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Developing a Coordinated Signal Control System for Urban Ring Road Under the Vehicle-Infrastructure Connected Environment

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ABSTRACT Ring roads have been widely built in many cities, especially in the central districts with excessively heavy traffic demands and frequently generated congestion. In order to improve the operations and reduce traffic delay on urban ring roads, this paper developed a coordinated signal control system for urban ring roads under vehicle-infrastructure connected environment. The speed guidance would be provided to motorists utilizing four sub-systems including detection, communication, signal control, and expected speed calculation in the system. The signal timing parameters such as cycle length, green split, and offset, would be adjusted based on the artificial bee colony-shuffled frog leaping algorithm. The proposed signal control system had been test using VISSIM simulation model and the simulation results showed that the average delay, number of stops, and queue length were significantly improved compared with the conventional traffic control system.

INDEX TERMS Intelligent transportation system, vehicle-infrastructure connected environment, traffic signal control optimization.

I. INTRODUCTION

As one of the most important components of urban transportation system, the ring roads in the central districts, have carried increasingly heavy traffic demands. The operating performance of these ring roads has been significantly deteriorated as the result, even congestions are generated frequently in some places. On the other hand, connected vehicle-infrastructure technologies have been maturing in recent years, which are able to implement the real-time information interaction comprehensively and help traffic engineers develop better control systems [1].

Improving traffic operations along the ring roads using connected vehicle-infrastructure technologies becomes a hot research topic currently. The coordinated traffic control of ring road is installed to unite all signals to smooth traffic by providing progressions to vehicles on the ring road [2]. The benefits of coordinated traffic control could be reinforced if the control algorithms could better accommodate the time-varying traffic conditions, and the real-time traffic condition can be captured by the connected vehicle-infrastructure technologies. Therefore, this paper aims at developing a coordinated traffic control system for ring road based on the connected vehicle infrastructure technologies in order to improve the operating performance on ring roads.

II. LITERATURE REVIEW

Some of research scholars have carried out research to provide better progressions in the coordinated traffic signal control system. Park *et al.*(2001) [3] proposed a stochastic signal optimization method, which combined a GA-SOM interface with the simulation optimization model to optimize the signal control parameters. Zhao (2001) [4] introduced the relevant part of the XATM intelligent traffic signal system in detail. This system could realize the multi-phase and variable phase sequence control with the mixed traffic flow problem. Pei *et al*. (2004) [5] performed traffic survey data as the main basis aiming at designing signal coordination control system for urban trunk road. Ceylan and Bell (2004) [6] proposed a road traffic signal timing optimization scheme based on a genetic algorithm. Shenoda and Machemehl (2006) [7] proposed a minimal delay adaptive traffic signal control technology based on heuristic search. Warberg *et al*. [8] analyzed several current wire control systems and elaborated them on the method of DOGS trunk signal control parameters optimization. Based on the urban traffic signal system's research, Xu (2011) [9] put forward the idea for solving the problem of urban traffic congestion by constructing continuous flow for green-wave traffic situation. The author elaborated on the system objectives, functional modules and system advantages for continuous flow in urban green wave traffic control system. Successful cases showed that this system played an important role in the construction of urban continuous flow and solved the problem of urban traffic congestion. Based on the study of the dynamic traffic of urban roads, Sha (2013) [10] built a dynamic wire control simulation platform based on hardware-in-the-loop simulation technology. In addition, the green wave coordination control system software of trunk road is designed and realized in reality. Singh *et al*. (2013)[11] proposed a real-time traffic signal control strategy for intersections by using genetic algorithms. Zhou and Cai (2014) [12] proposed a signal control multi-object optimization method combined comprehensive modal emissions model and genetic algorithm. Hou (2015) [13] proposed two improved models based on the traditional model at the green band mode. These models optimized the offset for the wire control system and this situation is verified by VISSIM simulation software. Shi *et al.* (2015) [14] used the microscopic simulation software VISSIM to evaluate the implementation effect for the bi-directional green wave traffic on urban trunk roads. The simulation results have shown that the best green wave speed could be found by using the VISSIM simulation system. Jovanović *et al.* (2017) [15] described a new method of optimizing traffic signal settings. The area-wide urban traffic control system developed in the paper is based on the bee colony optimization technique. Hao *et al.* (2018) [16] presented a robust optimization algorithm for signal control parameters based on Tabu search-artificial bee colony algorithm under unsaturated flow condition. However, there are still several problems existed in the current research:

(1) The ring road is ubiquitous on the urban road network. Focusing on the structural characteristics of the ring road, there are few research results on the design of the ring road green wave traffic system.

(2) Under the traditional green wave traffic control conditions, it is difficult for the driver to drive on the road at a pre-given speed. In recent years, the cooperative vehicle infrastructure system (CVIS) is gradually emerging and

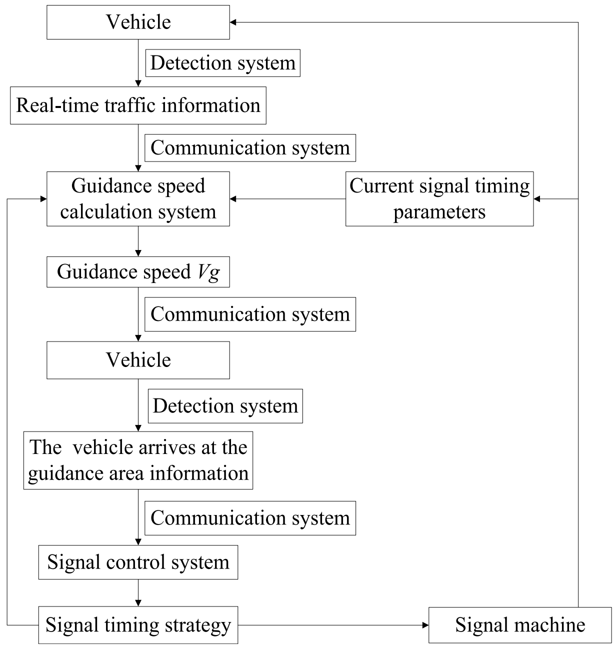

FIGURE 1. Schematic diagram of ring road coordination control system based on cooperative vehicle infrastructure.

has become a research hotspot in the field of intelligent transportation system with the development of wireless communication, automatic control and sensor detection. The information of space-time operational status and road network traffic status can be fully acquired by the cooperative vehicle infrastructure system. As a result, this system can realize the dynamic interaction between the signal control and traffic flow by speed guidance and it will provide opportunities to improve the traffic signal control models.

Based on the above analysis of previous studies, the innovation of our paper will be considered from the following two parts, one is to construct the coordinated signal control system for urban ring road, and the other is to set up the optimization model to solve the algorithm for coordinated signal control system. This paper is organized as follows. Section III presents the components of coordinated signal control system for urban ring road under the vehicle-infrastructure connected environment situation. Section IV proposes the coordinated signal control model, algorithm and process for urban ring road. Section V discusses the case study and section VI presents the conclusion.

III. THE COMPONENTS OF COORDINATED SIGNAL CONTROL SYSTEM FOR URBAN RING ROAD UNDER THE VEHICLE-INFRASTRUCTURE CONNECTED ENVIRONMENT

A. COOPERATIVE VEHICLE INFRASTRUCTURE SYSTEM

The green wave traffic control system under the cooperative vehicle infrastructure environment includes five systems: detection system, communication system, signal control system, intelligent vehicle system, and guidance speed calculation system. The cooperation working principle is shown in Fig 1. The key parts of this research are the calculation of guidance speed and the adjustment of signal timing. This paper calculates the guidance speed according to the calculation of the detected vehicle arrival time, the initial speed and other parameters. The speed combined with the signal control system obtains the cycle time, green split and offset for the ring road coordination control system. The green wave traffic control of ring road is realized under the cooperative vehicle infrastructure environment.

B. METHOD OF OBTAINING PARAMETERS

Due to the limitation of data collection and information exchange under the traditional traffic control environment, most of the previous models considered the coordinated route, initial queue length and section design speed as the fixed parameters for the traffic coordination design. In conclusion, previous optimization methods mainly have the following flaws:

(1) Because the traffic arrival is stochastic, and the traffic flow is fluctuant, the coordinated control method of the fixed inputs cannot dynamically adapt to the dynamic change of traffic flow;

(2) The initial queue length has great influence on the effect of traffic coordination control. In addition, the random fluctuations will reduce the implementation effect of traffic coordination;

(3) The influence produced by actual green wave bandwidth and coordination is directly affected by the real-time driving speed.

However, the vehicle can transmit the information to the signal control system in real time under the cooperative vehicle infrastructure environment. After receiving data processing information, the signal control scheme and the proposed speed were sent to the intelligent signal machine in real time. This achieved the target to exchange and share the information in order to provide communications information to overcome previous deficiencies. Abu-Lebden and Benekohal(2000) [17] explored the benefits of green wave coordination at intersections with variable speeds. Nevertheless, its research was limited to the optimization of unidirectional green wave only with known coordinated paths, and the systematic optimization model has not been proposed, this paper is going to build the model with the coordination path, dynamic signal timing and vehicle speed as the parameters to minimize the total delay and number of stops under the cooperative vehicle infrastructure environment. This model will overcome the shortcomings of the traditional model as well as improving the signal coordination benefits at intersections.

Through the advanced technology of cooperative vehicle-infrastructure, the coordination control parameters such as cycle, green split, phase difference, vehicle arrival time, current phase and remaining time, real-time operating speed and other parameters are dynamically and accurately obtained

In signal control of intersections, the information data obtained by traditional methods are generally characterized by its fragmentation and information lag. The limited means of information collection leads to fewer practical sources of collected information. Since the information interaction mechanism hasn't been established, some information cannot be achieved according to the real-time transmission interaction between road and vehicle. Compared with the traditional means, the cooperative vehicle infrastructure system expands not only the scope of information collection, but also improves the speed and the accuracy of it. The information acquisition method for the signal control system is compared and shown in table 1.

TABLE 1. Traffic signal control system access to information under different conditions.

Parameter requirements	Traditional acquisition methods	Acquisition methods under cooperative vehicle infrastructure environment
Vehicle arrival time	The detection position of the fixed coil is obtained by calculating the static velocity of the statistical road. Only one calculation result can be obtained, and the cumulative error is large.	The vehicle GPS sends location information in real time, and the real-time speed of the section is calculated and extracted by using the taxi GPS floating car. The guidance speed is put forward based on the model, and the vehicle arrival time can be corrected in real time.
Signal timing scheme	Static computing acquisition.	Real-time acquisition through terminal communication.
Current phase and remaining time	Combined with the opening time of the calculation, there may be time migration.	Real-time acquisition through terminal communication.
Operation of other vehicles in the section	Video acquisition, but cannot accurately obtain information about model composition, number of vehicles and so on.	Terminal perception model, number of vehicles and real-time acquisition through communication.
Cycle length	Calculated and determined by signal timing scheme and formula obtained by static acquisition.	Real-time acquisition through terminal communication.
Green split	Determined by signal timing and formula calculation.	Real-time acquisition through terminal communication.
Real time running speed	Determined by the limited design speed of the road grade.	The vehicle GPS sends location information in real time, and the real-time speed of the section is calculated and extracted by using the taxi GPS floating car.
Phase difference	Determined by the signal timing and formula calculation.	Real-time acquisition through terminal communication.

IV. COORDINATED SIGNAL CONTROL MODEL, ALGORITHM AND PROCESS FOR URBAN RING ROAD

A. MOVEMENT OF VEHICLES AT INTERSECTIONS

The vehicle arrivals at uncoordinated intersections usually can be treated to be random and fluctuated over time. For those vehicles arriving at the intersection during the green light, some vehicles can pass smoothly without any stop or slowing down, but some other vehicles may be forced to reduce speed. Specifically, the upstream vehicles may encounter the following situations when they arrive in the downstream intersection (assumed there is no over-saturated situation):

(1) When the vehicles in the queuing line are completely dissipated and the traffic light keeps showing green, the vehicles will pass through the intersection at the current speed without any obstruction;

(2) Vehicles arrive when the green light is on but the initial queue has not been completely cleared. As a consequence, these vehicles may slow down and then speed up to go through the intersection;

(3) Vehicles arrive at the intersection with the red light on and these vehicles will stop and become the initial queue for the next cycle.

B. COORDINATED TRAFFIC CONTROL OPTIMIZATION MODEL AND ALGORITHM FOR RING ROAD

1) ASSUMPTIONS OF THE MODEL

(1) The related technologies have been mature and their penetrations are high enough for the implementation of the proposed control system in this paper. For instance, all the vehicles should be equipped with the devices which can achieve functions of vehicle positioning, real-time communication, and notification to the drivers. Roadside detection and communication system have been deployed in a density area which can collect the necessary data for future research.

(2) All the vehicles are assumed to safely and quickly pass through the corresponding signalized intersections if they obey the speed guidance. According to the multi-vehicle coordinated speed guidance model, the guidance speed is calculated for each isolated intersection in the system.

(3) This research is limited to only count the motor vehicles and the impacts of bicycle and pedestrian are not taken into consideration.

(4) All the vehicles and the platoons are assumed to not pass the vehicle or take lane-change under the connected vehicle-infrastructure environment.

2) THE MODEL FOR SPEED GUIDANCE

Under the vehicle-infrastructure connected Environment, the detection system can collect the key information such as real-time vehicle positions, vehicle speeds, vehicle types, the queue length on each approach, and traffic volume [18], [19]. The controller information such as the current status of timing plan can be accessed in real-time [20], [21]. The data group for vehicle speed, the queue length, and the current status of timing plan at intersections can be directly introduced into the model. In the proposed coordinated signal control system, the author expected to provide speed guidance to motorists which can correct their speeds and reduce their travel delay at the intersections. There are interactions designed between the speed guidance and signal timing plan at intersections with the current timing status affecting the speed guidance and vehicle speed guidance. Therefore, it is necessary to consider how to find a balance point for these two variables in order to achieve optimal operations for both the platoon on ring roads and isolated intersections.

The system broadcasts the guidance speed to the vehicles with driving on the ring road and the speed guidance for the vehicles would be given regarding the existing timing plans. After the steady platoons formed, some parameters of signal timing plan can be adjusted according to speed guidance.

(1) Build the guidance speed model

To achieve the objective to pass the intersection smoothly without any stops, the author analyzed the vehicle travel process with two stages. The first stage is mainly about a transition from the initial speed to the guidance speed, and the second stage is to let the vehicle pass the intersection following the guidance speed. It is developed as the following two stages:

① Obtain the moment *Ti* of vehicle *i* passing through the stop line at intersections:

$$T_{\mathrm{i}} = T_O + \left|\frac{v_g - v_o}{a}\right| + \frac{L_k - \left|\frac{v_g^2 - v_o^2}{2a}\right|}{v_g} \quad (1)$$

where T_i is the time for vehicle *i* passing through the stop line, the unit is *second*; T_o is the initial moment, the unit is *second*; v_g is the guidance speed for vehicle *i*, the unit is m/s; v_o is the speed of vehicle *i* in the initial moment, the unit is m/s; α is the acceleration of the vehicle *i*, the unit is m/s^2; L_k is the distance of the vehicle *i* towards the stop line, the unit is *m*.

① Calculate the time period T_k of the vehicle *i* from the initial moment to the moment that vehicle *i* has passed the stop line:

$$T_k = T_i - T_o \quad (2)$$

② Calculate the guidance speed v_g for vehicle *i*:

a. If the speed of vehicles is lower or equal to the guidance speed, then the guidance speed v_g should be calculated as follow:

$$\mathrm{v_g} = v_o - aT_{\mathrm{k}} + \sqrt{a^2T_{\mathrm{k}}^2 - 2aT_k v_o + 2aL_k} \quad (3)$$

b. If the vehicles need to speed up to reach the guide speed, then the guidance speed v_g should be calculated as follow:

$$\mathrm{v_g} = v_o + aT_k + \sqrt{a^2T_k^2 + 2aT_{\mathrm{k}} v_o - 2aL_k} \quad (4)$$

where T_k is the moment that the vehicles arrive the stop line by the initial speed v_o, and other parameters are the same as the previous.

(2) Solve the proposed model

According to the guidance speed model mentioned above, there was a designed solution which can be depicted as a flow chart shown in Fig 2.

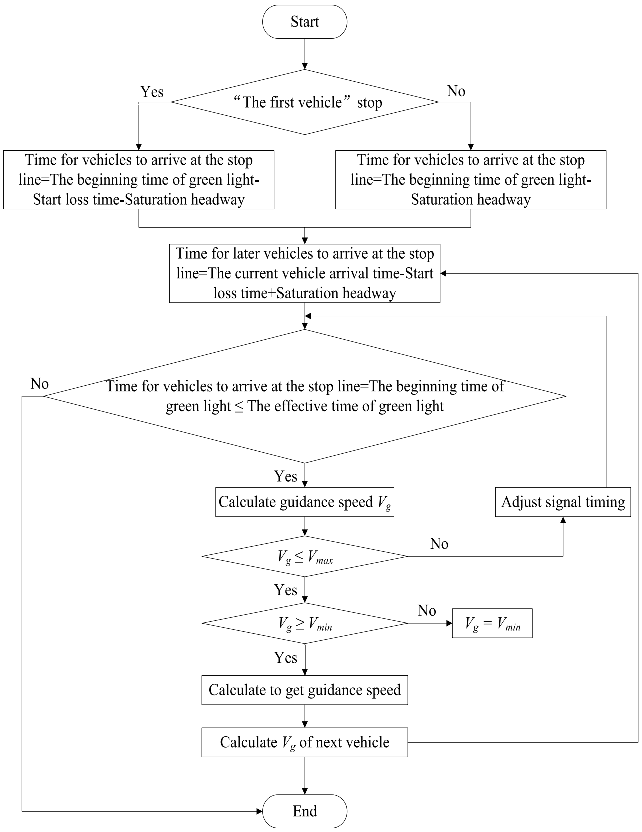

FIGURE 2. **Guidance speed solution flow chart.**

C. THE METHODOLOGY FOR SIGNAL TIMING ADJUSTMENTS

The key purpose of adjusting signal timing plans in this paper is to provide the right-of-way for motorists. A methodology with three major steps is proposed in our research.

(1) Determine the guidance distance

The guidance distance can be set as 200 meters to the nearest stop line. The system is expected to detect the spatial and temporal information of platoons within guidance distance. The speed guidance can be provided with the consideration of the signal timing adjustments.

(2) Determine the triggering condition

Signal timing adjustments are activated if there is a certain difference between the target platoon's speed and the guidance speed. In addition, the target platoon would not be able to pass through the intersection within the current green period.

(3) Calculate the green extension

The optimization model and algorithm will be established to calculate the green extension given the consideration of capacity allocation for each approach. As a result, the cycle length, the split, and the offset of the whole control system need to be updated according to the adjusted timing plan.

1) OPTIMIZATION MODEL

There are z signalized intersections considered in a ring road area condition, the objective in this paper is proposed to minimize the total delay and the number of stops under the connected vehicle-infrastructure environment. The optimization model can be expressed as follows:

$$\min f = \sum_{z} \left\{ \left[\sum_{i} n_i(T) w_i (C - T) + \sum_{j} n_j(T) w_j (T - T_{\min}) \right] \left(1 + \frac{q}{d_h}\right) \right\} \tag{5}$$

$$s.t.\ T_{\min} \le T \le T_{\max} \tag{6}$$

$$O_f^{1,i} + O_f^{2,i} = n \cdot C \tag{7}$$

$$g_i > g_{\min} \tag{8}$$

where T is the duration period of target phase. n is the number of vehicles delayed per target phase as a function of T. C is the cycle length. T_{min} is the minimum length of target phase. T_{max} is the maximum length of target phase. w is the weight for each phase. d_h is the delays caused by vehicle acceleration and deceleration. q is the traffic volume of intersection. $O_f^{1,i}$ and $O_f^{2,i}$ are the offsets of two opposing directions of section i. $g_{\min}$ is the shortest green time. g_i is the actual green time for phase i.

2) OPTIMIZATION ALGORITHM

The optimization model of coordinated signal control system for ring road is a nonlinear programming model. Therefore, the traditional simple algorithm cannot be used to effectively solve the model. An artificial bee colony-shuffled frog leaping algorithm is proposed to solve the optimization model mentioned above. Based on swarm intelligence, the shuffled frog leaping algorithm (SFL) is a sub-heuristic algorithm proposed by Eusuff and Lansey (2003) [22]. This algorithm possesses the advantages of the memetic algorithm and the particle swarm optimization algorithm. By simulating the foraging process of the frog population, this algorithm can be searched by considering the means of local search and global information exchange. SFL algorithm has attracted a great deal of attention from scholars because it is easy to practice with simple requirements of inputs.

The standard SFL algorithm is a heuristic algorithm which can simulate the information exchange features in the foraging process of frogs. It achieves the goal of population evolution by a combination of certainty and uncertainty methods.

In the D-dimensional searching space, the frog population can be expressed as

$$P = \{x_i = x_{i1}, x_{i2}, \cdots, x_{iD} \,|\, i = 1, 2, \cdots, S_N\}, \quad S_N = M \times N \tag{9}$$

where S_N is the total number of frogs in a frog group, M is the number of memetic groups, N is the number of frogs contained in each memetic group, x_i is the concrete expression of the i frog. In the SFL algorithm, frogs need to be sorted in descending order according to frog's fitness values, and assigned to$M$ memetic groups one by one, each containing N frogs.

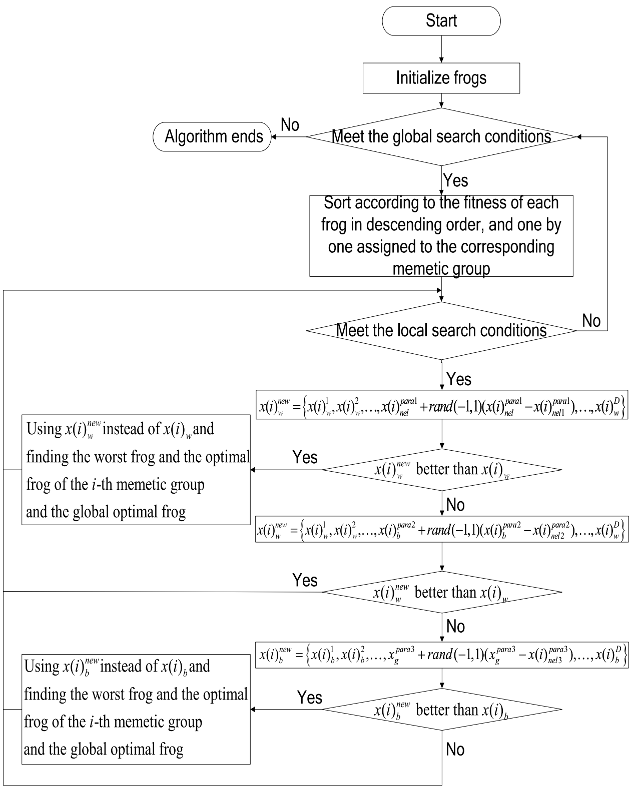

FIGURE 3. **ABC-SFL algorithm flow chart.**

In the process, the first memetic group contains, $M+1, \cdots, (N-1)M+1$ frog, the second memetic group contains 2, $M+2, \cdots, (N-1)M+2$ frog, and the M memetic group contains $M, 2M, \cdots, NM$ frog. However, in each memetic group, the local search for the entire memetic group is achieved based on the evolution of the worst frog in this memetic group, until all memetic groups complete the assigned iterations. And then all the frogs of the M memetic groups are sorted by descend ordering, and they are subdivided into M meme groups for local search one by one until the terminating condition of the algorithm is satisfied.

The frog can use the inspired information of other frogs in the memetic group at the first jump and search the optimal solution in multiple directions in order to improve the global search capability of frogs. Meanwhile, the frog's second jump should learn from the optimal frog from its memetic group in order to rapidly increase the overall quality of the frog population.

In the standard SFL algorithm, all searches are performed by the worst frog in memetic group, which lacks sufficient refinement search around the best individuals and slows the speed of convergence in later time period [23]. To avoid the drawback, the single-dimensional calculation method of the artificial bee colony (ABC) algorithm is introduced to the third jump of the frog, and the depth search ability of the algorithm is improved. This combination algorithm is called as ABC-SFL algorithm in our paper. The ABC-SFL algorithm with detailed process is shown in Fig 3.

The steps of the coordinated traffic control for ring road under the connected vehicle-infrastructure environment are designed as follows:

Step 1: According to the current traffic condition and the collected parameters, the optimal cycle for each intersection can be determined and the longest cycle should be selected as the common cycle for the whole control system;

Step 2: Based on the common cycle, the splits at each intersection can be calculated considering the traffic demand of each movement;

Step 3: The offsets for the whole control system are determined;

Step 4: The speed guidance to the vehicle and implement ABC-SFL algorithm are provided to achieve the signal timing adjustment.

The control process of the proposed traffic control system under the connected vehicle-infrastructure environment is shown in Fig 4.

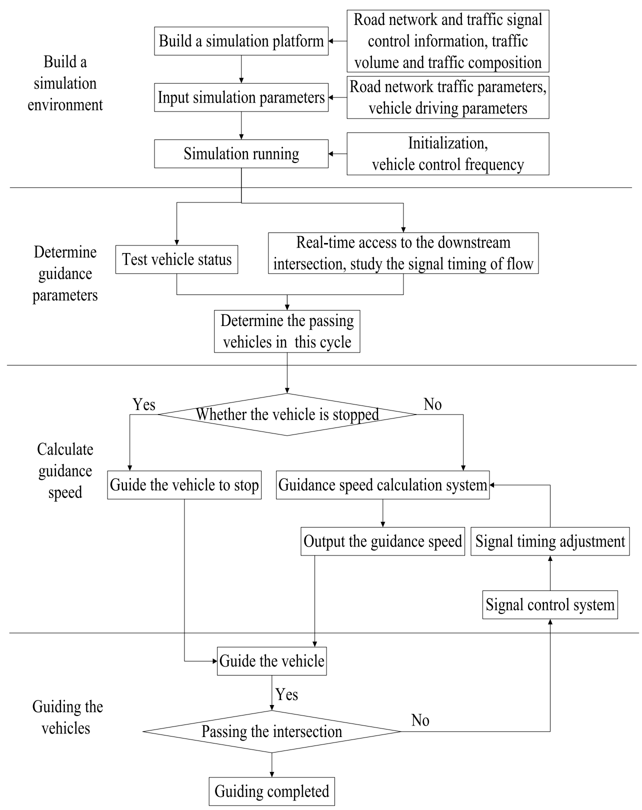

FIGURE 4. **Urban ring traffic coordination control system optimization flow chart.**

V. CASE STUDY

The road network of Zhangye City in China was selected as the case study in this paper and its scope was shown in Fig 5. The selected road network was a closed ring road consisting 11 intersections. In this paper, the VISSIM traffic simulation software is used to analyze the performance of the coordinated traffic control system under the connected vehicle-infrastructure environment.

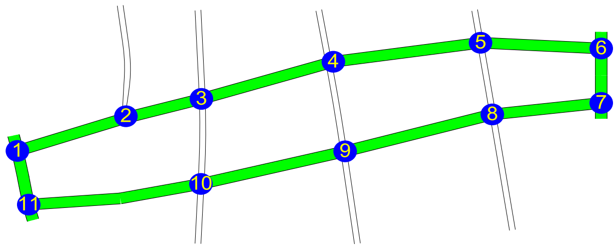

FIGURE 5. Ring road of Ganzhou District, Zhangye city.

The guidance strategy can be divided into different parts of the simulation environment set-up, the guidance object determination, the guidance speed calculation, and vehicle guidance broadcasting.

For the difference speeds, the following three guidance strategies are created:

① When $v_g < v_{min}$, the vehicles have to stop;

② When $v_{min} \le v_g \le v_0$, the vehicles can pass through the intersection without any stop;

③ When $v_0 \le v_g \le v_{max}$, the vehicles need to accelerate to pass through the intersection.

The joint simulation using Visual Basic 2010 and VISSIM 4.3 COM is developed. The parameters are set as frog group size $S_N = 100$, the number of memetic groups $M = 10$, each memetic group contains the number of frog $N = 10$, and local search times of memetic group $l = 10$.

The initial speed of all the vehicles entered the simulated road network was set as 32 *km/h*, and the guidance speed was calculated to be 38 *km/h*. Therefore the vehicles need to accelerate to pass the intersection smoothly. The simulation results of the process are shown in Fig 6 and Fig 7.

After several simulation runs, the results are shown in Table 2.

FIGURE 6. Simulation result of road section.

FIGURE 7. Simulation result of intersection.

TABLE 2. Parameters comparison of different control methods.

Control method	Average delay /s	Average number of stops	Average queue length /m
Conventional coordinated traffic control	25.62	0.62	13.21
The proposed coordinated traffic control	11.25	0.31	5.06

The proposed coordinated traffic control for ring road under the connected vehicle-infrastructure environment can significantly reduce travel delay, vehicle stops, and the queue length at the intersections as shown in Table 2. More specifically, the system average delay can be reduced from 25.62 seconds to 11.25 seconds which resulting in more than 50% improvement. These obvious improvements can also be found for average number of stops and the queue length.

VI. CONCLUSION

(1) This paper builds coordinated signal control system of ring road based on the cooperative vehicle infrastructure technology and the repeated simulation test results. Base on this analysis, it is clearly to find that our proposed system is superior to the traditional trunk coordination control system.

(2) The ABC-SFL algorithm can effectively balance the global search and depth search opportunities of the algorithm based on the frog's three-jump operation. Along with improving the search coverage of the algorithm, this algorithm can also develop some areas of excellent frogs and reduce the blindness of the frogs' learning direction. Learning from the evolutionary formulas of the ABC algorithm, the frog can learn from other excellent frogs with higher efficiency.

(3) This paper builds up a green wave traffic control system of ring road under the vehicle-infrastructure connected environment with the purpose to monitor and predict the running status of the ring road. The recommendation of the guidance speed and the dynamic adjustment of the signal timing scheme will also be achieved according to utilize this system. As a consequence, this system is expected to be popularized and applied in the ring road in order to improve the traffic efficiency.

It is also important to construct a real cooperative vehicle infrastructure control system and carry out the real vehicle test in the future studies. The performance of the ring road green wave traffic control system will be tested with cooperative vehicle infrastructure system considered in our future task.

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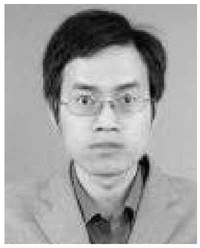

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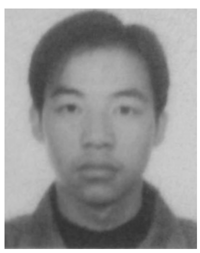

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