g \times \sin\theta) \times v \tag{2}$$

v is vehicle speed (m/s); a is vehicle acceleration(m/s^2); g is the gravitational acceleration(m/s^2); M is vehicle mass (kg); θ is road grade (degree); and A, B, and C are road load coefficients for rolling, rotating, and drag terms, respectively.

Experimental results show that the system can save up to 38% of fuel under high congestion (600pcu/ln/h), which has a significant effect on improving fuel economy. At the same time, the study found that as the range of communication shrank, the fuel savings plummeted. Therefore, this method is more suitable for use in areas with high traffic congestion and wide communication range.

Lu Yinrong et al. proposed a speed control strategy when the arrival of vehicles is subject to Poisson distribution and the traffic flow density is small[4], which is subdivided into acceleration strategy and deceleration strategy. Select an acceleration a that the driver feels comfortable with, and judge whether the signal light is green when the current vehicle accelerates to the speed limit $v_{\max}$ of this section and reaches the stop line at the junction. If it is green, the acceleration control model will be started; otherwise, the deceleration control model will be started. Figure 2 is a flow diagram of the control model solution.

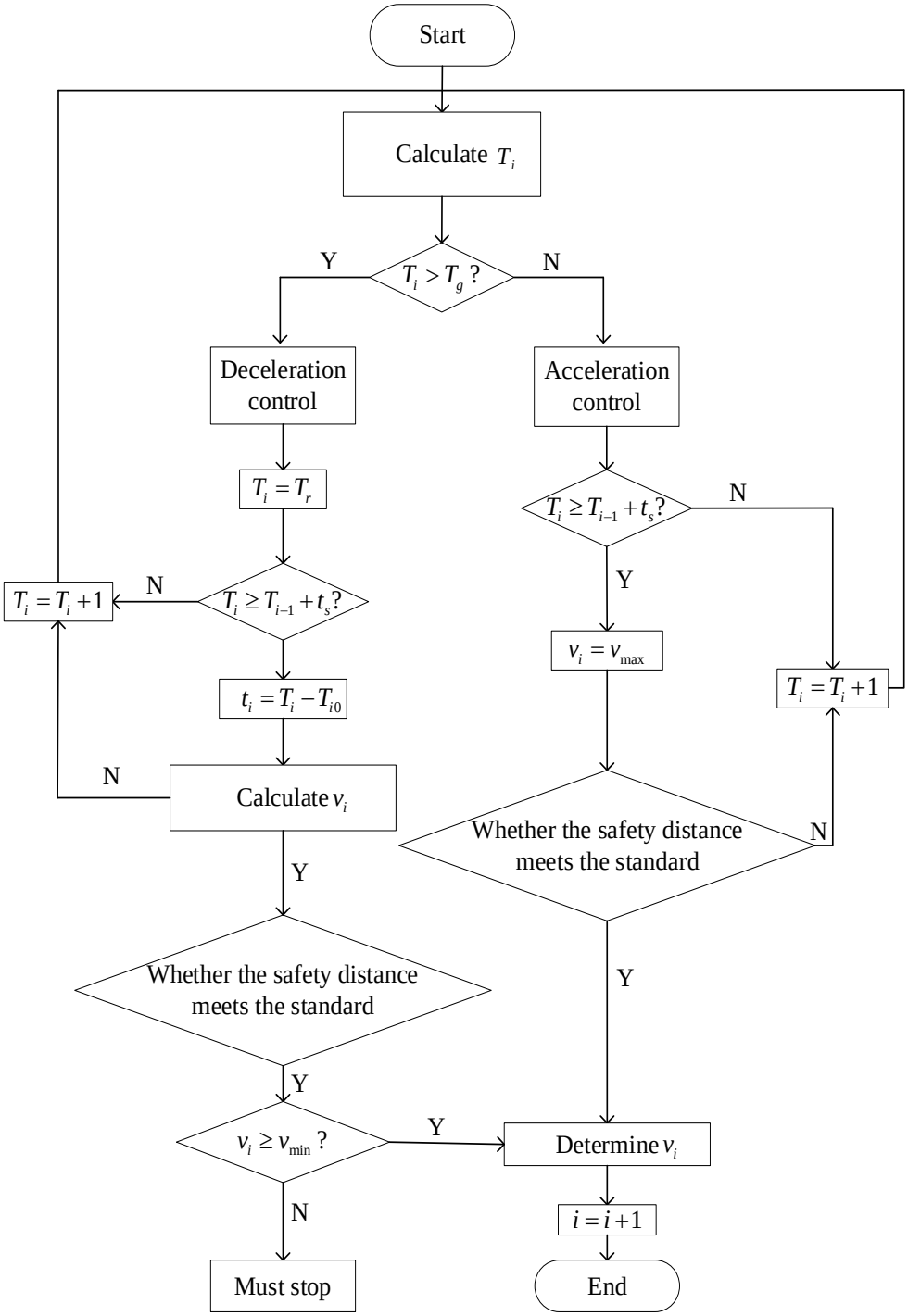


Fig. 2 Flow chart of speed control model solution

v_{max} is the maximum speed of vehicles on the road section; v_{min} is the minimum speed of vehicles on the road section; a is the absolute value of vehicle acceleration; d is the absolute value of vehicle deceleration; T_i is the moment when the first car passes the stop line (s); L adjusts the length of the region (m) for the set speed; a is the pre-set vehicle acceleration (m/s^2); v_{i0} is the speed of the vehicle entering the speed control area (m/s); T_{i-1} is the time when a car passes the stop line (s); T_g is the end of the green light (s); t_s is the minimum time headway (s); T_{i0} is the moment when the first vehicle starts to enter the speed control area (s); S is the safe distance between the front and rear

vehicles (m); Δt is the sum of reaction, mechanical delay and other loss time (s); L_{i-1} is the length (m) of the $i-1$vehicle .

According to the experimental results, the average driving time of the vehicle is reduced by more than 60%, the fuel consumption per unit time is reduced by 40.6%, and both HC and NO_x emissions are reduced by more than 70%. This indicates that the average driving time, total fuel consumption and pollutant emission of vehicles through the signalized intersection are significantly reduced after the adoption of this control model. This model can achieve a higher traffic efficiency, allowing vehicles to pass through the intersection as soon as possible. However, this model is derived on the premise that vehicles arrive and obey the Poisson distribution, so it is not suitable for use in the case of high traffic density. In individual cases, compared with the traditional driving environment, the driving time, fuel consumption and emissions of vehicles under this speed control model are higher, and the optimal speed control of individual vehicles may not necessarily be the optimal system.

The following introduces a multi-lane speed guidance control method. Hao Yang et al. developed a multi-lane green driving (MGD) algorithm using the mobile bottleneck mechanism[5]. The proposed rate limit estimation based on MGD algorithm is shown in Figure 3. D is the steady state. A straight line is drawn from point D, tangent to the basic diagram of the road with traffic jams. The tangent point is E, the intersection point Qo(ρ) is C, and the slope of the line is v_{CD} . Then, the MGD algorithm sets the recommended speed limit for connected vehicles as $v_0 = v_{CD}$.

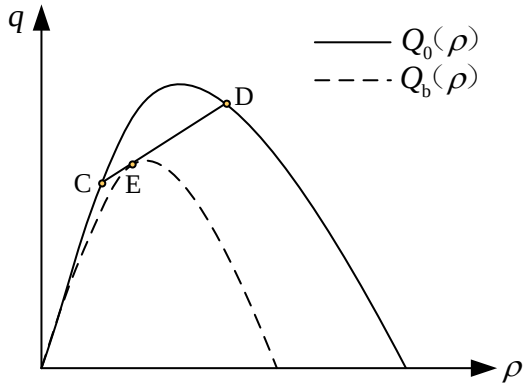


Fig. 3 Advisory speed limit estimation with the MGD algorithm

q is road flow, $Q_o(\rho)$ is not blocking road flow, $Q_b(\rho)$ is blocking road flow; ρ is road density.

The microsimulation results showed that the average travel time delay for all vehicles was reduced by 1.4%, and fuel consumption and CO2 emissions were reduced by 0.4%. MGD algorithm can effectively alleviate the vibration of all vehicles on the highway and reduce fuel consumption and vehicle emissions. In literature[6], the proposed MGD algorithm is systematically analyzed. When more lanes are blocked at the same time, MGD algorithm estimates a higher recommended speed limit, and a higher value can improve the coincidence rate of the algorithm. However, when the steady state is in extremely crowded condition (over 220 veh/km), the MGD algorithm cannot estimate the speed limit required for smooth oscillation. The analysis reveals the limitations of the algorithm in the case of severe traffic congestion. When multiple lanes are blocked, this algorithm can have good control effect and effectively solve the congestion problem of vehicles on multiple lanes, but it is not applicable in the case of serious traffic congestion.

Speed guidance without changing the timing of the original signal can create smoother traffic flow, enhance driving comfort and reduce pollution and fuel emissions. However, due to the periodic interference of intersection signals when vehicles are running, only speed optimization is considered while traffic signal optimization is ignored to improve the capacity of the intersection, which may also lead to problems such as decreased intersection efficiency, vehicle delay, fuel consumption and

pollutant emission increase. At the same time, it is difficult to adapt to the high-density traffic flow environment.

3. Optimized Signal Timing Method

Traffic signal timing optimization is also one of the most cost-effective ways to improve congestion in urban traffic networks. A fixed time control method is introduced first. Chunhui Yu et al. proposed a fixed-time signal control scheme for isolated intersections based on a time-slot generalized periodic structure[7]. The signal scheme optimizes the number of subcycles in a cycle as well as the phase sequence, period length and green segmentation in each subcycle. The nonlinear programming model of vehicle delay minimization and intersection capacity maximization is established. The objective function of the model is as follows:

$$\min D = \frac{3600\sum_{i\in I}\sum_{n=1}^{N}(D_n^i)^2}{\mu C\sum_{p\in P}a_p} \tag{3}$$

$$\max \mu \tag{4}$$

i : Ring index in the phase scheme table; i =1,2;
n : Time-slot index in the phase scheme table;
N : Time-slot number in one cycle; n=1,2, . . . , N ;
p : Phase index; p=1,2, . . . ,8;denote P^1= {1,2,3,4}, P^2= {5,6,7,8} , and $P = P^1 \cup P^2$;
P^i : the set of the phases in the ith ring;
a_p : Average vehicle arrival rate in phase p , veh/h
C : Cycle length,s;
μ : Demand multiplier;
D_n^i : $\left(D_n^i\right)^2$ is the vehicle delay in time-slot n in the ith ring, s.

Formula 3 is transformed into an easy to solve mixed integer quadratic programming model by fixed cycle length. Then Formula 3 is solved by solving a series of mixed integer quadratic programming models and listing the feasible cycle length. By applying the bidirectional search procedure, Formula 4 is solved by solving a series of mixed integer linear programming models.

According to the numerical study, when the demand is not balanced, the capacity can be increased by up to 12%, and when the demand and phase minimum green times are reverse unbalanced, the delay can be reduced by up to 21.11%, which proves that the proposed traffic signal optimization model has significant advantages in improving the intersection capacity and reducing the average vehicle delay. Ouyang et al. also proved that even time-varying fixed-time traffic flow control can achieve near-optimal performance[8]. Therefore, this model can well deal with the problem of unbalanced demand, and does not require high detector maintenance cost, low cost, and does not require high penetration rate of intelligent networked vehicles. However, the model is relatively complex, and the assumed demand structure is simple and fixed, which also limits the generality of the conclusion and makes the application more complex.

Next, the traffic signal fuzzy control method is introduced. Wulan Naren et al. proposed a coordinated control method based on fuzzy control for phase sequence changes at two adjacent intersections[9]. Considering the discrete law of vehicles, the duration of red light T_R and the predicted queue length of red light phase $Q_R^{'}$ are taken as inputs, and the urgency of red light phase T_R is output. Fuzzy controllers all adopt triangular membership function, as shown in Figure 4.

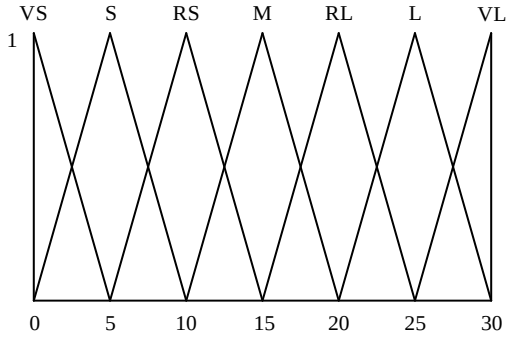


Fig. 4 Membership Function of Input of Candidate Phase Selection Controller

The algorithm selects the phase of the red light with the highest urgency as the candidate release phase according to the real-time changing traffic flow information, and obtains the phase switch value according to the maximum urgency of the red light phase and the working intensity of the green phase, and corrects the phase switch value based on the incoming and outgoing vehicles at adjacent intersections. Before the end of the current green phase time, it is decided to extend the current green time or switch the green phase to the candidate release phase according to the corrected phase switch value. The simulation results show that compared with timing control, the maximum improvement degree of fuzzy control on average vehicle delay can reach 59.78%, which can significantly reduce the average vehicle delay at intersection. The algorithm preferentially releases phases with high urgency, so as to improve the utilization rate of intersection green light faster and more efficiently. Aiming at the problem of signal timing at urban isolated intersections in the incomplete Internet of Vehicles environment, Wang Zhihui et al. proposed a fuzzy control method based on double-loop phase sequence optimization[10]. Double-ring phase sequence combination and control frame are shown in Figure 5.

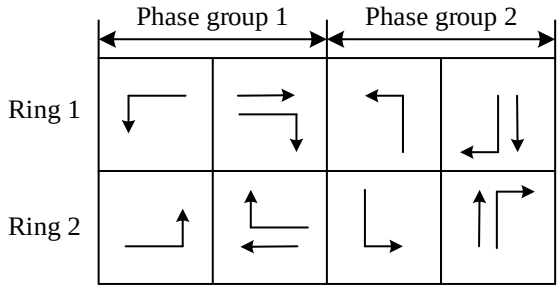


Fig. 5 Phase diagram of double ring road at intersection

According to the number of queuing vehicles in the current green stage, the algorithm comprehensively considers the green delay and the real-time traffic flow of the phase group to select the candidate green phase group. The fuzzy controller processes the input data, and then fuzzy reasoning and decision, calculating the green phase extension time. The SUMO simulation software was redesigned to realize the phase-sequence optimization fuzzy control method. Compared with timing control and fuzzy control methods, the results show that the fuzzy phase-sequence optimization control can effectively reduce the average waiting time of vehicles and improve the crossing efficiency when the penetration rate of intelligent connected vehicles is less than 90%. Fuzzy control avoids the establishment of complex and accurate mathematical model, fuzzy value control intersections, so it can better adapt to the changing traffic flow of intersections. The fuzzy system also has excellent stability, simple design and easy debugging. But this way is suitable for relatively simple traffic conditions, not suitable for non-motor vehicle more intersections.

To sum up, optimizing signal timing method can improve intersection traffic efficiency and green utilization rate on a macro level. However, only traffic signal control optimization does not consider vehicle trajectory, which is easy to cause frequent acceleration and deceleration of vehicles, reducing

fuel economy and driving comfort. At the same time, it is difficult to realize personalized control of individual vehicles with low control accuracy and limited improvement of optimization efficiency.

4. Collaborative Optimization of Speed and Timing

According to the above introduction, it can be seen that simple control of traffic lights or speed cannot fundamentally control vehicle running problems. In complex traffic scenes such as saturated intersections, speed guidance and traffic signal control co-optimization can improve traffic efficiency and reduce energy consumption and delay more than a single method.

The following introduces a two-layer optimization structure[11-12], which does not consider the division of the fleet. The upper layer optimizes the traffic control signal and the arrival time of vehicles at each intersection, and the lower layer realizes the fuel economy of each vehicle through the optimal control. On the upper floor, Biao Xu et al., aiming to reduce the total vehicle travel time, cyclically optimized traffic signal timing and vehicle arrival time[11]. It is solved by enumeration method, and then the optimal arrival time of the vehicle is sent to the corresponding vehicle.

The optimization model is as follows:

$$\begin{aligned}&\left\{t_{SBT}^{*}, t_{NBL}^{*}, t_{NBT}^{*}, t_{SBL}^{*}, t_{EBT}^{*}, t_{WBL}^{*}, t_{WBT}^{*}, t_{EBL}^{*}, \tau_{L}^{(i)*}\right\} \\ &= \arg\min \sum_{L \in F} \sum_{i=l}^{N_L} \tau_{L}^{(i)}\end{aligned} \tag{5}$$

$t_{SBT}^{*}, t_{NBL}^{*}, t_{NBT}^{*}, t_{SBL}^{*}, t_{EBT}^{*}, t_{WBL}^{*}, t_{WBT}^{*}, t_{EBL}^{*}$, and $\tau_{L}^{(i)*}$:the optimal signal timing and the vehicles' optimal travel time;

L : the movement belongs to a vehicle;

$F=\{NBL,\ NBT,\ WBL,\ WBT,\ SBL,\ SBT,\ EBL,\ EBT\}$;

NBL :northbound left;

NBT :northbound through;

WBL : westbound left; WBT : westbound through;

SBL : southbound left;

SBT : southbound through;

EBL : eastbound left;

EBT : eastbound through;

N_L : the total vehicle number of traffic movement L.

In the lower layer, constraints such as vehicle dynamics, arrival time and following safety are considered. With the goal of reducing vehicle fuel consumption, the pseudo-spectral method is adopted to solve the problem. The engine power, braking force, speed distribution and trajectory of adjacent vehicles are optimized.

$$\left\{P^{*}, F_{b}^{*}\right\} = \arg\min k_1 \int_0^{t_f} F_C(t)dt - k_2 v(t_f)^2 \tag{6}$$

k_1 : the weight coefficients of the fuel consumption ;

k_2 : the weight coefficients of the vehicle kinetic energy;

P : the vehicle engine power ;

F_b : the braking force;

F_C : the fuel consumption rate;

t_f : the fixed terminal time.

Numerical experiments were carried out in the simulation, and the proposed method was tested, and the performance of the proposed method was compared with two benchmark algorithms with different flow requirements, cycle length and communication range. The vehicle travel time of the three methods in the whole trip was 49.7s, 59.2s and 79.5s, respectively. The collaborative method significantly reduced the travel time. It also uses less fuel. Using the same idea, Yunfei Hou et al put forward the upper level MEETS control strategy to find the optimal signal timing by clearly considering the arrival time and energy distribution of each vehicle[12]. The lower layer is designed with ECC algorithms to ensure that vehicles follow the specified schedule and pass the intersection with minimal energy consumption. The results show that the approach has the potential to reduce energy consumption by up to 31% and significantly improve traffic flow at signalized intersections by reducing queue length by up to 95%, increasing traffic efficiency and fuel economy. However, all of the above studies are based on fully autonomous vehicle environments, and in mixed traffic environments, vehicles cannot form stable fleets, thus affecting the model. At the same time, the intersection scene is limited and does not consider the coordination between multiple intersections, so its applicability is limited.

Long Kejun et al. proposed an integrated model of coordinated signal control and active vehicle speed control for urban trunk lines[13]. Aiming at the maximum green wave bandwidth, minimum vehicle delay and minimum number of stops, they achieved the optimal vehicle control speed and phase difference through collaborative optimization. The objective function is as follows:

$$\begin{cases} \max B = b_i + b_i^{'} \\ \min N = \sum_{i=1} \sum_{j=1} s(i, j) \\ \min D = \sum_{i=1} \sum_{j=1} d(i, j) \end{cases} \tag{7}$$

i: intersection number;
j: vehicle number;
B: sum of bidirectional green wave bandwidths of trunk;
N: total number of stops;
D: total vehicle delay;
b_i: upstream green wave bandwidth at the intersection i;
$b_i^{'}$: downstream green wave bandwidth at intersection i;
$s(i, j)$: number of stops per vehicle;
$d(i, j)$: delay per vehicle;

Considering the multi-dimension of the model decision variables and the real-time requirement of the optimization model, a multi-objective search algorithm based on particle swarm optimization and a rolling time window optimization method was proposed. In the simulation period, compared with the model and the conventional coordinated control scheme, the upstream and downstream green wave bandwidths of the proposed model increase by 14.3% and 6.2%, respectively, and the bidirectional green wave bandwidths increase by 9.5%. The average number of stops decreased by more than 30%. This model improved the current method of signal timing passive adaptation to vehicle arrival changes, traffic control passive to active, can simultaneously optimize vehicle speed and phase difference, increase green wave bandwidth, reduce the number of stops, significantly improve the efficiency of traffic trunk coordination control. However, this method is not suitable for mixed traffic environment and lacks algorithm research on different market shares of iot. Whether multiple objective functions affect each other also needs to be studied.

The collaborative optimization of vehicle speed and timing can effectively adjust the timing of traffic signals according to real-time traffic conditions, and generate the optimal vehicle trajectory and speed distribution, which can improve transportation efficiency and vehicle fuel economy. However, the application scenario is limited, the research on the mixed driving stage of natural vehicles and connected vehicles is insufficient, and the optimization model is complex and the optimization variables are many.

5. Zoning Control

The above studies have not changed the traffic organization mode based on traffic light control and have not considered enough traffic flow in the connected vehicles environment. Lin Peiqun proposed the idea of zoning control of traffic flow at intersections, established a mathematical model of system optimization[14], and finely organized vehicle movement process. The intersection is divided into variable speed zone and uniform speed control zone. Zoning diagram 6 is as follows.

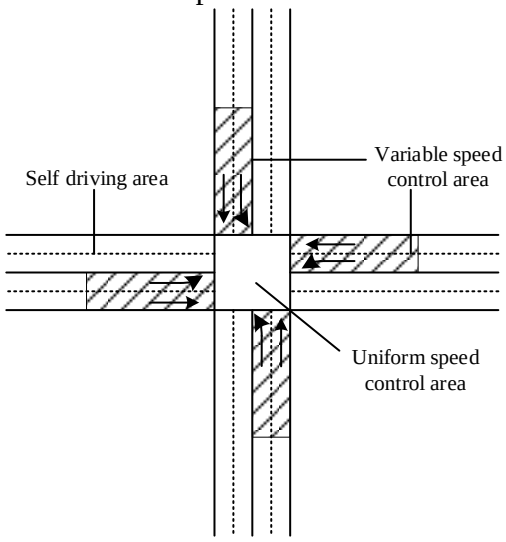


Fig. 6 Zoning Control

The objective function of system optimization established by the model is as follows:

$$\min Y = \sum_{k=1}^{n} \left\{ t_1[V(k)] - t_o[V(k)] + \frac{L_G[V(k)]}{v_1[V(k)]} \right\} \tag{8}$$

$t_1[V(K)]$ is the time when the vehicle $V(K)$ enters the uniform speed control area; $t_o[V(K)]$ is the time when the vehicle $V(K)$ enters the transmission control area; $L_G[V(K)]$ is the length of the road segment that the vehicle $V(K)$ needs to drive through the internal area of the intersection; $v_1[V(K)]$ is the speed at which the vehicle $V(K)$ enters the uniform speed control area.

In order to solve the model, a method to obtain the spatio-temporal trajectory of vehicles in the uniform speed control area and a method to solve the dynamic parameters of vehicles in the variable speed control area were proposed, so that the vehicles could pass through the intersection without conflict and achieve the purpose of motion control. The procedure for solving the algorithm is shown in Figure 7. $S_1(v_1, t_1)$ is the time and speed of entering the intersection uniform speed control area.

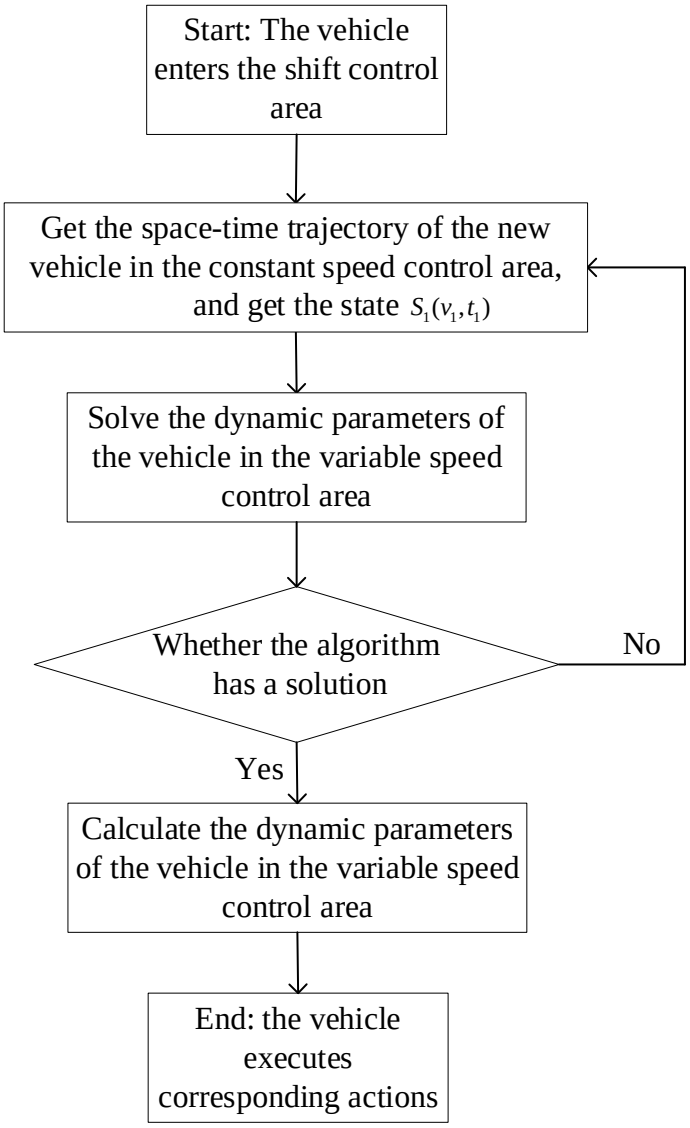


Fig. 7 Solution algorithm steps

Typical intersections in Guangzhou are selected for simulation analysis. The results show that most vehicles do not need to stop at intersections in the connected vehicles environment, but in the environment of signal control, the number of vehicles stopping at intersections increases significantly. When the input flow in each direction reaches 1100 $\mathrm{pcu}\cdot\mathrm{h}^{-1}$ or above, the intersection under signal control will be in a saturated state. However, this traffic condition can still be applied under the Internet of Vehicles control technology, which shows that the technology has a great role in improving the capacity of the intersection. But the method uses enumeration, traversal and other methods to solve the control parameters, the solution process is quite complicated.

In literature[15], Luo Xia et al. proposed an improved control method based on the idea of zoning control. Firstly, the vehicles entering the intersection are grouped and arranged according to the principle of no conflict. The spanning tree method is used to traversal to solve the problem through vehicle sequence combination and safe passage combination. The artificial bee colony algorithm is introduced to solve the control parameters of the variable speed zone, which simplifies the calculation and improves the calculation efficiency. At the same time, the rolling algorithm is used to optimize the model, so that the results do not fall into the local optimal solution. Compared with non-rolling optimized vehicles, the average time required by rolling optimized vehicles to pass the intersection is shorter, and the control efficiency is higher.

The zoning control method provides a new idea for the control of intersections in the connected vehicles environment. It is more reasonable to consider the traffic flow in the new environment of the

Internet of vehicles. However, it needs further research and optimization in the aspects of redundant control, emergency handling, communication devices, etc., so as to adapt to more complex traffic flow.

6. Summary

The Internet of Vehicles technology connects the intersection signal light with the intelligent networked vehicle, greatly improving the perception and control ability of the vehicle and the road. It can realize the optimization of the traffic signal and vehicle movement trajectory at the signalized intersection in the connected vehicles environment, so as to improve the road capacity and solve the problem of traffic congestion at the intersection at the present stage. This paper focuses on the control algorithm of signalized intersection, including speed guidance, signal timing optimization and zoning control, which can improve traffic congestion at the intersection and improve fuel economy. However, there is still a long way to go to realize all vehicle networking on the road network, and there are many unsignaled intersections on the road, more non-motor vehicles and the road network is more complex, and there will inevitably be a transition stage of some vehicle networking environment. Therefore, the control method of unsignalized intersection and partial vehicle networking environment will also be an important topic of future research.

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