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Bus priority intersection signal timing optimization model under vehicle-road collaborative environment

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Abstract With the priority of public transport being comprehensively upgraded to a national strategy, prioritizing the development of public transport has gradually become a consensus to reduce congestion and improve operational efficiency. However, the main research on bus signal priority is still relatively fixed, and the active priority control of detector detection demand is set at the intersection. Therefore, it is important to apply the cooperative vehicle infrastructure system to bus priority.

Keywords Cooperative Vehicle Infrastructure System (CVIS), bus priority; signal timing; intersection

Introduction

In recent years, with the rapid development of China's social economy and the gradual acceleration of urbanization, the Ministry of Public Security of the People's Republic of China pointed out that by the end of 2019, the country had 348 million motor vehicles. Compared with the higher growth rate of vehicle ownership, the construction and optimization of road facilities are obviously lagging behind. The improvement of urban mobility does not improve people's travel efficiency. On the contrary, a series of traffic problems, such as urban traffic congestion and substantial increase in traffic energy consumption, have become increasingly serious due to the increasing use of unit road resources, which to some extent limits the development of cities.

Reforming the existing road layout planning or building some new road infrastructure can only alleviate the pressure of urban traffic travel to a certain extent, and can not really solve the traffic problems caused by the growth of traffic demand. Therefore, priority development of public transport has gradually become the consensus of major cities to alleviate traffic congestion and improve traffic efficiency. Compared with civil vehicles, the advantages of public transportation are obvious: large capacity, energy conservation and environmental protection, small per capita occupancy of road resources, and high operation efficiency. Public transportation is an environmentally friendly and efficient transportation mode.

Michael Eichler *et al* [1] reduced the travel time of the bus by means of the departure frequency of the bus, the saturation of the traffic road network and the establishment and improvement of the bus lanes. At the same time, they analyzed the factors affecting the intermittent special roads and established timing model for optimizing the travel time of the bus. J Lee [2], A Shalaby, etc., from the perspective of bus station, summarized and analyzed the related prediction methods of bus travel time, and studied the timing method when the bus station is closer to the road intersection. GM Mchale *et al* [3] proposed an improved proposal for the system of traffic signal control analysis with priority request based on the comparative analysis of the difference in travel time between priority control vehicles and non-priority control vehicles under the premise of setting priority or not. Dresner K M *et al* [4] proposed an alternative mechanism to coordinate the movement of automatic vehicles through intersections. Drivers and intersections in this mechanism are regarded as autonomous agents in multi-objective systems. In this multi-objective system, the intersection uses a new reservation-based approach based on a complex communication protocol. The mechanism includes the popular intersection control method, which can imitate traffic lights and stop signs. The simulation results show that the mechanism is superior to the existing intersection control method, rail traffic lights and stop signs. Alonso J *et al* [5] introduced the collaborative operation between three kinds of dual-mode vehicles equipped with sensors and actuators. The goal is to solve two priority conflict decision algorithms in intersection test, and the purpose is to enable autonomous vehicles to determine how to cross the intersection with artificial vehicles without changing or adding infrastructure. To achieve this, it is necessary to obtain the information of vehicle position, speed and steering intention, and the purpose of the experiment in this paper is to adjust the speed of manual driving vehicles so that three vehicles can pass through the intersection at the same time. Taking per capita delay as the optimization goal, Lu Qingchang [6] established a bus priority cycle model for minimizing per capita delay, and finally verified the feasibility of the scheme through strength. Based on the analysis of the relationship between bus departure time interval and signal timing cycle, Ma Wanjing *et al* [7] studied the relationship between lane-sharing control and green signal ratio, and established a bus priority optimization control model based on space-time resource combination. Guan Wei *et al* [8] considered the departure interval of bus, designed the optimal control scheme based on departure interval under different vehicle arrival rates. The experimental verification shows that the reasonable control of the threshold between the car flow and the bus frequency can effectively reduce the passenger travel delay. Liu Honghong *et al* estimated the phase shortest green light time, using this time control can give the bus priority time, realize the bus priority control; Based on a time window rolling prediction method, Zhang Cunbao *et al* [9] proposed a control flow to improve the signal control optimization of intersection, and established a signal control optimization model of road intersection under vehicle-road cooperative environment. The simulation results show that this method is better than induction control, and can effectively reduce the average delay time and stop times of intersection under different traffic flows. Based on the phenomenon of time offset distribution of traffic flow operation, Hu Xinghua *et al* [10] described the delay change of subsequent intersection caused by the change of left and right ends of individual phase green by probability expectation. Through the combination optimization method, the upper and lower layers of optimization model were established. The upper layer was the optimization of bus traffic benefit based on speed guidance, and the lower layer was the delay optimization model of bus priority control. The effectiveness of the bus priority model was verified by example analysis and the negative impact on the surrounding intersection after taking bus priority was reduced.

The above research on the control scheme of signalized intersection dominated by bus priority is relatively mature in foreign countries, which is applied to practice on the basis of good road conditions, while the domestic research has not been applied in a wide range. At the same time, among the three strategies of bus priority control, the section with relatively large bus flow is more suitable for passive control scheme. Active priority strategy is not easy to implement in multiple requests. The real-time priority control scheme can improve the overall operation benefit of the intersection under the condition of improving the bus punctuality rate, and has good applicability. The traditional intersection signal timing optimization fails to balance the communication between vehicles and roads, and the optimization effect still has room for improvement [11]. The development of vehicle-road collaborative technology provides a new idea for solving intersection control problems.

This paper studies the timing optimization of signal control intersection under bus priority, which applies the interactive communication information between bus and signal controller to the actual signal control intersection in the vehicle-road collaborative environment. The theoretical design is that all buses are equipped with satellite positioning and navigation equipment, and the real-time position and trajectory information of the vehicle can be obtained through the high-precision electronic map platform. At the same time, according to the real-time position information of the vehicle and the electronic map, the distance information of the parking line and the speed information of the vehicle at the intersection in the actual operation state can be obtained. In addition, the intersection is equipped with the control processing equipment that can accept the application of vehicle priority request, and receives the application of bus priority request in real time. According to the real-time situation of the planning of the remaining phase lanes of the intersection and the corresponding traffic volume, it can determine whether to give priority to the bus counterparts, and can control the intersection signal controller to switch the phase in real time to meet the normal traffic demand.

Basic Echnology and Theoretical Method

Vehicle Navigation and Positioning Technology

Accurate vehicle positioning system is the basis of intelligent transportation research, and the key to realize vehicle-road cooperative control is also here. The importance of satellite positioning system is self-evident. Therefore, this paper studies the intersection traffic under the vehicle-road collaborative environment, it is necessary to obtain accurate real-time location data information of vehicles through satellite positioning system. At present, there are six sets of satellite positioning systems in the world, of which four are recognized by the United Nations, namely, the United States Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the European Galileo Satellite Navigation System (GALILEO) the Chinese BeiDou Navigation Satellite System (BDS). Four satellite systems are shown in Table 1.

Table 1: Comparison of four satellite systems

Comparison category	**GPS**	**GLONASS**	**GALILEO**	**BDS**
Satellites launched	32	33	30	55
available satellite	24	30	30	35
orbital altitude	20200km	19000km	24126km	36000/21500km
positioning accuracy	5-10km	1-10km	10-15km	10km
coverage	global	global	global	global
User range	Military, civilian	Mainly military	Mainly for civil use	Military, civilian

Vehicle-road synergy theory and technology

Cooperative Vehicle Infrastructure System (CVIS) is the latest development direction of Intelligent Traffic System (ITS). CVIS refers to the realization of real-time information interaction such as V2V and V2I on the basis of Internet communication technology. Based on these informations, the safe passage of vehicles and the collaborative management of roads are realized, and the road utilization rate and vehicle operation efficiency are improved. In short, CVIS collects the current road traffic and vehicle operation information in real time, transmits these informations through the information between vehicles and vehicles, vehicles and roads, optimizes traffic control, coordinates vehicles, roads and the environment, and realizes safe and efficient traffic operation.

CVIS mainly includes roadside intelligent subsystem, intelligent vehicle subsystem and communication network subsystem. The roadside intelligent subsystem mainly monitors the traffic information of pedestrians, non-motor vehicles and other traffic participants, and monitors the current traffic flow information and road conditions in real time. The main functions of the intelligent vehicle subsystem are vehicle body positioning, self-vehicle running state information collection, and information interaction with other vehicles or roadside units. The communication network subsystem is mainly responsible for the interactive transmission of information between vehicles, vehicles, roads and roads, and the instructions of the control center are transmitted to the road test unit and vehicles. CVIS has four main features:

(1) Real-time updating of traffic participation elements information, that is, in the vehicle-road collaborative environment, traffic subjects and traffic environment information are transmitted through real-time information.

(2) In the process of information transmission through CVIS, the traffic control and decision-making center receives the information transmitted by vehicles and roads. At the same time, the feedback transmission of information is carried out after the analysis and processing of cloud computing platform. The transmission process of information is bidirectional, and the information is transmitted after accurate calculation to ensure that users can receive clear information.

(3) Under the premise of people-vehicle-road collaborative control, the user experience is not only limited to accepting road operation instructions, but also can participate in the process of information transmission, actively feedback their own information to the control platform, participate in the process of road optimization decision-making, and realize the full interaction of real-time information.

(4) Based on the premise of two-way transmission and two-way communication, compared with the traditional traffic control measures, CVIS can better take into account different traffic needs, select different solutions, and fully realize the efficiency of traffic operation.

Bus Priority Control Method

'Public transportation priority ' means to protect the rights and interests of bus operation and ensure the priority of bus traffic in the process of urban road driving. Therefore, it includes not only the conditions and policies that can be provided for bus driving in road operation, but also the convenient conditions that can be provided for bus traffic in traffic control, such as financial subsidies for public transport, improvement of bus system facilities at the technical level, traffic control to provide priority traffic rights for buses, and road construction of bus lanes.

Public transit priority can be divided into two parts: time priority and space priority. Space priority mainly includes setting bus lanes on the road or setting bus lanes at the intersection entrance. Time priority is the right to give bus priority at the signalized intersection by adjusting the phase operation state.

At present, there are two main ways of bus space priority:

Bus lane: the independent road right driving channel specially designed for bus vehicles belongs to the infrastructure allocated to urban network construction, and its biggest role is to give bus independent road right, which can effectively avoid road congestion in peak hours.

(2) Bus dedicated entrance: expand the number of lanes at the intersection, divide bus dedicated entrance or provide lanes for bus priority queue. Affected by the special traffic characteristics and signal control of the intersection, the road capacity is smaller than that of the intersection road section, so the vehicle delay and queuing at the intersection are larger than those of the road section. The setting of bus special entrance can give bus greater traffic right at the intersection, which is convenient for vehicles to quickly pass through the intersection, reduce vehicle delay and improve vehicle operation efficiency.

Bus time priority mainly refers to the priority of bus signal in time by adjusting the phase of the signal lamp at the road signalized intersection. It mainly includes passive priority, active priority and real-time priority.

At present, the most common way of bus priority is space priority, that is, to set special lanes. It is not common for intersections to achieve bus priority through signal timing adjustment. Combined with the analysis of the current research status, the bus delay at the intersection accounts for more than half of the total bus delay. Therefore, the implementation of bus signal priority at intersections is of great significance to improve the efficiency of bus operation.

Signal Timing Optimization of Intersection

The bus priority signal control system under vehicle-road collaboration is mainly composed of the following four parts : bus navigation and positioning system (obtaining vehicle position data information), wireless communication system (transmitting vehicle traffic information and control instructions at intersections), data control system (balancing intersection operation efficiency and selecting priority control scheme), and intelligent signal control system (controlling phase switching of signal lights).

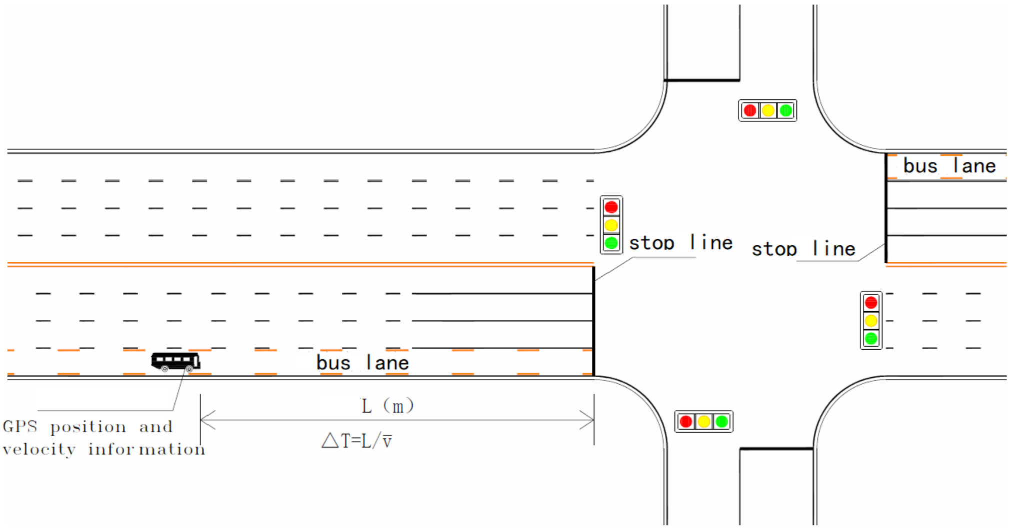

Figure 1: Intersection monitoring schematic under vehicle - road coordination

Using the bus navigation and positioning equipment, the implementation monitoring of the bus position data is realized to obtain the bus arrival information. Combined with the running state of the bus in the upstream section and the distance between the vehicle and the parking line, the arrival time of the bus is predicted. On this basis, the corresponding signal phase operation is analyzed, and the corresponding control strategy is selected to realize the bus signal priority at the intersection. The monitoring is shown in Figure 1.

Traditional signal timing does not distinguish between various types of vehicles, it is regarded as the same model. For the bus priority strategy, the characteristics of large passenger capacity of buses are not considered. Therefore, this paper takes passengers as the basic unit of road travel and the control optimization goal, and establishes the single-point control optimization model of intersections based on bus priority.

Bus passenger number estimation

As one of the important reference data for public transport planning and operation, OD of public transport line is difficult to obtain. Therefore, the number of people on and off buses that are easy to obtain is selected as a parameter for research. The pipe flow analogy assumes that the bus system is a closed pipe, and the passengers on the bus are the liquid in the closed pipe, and the whole pipe complies with the total conservation, that is, the total conservation of the whole bus system. The total number of passengers on and off the bus is equal.

In addition, in the pipe flow analogy method, we only consider that the liquid in the closed pipe flows only in one direction and in the closed pipe, the velocity of the liquid flow (including the velocity of the liquid flow in and out) has a certain degree of correlation with the flow of the pipe inlet and outlet and the residual flow in the pipe.

When this method is used to estimate the number of bus passengers, the shortest travel distance of bus passengers is set as the distance of one stop. There are $n\left(n \geq 2\right)$ bus station in the bus line, assuming B_i that the number of people on the bus stop i, A_i is the number of people off the bus stop i, T_{ij} is the number of passengers from the bus stop i to the bus stop j, the relationship between the number of people on the bus stop and the starting and ending points of the bus line is shown in Table 2.

Table 2: Relationship between the number of people on and off buses and the starting and ending points of bus routes

Site number	**1**	**2**	**3**	**⋯**		**⋯**		**Number of people on board**
1	-	T_{12}	T_{13}	⋯	T_{1i}	⋯	T_{1n}	B_1
2	-	-	T_{23}	⋯	T_{2i}	⋯	T_{2n}	B_2
	-	-	-	⋯	⋮	⋮	⋮	⋮
	-	-	-	-	$T_{i(i-1)}$	⋯	$T_{(i-1)n}$	B_{i-1}
	-	-	-	-	-	⋯	⋮	⋮
	-	-	-	-	-	-	$T_{(n-1)n}$	B_{n-1}
Number of people getting off		A_2	A_3	⋯	A_{i-1}	⋯	A_n	

Note: ' - ' means no data here.

According to tab 2, A_n the total number of passengers leaving at station n (terminal) is as follows:

$$A_n = T_{1n} + T_{2n} + T_{3n} + \cdots + T_{(n-2)n} + T_{(n-1)n} \tag{1}$$

Formula: T_{kn} the number of passengers from station *k* to station *n*.

Because the simplified closed pipe obeys the energy conservation, the *j* station has the same attraction to the people who get on the bus from any station *i*, which can be understood as the probability of the passengers who get on the bus from the *i* station and the passengers who get on the bus from the other stations at the same bus station *j*. Assuming that the attraction of getting off is Ae_n , the above expression can be expressed by Equation (2):

$$\frac{T_{1n}}{B_1-\sum_{i=1}^{n-1}T_{1i}}=\frac{T_{2n}}{B_2-\sum_{i=2}^{n-1}T_{2i}}=\frac{T_{kn}}{B_k-\sum_{i=k}^{n-1}T_{ki}}=\cdots=\frac{T_{(n-1)n}}{B_{n-1}-\sum_{i=n-1}^{n-1}T_{(n-1)i}}=Ae_n \qquad (2)$$

Formula: Ae_n Relative attraction parameter for station *n*.

Among them, the traffic volume of the OD of the bus line Ae_n is closely related to the relative attractiveness parameter, and the value Ae_n found by the analysis is $0 \le Ae_n \le 1$, which can be understood as the ratio of the number of people getting off and on the bus. That is, passengers ' corresponding attractiveness can be expressed as formula (3):

$$Ae_n=\frac{T_{1n}+T_{2n}+\cdots+T_{(n-2)n}+T_{(n-1)n}}{\sum_{i=1}^{n-1}\left(B_i-\sum_{j=1}^{n-1}T_{ij}\right)}=\frac{A_n}{\sum_{i=1}^{n-1}B_i-\sum_{j=1}^{n-1}A_i} \qquad (3)$$

According to formula (1) and formula (2):

$$T_{kn}=\frac{B_k-\sum_{j=1}^{n-1}T_{ij}}{\sum_{i=1}^{n-1}B_i-\sum_{j=1}^{n-1}A_i}\times A_n \qquad (4)$$

Formula: T_{kn} the number of passengers from station k to station n.

The traffic analogy method can be used to estimate the bus passengers at the intersection, which provides the necessary support for establishing the optimization model with the per capita delay as the control objective.

Timing optimization model

Most of the signal timing at traditional intersections is determined by reducing the total vehicle delay as the control goal. However, under the premise of bus priority, transportation is for the purpose of transferring people and things, rather than just focusing on the transfer of things. Since the passenger load of buses is generally much larger than that of cars during the operation of intersections, this paper takes the total delay of passengers as an optimization objective of signal timing at intersections, and determines the optimal timing scheme with the minimum total delay of passengers. This scheme is to achieve a priority level distinction between buses and cars by improving the weight proportion coefficient of buses at intersections to a certain extent.

Compared with the bus priority under the traditional mode, the bus priority under the vehicle road collaborative environment is accurately predicted Buses have certain advantages in the time to reach the parking line and the choice of priority strategies. Firstly, the on-board positioning and navigation system of the bus monitors the current position of the vehicle in real time through real-time data transmission with the information control and scheduling center, predicts the arrival time of the intersection in advance and adjusts the phase sequence accurately to achieve the purpose of real-time priority.

The objective function of the improved bus priority control timing optimization model is:

$$Min\sum_{t=1}^{C}\left[\sum_{a=1}^{N_A}\left(D_{q,car}*P_{car,a}\right)+\sum_{b=1}^{N_B}\left(D_{q,bus}*T_{kn,b}\right)\right] \quad (5)$$

Mode: $D_{q,car}$ for car arrival rate under the car q_{car} delay, unit: s;

$D_{q,bus}$ for bus arrival rate under the car q_{bus} delay, unit: s;

$P_{car,a}$ for the average passenger carrying capacity of the car, according to the survey observation valuation calculation, this paper values;

T_{kn} for bus passenger volume;

t is the time variable in the period;

$a$and b are intermediate variables in the calculation of per capita delay;

C is the period length, unit: s;

N_A for the total number of cars, unit: pcu;

N_B for the total number of buses, unit: pcu.

At the same time, under the premise of ensuring bus priority, the bus priority strategy will produce a certain degree of delay for non-priority vehicles, which is collectively called green time loss. Therefore, in the process of timing optimization, the loss of non-priority phase still needs to be considered. At the same time, based on the characteristics of traffic flow aggregation, in urban road intersections, the arrival rate of the phase vehicle at the end of the phase green light operation is significantly reduced. Therefore, the extension of the green light time is not conducive to the improvement of the overall traffic efficiency of the intersection at this time. Therefore, the above model still needs to meet the constraint conditions as shown in Equation (6):

$$\begin{cases} g_{i\min} \le g_{i,\mathrm{n}} \le g_{i\max} \\ C=\sum_{i=1}^{n} t_i + L \\ \dfrac{q_{car}C}{s_{car}t_i} \le 0.9 \\ \dfrac{q_{bus}C}{bs_{car}t_i} \le 0.8 \\ g_e + I_e - g_s \le C_{max} \end{cases} \quad (2.6)$$

q_{car} for car arrival rate, unit : pcu / s ;

s_{car} for the saturated flow of the car, unit: pcu / s;

q_{bus} for bus arrival rate, unit: pcu / s;

bs_{car} for the saturated flow of buses, unit: pcu / s;

g_e end time for the last phase of the green light;

I_e for two adjacent period conversion interval time;

g_s for the beginning of the periodic green light.

According to the Webster delay calculation model, the number of vehicles carried at the intersection is improved. Passenger delay D (T) is as follows:

$$D(T)=\frac{D_{bus}(T)+D_{car}(T)}{\sum_{i=1}^{n}\sum_{j=1}^{m_i}\left(P_{car}q_{car}+T_{kn}q_{bus}\right)} \tag{7}$$

Mode:

$D(T)$ for the intersection passenger average delay, unit: s;

$D_{bus}(T)$ for the bus passenger total delay, unit: s;

$D_{car}(T)$ for the total delay of car passengers, unit: s;

$i=1,2,\ldots,n$ phase number for the period;

$j=1,2,\ldots,m_i$ lane number for phase *i*.

In Equation (7), $D_{bus}(T)$ the total passenger delay time of the bus and $D_{car}(T)$ the total passenger delay time of the car are calculated as shown in Equations (8) and (9):

$$D_{bus}(T)=\sum_{i=1}^{n}\sum_{j=1}^{m_i}\left[\frac{C\left(1-\frac{t_i}{C}\right)^2}{2\left(1-\frac{t_i}{C}bs_{bus}\right)}+\frac{{bs_{bus}}^2}{2q_{bus}\left(1-bs_{bus}\right)}\right]q_{bus}T_{kn} \tag{8}$$

$$D_{car}(T)=\sum_{i=1}^{n}\sum_{j=1}^{m_i}\left[\frac{C\left(1-\frac{t_i}{C}\right)^2}{2\left(1-\frac{t_i}{C}bs_{car}\right)}+\frac{{bs_{car}}^2}{2q_{bus}\left(1-bs_{car}\right)}\right]q_{car}P_{car} \tag{9}$$

The improved bus priority control algorithm model generally belongs to the optimization model of multi-objective problems, and the calculation algorithms for such models generally include genetic algorithm and particle swarm optimization algorithm. In this paper, the optimization algorithm of particle swarm optimization is selected as the solution algorithm of the basic model to realize the possibility of bus priority control. Particle swarm optimization (PSO) is generally the process of setting a maximum number of iterations and iterative algorithm until the optimal solution of the model is obtained.

When the particle swarm optimization algorithm is applied to the solution of the bus priority control model, it is necessary to assume that the model has a total of M potential solutions, and the corresponding expression in the algorithm should be that particle swarm X contains a total of M particles, namely $X=\left\{X_1,X_2,\cdots,X_M\right\}$;

Then, according to the number of variables contained in the solution space of the objective function PI in the bus priority control model, the dimension of the position vector of the particle is determined at the same time. The velocity vector and position vector of N-dimensional particle after t iterations of particle i can be expressed as:

$$V_i(t)=\left[V_{i1}(t),V_{i2}(t),\ldots,V_{iN}(t)\right] \tag{10}$$

$$X_i(t)=\left[X_{i1}(t),X_{i2}(t),\ldots,X_{iN}(t)\right] \tag{11}$$

The solution flow chart is shown in Figure 2.

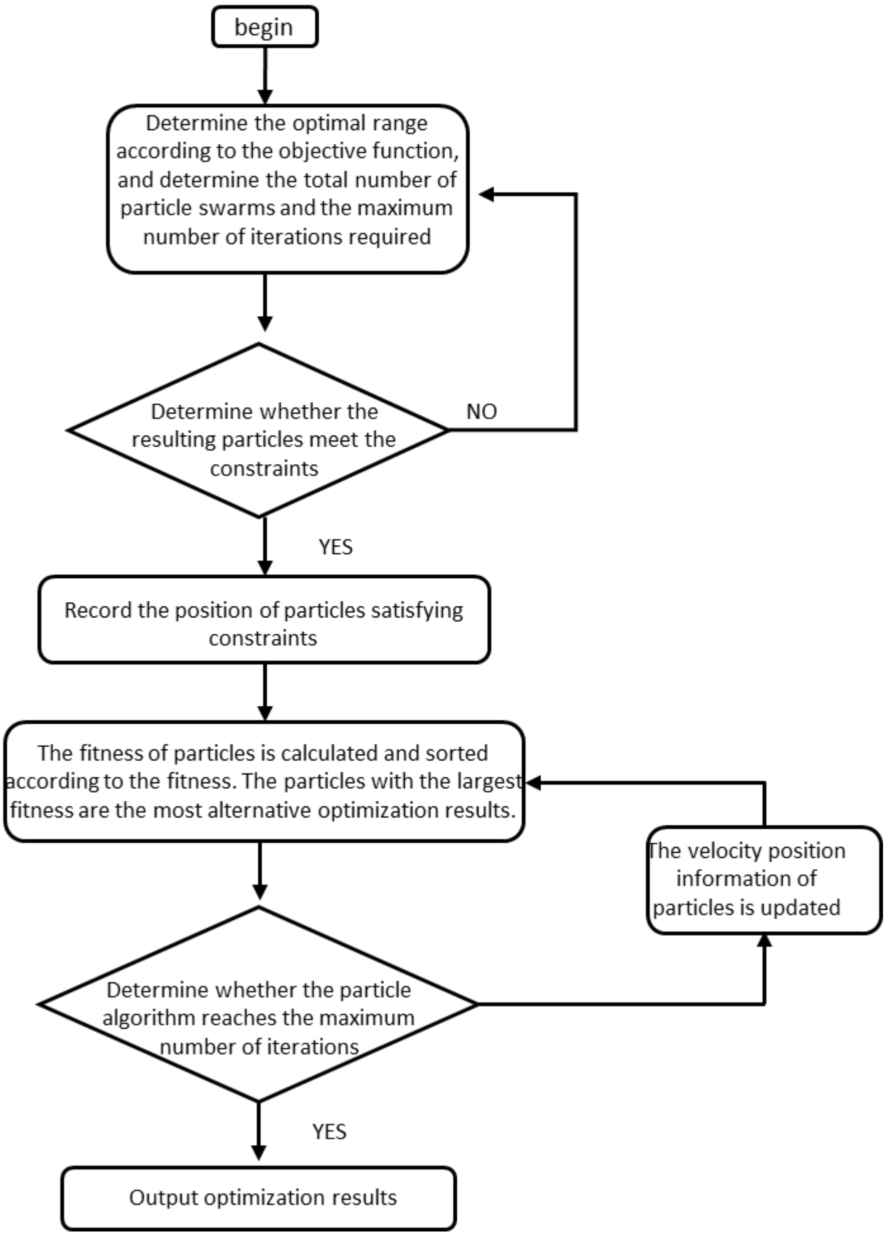

Figure 2: Particle swarm algorithm solving process

Conclusion

Based on the existing research results, this paper analyzes the applicability of bus priority control strategy and the bus priority control process at single intersection. By improving the calculation model of bus priority control parameters, on the basis of accurate prediction of vehicle arrival time, the bus priority control model under vehicle-road coordination is established to reduce bus delay and improve intersection operation benefit.

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