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교차로 교통 흐름 제어 최적화에 관한 연구

Research on optimization of traffic flow control at intersections

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요 약 현재 교차로에서의 보행자 교통흐름이나 비동력차 교통흐름의 신호제어에 대한 연구는 비교적 적다. 교통 흐름 신호 제어의 최적화 방안을 연구하여 보행자, 비동력차, 자동차 등의 전체적인 교통 흐름을 조화롭게 통제할 수 있게 하는 것은 교차로의 정체 상황을 개선하는 데 중요한 의의가 있다. 교차로의 교통 최적화를 위해 본 논문은 채널화 최적화와 위상 설계의 두 가지 측면에서 출발하며, 교차로에서의 충돌점의 수를 공간적, 시간적 할당으로부터 각각 감소시킨다. 고전적인 신호 타이밍 방법을 이론적 기반으로하고, 교통 여행객의 안전과 시간 적 이익 보장을 목표로 교차로의 채널화 최적화 및 신호 제어 방안을 제안한다. 자동차, 비자동차, 보행자를 객체로 하는 교차로의 채널화 및 위상 설계 방법에 대해 논의하고, 교차로의 채널화 최적화 개선 방안을 제안한다. 교차로 신호제어의 다목적 최적화 모델을 구축하였으며, NSGA-II 알고리즘을 기반으로 모델을 해결하였다.

Abstract At present, there are few studies on signal control of pedestrian traffic flow and non-motor traffic flow at intersections. Research on the optimization scheme of mixed traffic flow signal control can coordinate and control the overall traffic flow of pedestrians, non-motor vehicles and motor vehicles, which is of great significance to improve the congestion at intersections. For the traffic optimization of intersections, this paper starts from two aspects: channelization optimization and phase design, and reduces the number of conflict points at intersections from spatial and temporal right-of-way allocation respectively. Taking the classical signal timing method as the theoretical basis, and aiming at ensuring the safety and time benefit of traffic travelers, a channelization optimization and signal control scheme of the intersection is proposed. The channelization and phase design methods of intersections with motor vehicles, non-motor vehicles and pedestrians as objects are discussed, and measures to improve the channelization optimization of intersections are proposed. A multi-objective optimization model of intersection signal control was established, and the model was solved based on NSGA-II algorithm.

Key Words : mixed traffic flow, signal control, channelization-optimization

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Ⅰ. Introduction

As the node of the urban road network, the intersection is the bottleneck of the whole traffic system. At present, about the pedestrian traffic flow at the intersection and non-motorized traffic signal control problem of the study is less, in practice, some signal control scheme does not consider safe passage of pedestrians and non-motor vehicles, some pedestrians, non-motor vehicles and motor vehicle traffic flow management together, caused the mutual interference of an intersection traffic flow, influence the traffic operation efficiency. Therefore, it is of great significance to study the control optimization scheme of mixed traffic flow signals at intersections, to coordinate and control the traffic flow of pedestrians, non-motor vehicles and motor vehicles as a whole, and to rationally allocate the right of way at intersections.

Ⅱ. Relational Research

In many countries, traffic congestion is caused by urbanization, and some scholars have proposed the concept of signal optimization at intersections, the development of this theory has changed from simple to complex, from single-point signal optimization control to line coordination optimization control to regional comprehensive coordination optimization control[1].

At present, the main methods of single point control are Webster and HCM. Webster first studied the signal timing optimization model based on single-point signalized intersection, and took the average delay time of motor vehicles as the optimization objective of signal timing at the intersection. AKCELIK proposed an improved ARRB (Australian Road Research Board) method on the basis of the Webster method, determined a multi-objective signal timing model, and took the vehicle delay time and the minimum number of stops as the optimization objective, and introduced it into the model for the first time. The HCM (2010) research method was the first to analyze and define the shortest signal period formula, which ensures that all motor vehicles can exit the signalized intersection within the green light period[2].

The above several traffic control optimization models have been proved to be effective through practice. The primary consideration of these several timing methods is the rights and interests of motor vehicles, and less attention is paid to the rights and interests of pedestrians and non-motor vehicles.

Ⅲ. Research on Traffic Optimization of Intersections in Mixed Traffic Environment (Space Control)

From the perspective of space control, based on the existing theory, this chapter studies the channelization- optimization and phase design methods of mixed traffic at intersections with motor vehicles, non-motor vehicles and pedestrians as objects, and from the perspective of ensuring non-motor vehicles and pedestrians. From the perspective of safety, channelization design measures are proposed.

1. Traffic channelization-optimization at intersections

Traffic channelization refers to the use of special paints to mark traffic signs, road special lines, etc. on urban traffic roads, as well as the use of artificial green belts, road partition equipment and other infrastructure equipment to guide road traffic flow and fix the right of way. Allocating, isolating and controlling pedestrians, motor vehicles and non-motor vehicles of different directions and speeds, so as to achieve the purpose of directing various traffic flows, so that the traffic subjects on the road are in an orderly process during operation. The traffic flow guide organization method we call the channelized organization of traffic[3].

The purpose of optimizing the channelization of urban intersections is to ensure that pedestrians, motor vehicles, and non-motor vehicles can safely and efficiently pass through the intersection, improve the passing efficiency, and minimize waiting time.

(1) Motor vehicle channelization-optimization

In the design of the motor vehicle channelization- optimization scheme at the intersection, special consideration should be given to the motor vehicle flow of left-turn and right-turn, especially pedestrian-motor vehicle, motor vehicle-non-motor vehicle conflict will occur during the right turn process.

① Channelization of left-turn vehicle lanes

If there are more than five left-turn vehicles in the signal cycle of an urban road intersection, a left-turn motor vehicle lane can be set up. Access roads can be widened by changing the actual width of intersections.

When the width of the lane cannot meet the requirements, the left side of the forward direction of the intersection can be hardened and widened, and the left turn lane can be set up.

When there is a large left-turn traffic flow at the intersection, it is necessary to reconfigure the guide lane to make right-turn vehicles turn right ahead of time, and convert the original right-turn lane into a straight lane[4].

② Channelization of right-turn vehicle lanes

Additional right-turn lane: When the overall traffic volume is large and the right-turn traffic flow is small, a method of adding a right-turn lane can be established. Right-turning vehicles on the motor lane can directly enter the right-turning lane, reducing the impact on other motor vehicles.

Set a right turn ramp: When the traffic volume of vehicles is large or the turning speed is high, a right turn ramp can be formed by using deceleration, acceleration lanes and ramps[5].

(2) Optimization of non-motorized traffic canalization

Since non-motor vehicles start faster, the delay time after waiting for the green signal is very small. Moving the stop line of non-motor vehicle to the front of the stop line of motor vehicle can give full play to the advantage of quick start of non-motor vehicle and avoid the conflict between motor vehicle and non-motor vehicle to a certain extent[6].

(3) Pedestrian traffic channelization-optimization

In the process of passing through the intersection, due to its characteristics of flexibility, group nature, and poor compliance, pedestrian-motor vehicle conflicts and pedestrian-non-motor vehicle conflicts often occur at the intersection, and traffic accidents are prone to occur. Therefore, the pedestrian traffic flow should be rationally channelized.

① Set up crosswalks

When setting crosswalks at intersections, attention should be paid to the following: the crosswalks should be located near the intersection, perpendicular to the direction of the motor vehicle path as far as possible, and form a right Angle relationship with the urban traffic road as far as possible. When they are tilted with the road, they should be extended to the road direction to reduce the time for pedestrians to pass the road.

② Pedestrians cross the street for the second time

With the development of society, some urban roads have become wider and wider, and the time required for pedestrians to cross the road has increased. If a pedestrian waiting point is set up in the middle of a wider pedestrian crossing, the problem that pedestrians cannot pass the road during the green light period can be solved.

(4) Design process of signal channelization at intersections

The design flow chart of the signal channelization of the intersection is shown in Fig 1:

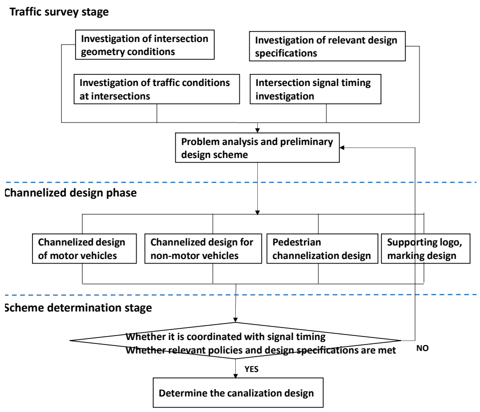

그림 1. 교차로 신호 채널화 설계 흐름도
Fig. 1. Flowchart of the design of signal channelization at intersections

2. Phase design of intersection signal

(1) Motor vehicle signal phase design

① Design of left-turn motor vehicle signal phase

Left-turn traffic is the main factor that causes delays in passing through signalized intersections and conflicts between traffic flows. Therefore, in the phase design of the intersection, adopting an appropriate method to deal with the left-turn vehicle flow becomes the top priority.

② Design of the signal phase of the straight vehicle

The phase design of the straight signal is relatively easy, but the setting of the straight phase must take into account the geometric shape and organizational form of the urban traffic intersection. At the same time, when allocating lanes, the number of straight vehicle lanes should be determined according to the straight traffic flow and the geometric characteristics of the intersection.

③ Design of signal phase of right-turn motor vehicle

This phase design is mainly aimed at intersections with large traffic flow. Since the right-turn traffic flow cannot conflict with the straight-through traffic flow in the same entrance direction, the design of the right-turn protection phase is usually not considered in the phase design. However, when the flow of non-motor vehicles at the entrance of the right-turn motorway is large, the optimal design needs to be considered.

(2) Non-motor vehicle and pedestrian signal phase design

Electric bicycles and other vehicles are very different from motor vehicles in speed, track and other characteristics. Especially in urban intersections where the signal control scheme is not perfect, the possibility of traffic conflicts is high. The following two points should be considered in phase design: analyzing the difference of traffic characteristics of non-motor vehicle flow, pedestrian flow and motor vehicle flow; Separate motor and non-motor traffic that interfere with each other.

Non-motorized traffic can be divided into left-turn, straight-turn and right-turn traffic according to the direction. At urban road signal intersections, right-turn traffic flow has little impact on traffic flow in other directions and can be almost ignored. Generally, all straight non-motor vehicles and motor vehicle flows share the right of way, so in the design of the signal phase, only the phase of the motor vehicle flow needs to be considered.

For the phase design of non-motor vehicle signals, two green light method and multi-phase release method of non-motor vehicle flow can be adopted.

Ⅳ. Research on the optimization scheme of intersection signal control in mixed traffic environment (time control)

Firstly, the advantages and disadvantages of several classical timing optimization models are compared and analyzed, and based on this as theoretical support, considering the current situation of mixed traffic flow, delay time, temporary stop rate and traffic capacity are selected as performance control indicators of the model, and a multi-objective model is constructed. Timing optimization model. At the same time, the NSGA-II algorithm in the genetic algorithm is used as the model solving method, and the basic idea and optimization process of the algorithm are summarized.

1. Classical signal timing algorithm

The current research on signal timing optimization model generally takes the classical signal timing model as the basic theory in this field.

(1) Webster algorithm

Webster, also known as TRRL (Transport and Road Research Laboratory) or F-B (F·Webster-B·Cobber), is characterized by simple structure and high accuracy. The optimization goal of this model is that the motor vehicle passes through the intersection with the least delay. In addition, green signal time and cycle length are also used as the two characteristic indicators of its optimization. The main parameters related to Webster algorithm are: optimized cycle time, green ratio and green light interval, etc.

Although Webster method is simple in calculation, this timing method also has some disadvantages: In Webster method, non-motor vehicles are incorporated into motor vehicles through conversion coefficients, and only the flow of motor vehicles is considered. When the flow of non-motor vehicle is too large, the calculated signal period is long and there is a large error. When the total flow ratio at the intersection is close to 1.0, $C_p \to \infty$ exists, which is obviously contrary to the actual situation. The study found that Webster method is suitable for intersection saturation between 0.6-0.85.

(2) ARRB algorithm

ARRB was improved by Akcelik based on Webster. In this method, the concept of "stop compensation coefficient" was proposed for the first time, and a multi-objective signal timing optimization model was established with the optimization objective of minimum total delay time and stop times. This method can realize the timing target of different signalized intersections by adjusting K value, thus enlarging the scope of application of ARRB method.

(3) HCM algorithm

The HCM algorithm takes the traffic capacity of the intersection as the optimization objective. When the signal cycle time is equal to its shortest signal cycle, it can meet the traffic requirements of the intersection, all vehicles at the intersection can be released within the signal cycle, and the shortest signal cycle is represented by C_m.

(4) Improved Webster

At present, the more commonly used signal timing method is the improved Webster method, which takes into account the conflict between motor vehicles and non-motor vehicles, and is suitable for solving timing problems in mixed traffic environments.

The calculation results of the improved Webster model are more in line with the actual needs of the intersection. However, this method is only suitable for signalized intersections with small traffic flow. If the traffic flow is large, only the conversion coefficient is used to add non-motorized traffic flow, and the saturation of the intersection and whether the road is overloaded are not considered, which will make The signal period becomes longer, and with it, the average delay of motor vehicles increases[7].

2. Intersection Signal Control Model

(1) Determine the objective function

Starting from the utilization rate of road traffic and the time benefit of travelers, optimize the effective green light time and the optimal cycle time. By coordinating the connections between traffic participants in a mixed traffic environment, the delay time of traffic participants, intersection capacity and vehicle temporary stop rate are used as signal control performance indicators to optimize timing parameters.

The models that need to be constructed are: phase green light time model, non-motor vehicle delay model, pedestrian average delay model, parking times model, and traffic capacity model.

(2) Building a multi-objective optimization model of signal control

For signalized intersections with large pedestrian and non-motor vehicle traffic, from the perspective of overall consideration of the benefits of traffic participants, the average delay time of pedestrians, the traffic capacity of the intersection, and the temporary stop rate of motor vehicles can be constructed as the optimization objective function. A multi-objective optimization model with the signal cycle duration and intersection saturation as constraints, and effective green light time and optimal cycle duration as decision variables[4].

The objective function that needs to be optimized in the model is shown in Equation 1:

$$\begin{aligned}
minM &= \frac{\sum_{i=1}^{n} M_i q_i}{\sum_{i=1}^{n} q_i} = \frac{\sum_{i=1}^{n} q_i \left(\frac{C(1-\lambda_i)^2}{2(1-y_i)} + \frac{1-\lambda_i}{2q_i} + \frac{q_i}{2s_i\lambda_i(s_i\lambda_i - q_i)}\right)}{\sum_{i=1}^{n} q_i} \\
minP &= \frac{\sum_{i=1}^{n} p_i q_i}{\sum_{i=1}^{n} q_i} = \frac{\sum_{i=1}^{n} q_i \frac{r_i C(1-\lambda_i)^2}{2(r_i - p_i)}}{\sum_{i=1}^{n} q_i} \\
minS &= \frac{\sum_{i=1}^{n} S_i q_i}{\sum_{i=1}^{n} q_i} = \frac{\sum_{i=1}^{n} \sum_j \alpha \frac{C(1-\lambda_i)^2}{1-y_{ij}}}{\sum_{i=1}^{n} q_i} \\
minQ &= \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} \sum_j S_{ij}\left(\frac{g_i}{C}\right)
\end{aligned} \tag{1}$$

Finally, transform each objective function into Equation 2:

$$\begin{aligned}
& min\, F(C,g) = min[M(C,g), S(C,g), -Q(C,g)] \\
s.t.\quad & \textstyle\sum_i g_i + L = C \quad i = 1,2,\dots\dots,n \\
& C_{min} \le C \le C_{max} \quad g_{min} \le g \le g_{max} \quad \alpha \le 0.9
\end{aligned} \tag{2}$$

In Equation 2: $M(C,g)$— the average motor vehicle delay time at the intersection (s);

$P(C,g)$—the average delay time between non-motor vehicles and pedestrians at intersections (s);

$S(C,g)$—the rate of motor-vehicle parking at intersections;

$Q(C,g)$—Traffic capacity at intersections (veh/h);

C—Intersection phase duration (s);

L—the total lost time at the intersection (s);

g_i—Green light time of the i-th phase (s);

α—Intersection Saturation, $\alpha = \max(y_i/\lambda_i)$.

① Constraint condition

The signal period is constrained. Signal cycle time should not be too short, otherwise it will not be conducive to the traffic safety of the intersection, generally take 30s. Should not be too long, otherwise it will increase the delay time of the vehicle, the general signal cycle time ≤ 180s.

The effective green time of each phase must meet the requirements of the shortest green time of pedestrians crossing the street.

Limit the saturation of intersections. In order to avoid the situation where intersection saturation is too small, that is, the traffic capacity is far greater than the traffic demand, the number of stops and vehicle delays will be unnecessarily increased, and the degree of saturation is set to be variable.

② Normalization of index coefficient

Let the sum of the coefficients of control performance indexes in the optimization goal be W, and motor vehicle delay w_i^1, pedestrian and non-motor vehicle delay w_i^2, temporary stop rate w_i^3 and traffic capacity w_i^4 respectively represent the weight coefficients of the sub-objective function, which satisfy $\sum_j^4 w_i^j = 1$.

3. The Flow and Coding of NSGA-II Genetic Algorithm

(1) NSGA-II algorithm optimization process

Since the control optimization model for the mixed traffic flow signal at the intersection is a multi-objective nonlinear integer programming model, it involves the comprehensive optimization of multiple objective functions, and the optimized objective functions all contain the decision variables in the model. The algorithm is difficult to solve the multi-objective optimization model in this paper. Therefore, this paper adopts the NSGA-II (Non-dominated Sorting Genetic Algorithm-II) to solve the model in this paper. The NSGA-II algorithm proposes a fast non-dominated sorting algorithm, which reduces the complexity of non-dominated sorting, introduces elitist strategy, and introduces crowding and crowding comparison operators.

The optimization flow chart of the NSGA-II is shown in Fig 2:

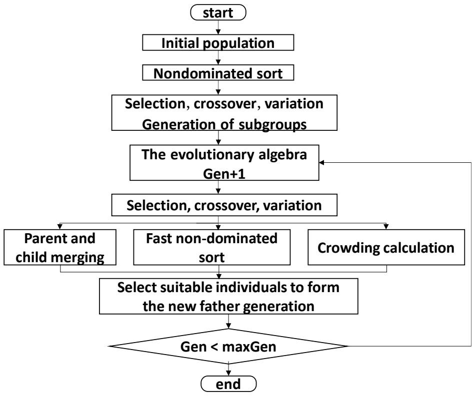

그림 2. NSGA-II의 최적화 흐름도
Fig. 2. Optimization flow chart of NSGA-II

Step1: Random generation of initial population with size N;

Step2: Rapid non-dominated ordering is performed on all individuals;

Step3: The first-generation progeny population is obtained through selection, crossover and mutation.

Step4: Merge the offspring population with the parent population, and conduct non-dominated ordering for all individuals;

Step5: Calculate the crowding degree of individuals in the non-dominated layer, and select appropriate individuals to form a new parent population based on the relationship between them and the crowding degree of individuals;

Step6: Generate new progeny population through selection, crossover and mutation;

Step7: Iterate until iteration conditions are met.

(2) Coding of NSGA-II

When the NSGA-II solves the optimization model of intersection signal control in mixed traffic environment, the following problems are mainly involved: coding of chromosomes, generation of initial solution, fast non-dominated sorting, calculation of congestion degree, congestion degree comparison operator and Elitist Strategy these few steps. In this section, the above problems involved in the NSGA-II will be described.

① Chromosome coding

Encoding is a mapping from phenotype to genotype, a mapping process in which a feasible solution to a problem is converted into a fixed length binary symbol. The 7-bit binary coding string is used to represent the green duration of i phases in a signal cycle: $g1$, $g2$ and $g3$ respectively. Then the three binary coding strings representing $g1$, $g2$ and $g3$ are connected together to form a 21-bit binary coding string, which constitutes a gene of chromosome.

② Generation of the initial population

NSGA-II starts its search strategy from a given initial solution. The initial solution is a feasible solution that satisfies all constraints. In this paper, the following method is used to generate the initial solution: randomly generate an integer g_i^n inside $[g_{\min}, g_{\max}]$, and use the value g_i^n as the first solution of the initial solution. Green light duration of n phases ;

NSGA-II should give the initial solution and then start its search strategy. The initial solution is a feasible solution satisfying all constraints. The following method can be used to generate the initial solution: randomly generate an integer g_i^n within $[g_{\min}, g_{\max}]$, the value of g_i^n is taken as the green light duration of the nth phase;

According to the above steps, the effective green time of each phase is generated, and the traffic data of signalized intersection is combined to determine whether the constraint conditions are met. If not, the next initial solution will be abandoned and judged until there are enough feasible solutions in the solution space to complete the generation of the initial population.

(3) Fast non-dominated sorting

For each individual i in the population, there are two parameters n_i and S_i, n_i is the number of individuals in the population that dominate the solution of individual i, and S_i is the set of individuals whose solution is dominated by i.

① Find all $n_i = 0$ individuals in the population and store them in the current non-dominated set $rank_1$;

② For each individual j in the current non-dominated set $rank_1$, traverse the individual set S_j it dominates, subtract 1 from the n_t each individual t in the set S_j , and if $n_t - 1 = 0$, store the individual t in another set H ;

③ Take $rank_1$ as the set of first-level non-dominated individuals, and the solution in this set is the optimal individual.

(4) Calculation of congestion degree

The calculation of crowding degree is an important factor to ensure the diversity of the population. The calculation steps are as follows:

① The crowding degree of each individual $i_d = 0$;

② For each optimization objective, perform fast non-dominated sorting of the population, and let the crowding degree of the two individuals on the boundary be $o_d = l_d = \infty$;

(5) Congestion degree comparison operator

After steps (3) and (4), each individual i in the population has: the non-dominated order determined by the non-dominated order $rank_1$ and the crowding degree i_d. According to these two attributes, crowding comparison operators i and j can be defined. As long as any of the following conditions are true, individual i wins.

① If the non-dominated layer where individual i is located is better than the non-dominated layer where j is located, then $rank_i < rank_j$.

② If two individuals in the population have the same level, that is $rank_i = rank_j$, and the crowding degree of individual i is greater than that of individual j , that is $rank_i = rank_j$, and $i_d > j_d$.

Among them, ① is used to ensure that the selected individual belongs to a relatively excellent non-inferior rank in the population; ② is to select two individuals in the same non-dominated layer according to the crowding distance of the individual.

(6) Elitist Strategy

The Elitist Strategy can not only retain the non-dominated solutions obtained so far, but some of the outstanding individuals can also be copied to the next generation of the population through the selection strategy. The specific steps are as follows:

① Perform pseudo-binary crossover and polynomial mutation on the individuals in the parent population P_t to generate offspring populations Q_t ;

② Sort the group R_t after the merger of P_t and Q_t ;

③ The new parent population R_{t+1} is filled according to the principle of the higher-level individuals in use R_t, and some of the last filled-in individuals of the same level are selected according to the principle of the larger crowding distance.

Ⅴ. Experiment and analysis

In order to verify the feasibility of the multi-objective optimal timing scheme proposed in this paper, a typical intersection peak hours and off peak hours were selected as an example to compare the multi-objective timing scheme proposed by us with Webster scheme. Due to the length of this paper, the specific process is not shown, and the relevant control performance indicators are shown in Table 1.

표 1. 서로 다른 신호 타이밍 방안의 비교
Table 1. Comparison of different signal timing schemes

Timing method	Cycle /s	Effective green time /s			Average vehicle delay /s	Non-motor vehicle, pedestrian average delay /s	Motor vehicle temporary stop rate	Intersection capacity /PCU·h-1
		Phase 1	Phase 2	Phase 3				
Webster scheme	160	61	52	33	53.42	43.45	0.2712	8632
Our Multi-objective optimization scheme	160	63	51	32	49.81	38.62	0.2353	9021

Among them, Phase1, Phase2 and Phase3 are the optimal green time solutions of the two timing schemes respectively.

Simulation results show that compared with Webster scheme, the multi-objective optimization scheme based on NASA-II algorithm reduces the average delay of vehicles by 3.61s, the average delay of non-motor vehicles and pedestrians by 4.83s, the parking rate by 3.59%, and the number of vehicles passing through the intersection by 389 vehicles per hour. The multi-objective optimization scheme based on NASA-II algorithm proposed in this paper is more excellent.

Ⅵ. Discussion

For the optimization of traffic flow control at intersections, this paper starts with channelization-optimization and phase design, and reduces the number of intersection conflict points from spatial right-of-way allocation and temporal right-of-way allocation respectively. From the perspective of traveler's safety, the canalization optimization method and phase optimization method of road traffic participants are studied and summarized, use the NSGA-II coding, intersection signal control model is established.

Ⅶ. Conclusion

Although NSGA-III has been released at present, there are few references to be found and few published source codes, resulting in very difficult coding and simulation. Therefore, NSGA-II was selected in this paper. NSGA-III and NSGA-II have similar frameworks, and the difference between them mainly lies in the change of selection mechanism. NSGA-II mainly sorted by crowding, and its effect in high-dimensional target space was not obvious, while NSGA-III made a lot of adaptation of crowding ranking, and maintained the diversity of the population by introducing widely distributed reference points. In the future, when more NSGA-III source code is released, we will improve the method proposed in this paper.

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