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Research on Signal Control at Single Point Intersections Based on Passive Bus Priority

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Abstract—**To address the problem that the passive bus priority method with the objective of "minimum passenger delay" may cause an increase in the number of non-priority phase stops, a two-stage improvement optimization model is developed, which is divided into two steps: the first step is to find the minimum intersection passenger delay, and then the delay is appropriately increased by a certain range on this basis, so as to determine the bus priority The first step is to find out the minimum delay of passengers at the intersection, and then the delay is appropriately increased by a certain range, thus determining the set of solutions for bus priority signal timing, and then selecting the solution that minimizes the number of non-priority phase stops from the set of solutions. The particle swarm algorithm is used to solve the model, and the specific ideas and steps are given. The intersection of Huanghe Road-Guangping Street in Dalian City, Liaoning Province, is selected as the study object, and the effectiveness of the improved optimization model is examined by using VISSIM. The results of the empirical simulations show that the improved optimization model can achieve bus priority and reduce the stopping rate of non-priority phases within an acceptable range of delay increase compared to the passenger delay minimum model.**

Index Terms—**urban traffic; improved optimization model; passive priority; non-priority phases; number of stops**

I. Introduction

In recent years, traffic congestion and environmental pollution have become increasingly significant as motor vehicle ownership continues to rise. To cope with these problems, governmental administrations have increasingly focused on the role of public transportation and recognized its great potential as a green form of motorized travel [1]. In the process of achieving the dual carbon goals of urban transportation systems and improving the quality of travel for residents, public transportation priority has become a key path choice. By promoting bus priority development, it can effectively reduce traffic congestion, reduce tailpipe emissions, and enhance the travel convenience and environmental comfort of urban residents. Therefore, bus priority has become one of the key strategies in today's urban planning and traffic management, providing key support for building a sustainable and livable urban environment. The main measures of bus priority are: bus lane priority, signal priority, station and route optimization [1]. Among the many priority measures, signal priority has an irreplaceable role [2].

The existing bus signal priority strategies can be divided into three types: active priority, passive priority, and real-time priority [3]. Passive priority is more widely used at single-point intersections, and many research results have been achieved by scholars at home and abroad.

(1) Simulation and evaluation of the effect of bus priority measures: the study of Alexander Skabardonis [4] and others found that the passive priority strategy can effectively improve the control effect when the bus vehicle flow is high and the operation status is stable.McHale` [5] proposed a method to predict the travel time of emergency and non-emergency vehicles under two conditions with or without priority by improved method to evaluate the travel time impact of emergency vehicle traffic signal priority systems for traffic planning analysis.Matías [6] evaluated the travel interval, load and traffic demand for transit priority strategies considering different conditions, such as BRT context.

(2) Optimization models with the objective of minimizing passenger delays or delays of traffic participants: researchers such as Yiming Bu [7] developed a model with the objective of minimizing average passenger delays by analyzing the relationship between cycle time, green letter ratio and delays. Qiao Wenxin [8] et al. proposed an optimization model with the minimum average passenger delay as the objective and the reliability of phase clearance as the constraint by taking a single-point intersection as the research object. Zheng Rui [9] established an optimization model with saturation, minimum green light duration as the constraint, and minimum total passenger delay at intersections and stops as the objective by analyzing the delay of bus vehicle stop overflow on post-vehicle and passenger delays. Ruijun Guo [10] established an optimization model with the objective of minimizing the average passenger delay at intersections by analyzing the relationship between passenger delays and vehicle delays. Yaran Zhang [11] used the smaller value of delay calculated by the green time difference model and Webster cycle model as the signal timing scheme for intersections with the objective of minimizing the average delay of passengers at intersections. Yugang Liu [12] developed a two-level planning model with the objective of optimal passenger delay and pedestrian delay variation. Zou Ruilin [13] fully considered the effect of bus priority on pedestrian crossing and combined the two to establish a signal control model with the objective of minimum per capita delay at intersections.

(3) Optimization model with the objective of minimizing traffic delays or reducing carbon emissions: Ma Wanjing [14] and other researchers established a weighted total average vehicle delay minimization model for the inlet lane by analyzing the spatial and temporal resources of the inlet lane with the saturation and minimum green light duration as

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constraints. Qiao W [15] proposed a multi-objective optimization model based on vehicle emissions and delay reduction and solved the model using genetic algorithm. Shi W [16] established a comprehensive optimization model with the objective of minimizing the weighted vehicle delay by analyzing and designing lane markings and dedicated lanes for buses and private cars at intersections.

In summary, it can be seen that foreign research on passive priority mainly focuses on the simulation and evaluation of priority measures; domestic scholars' research on passive priority mainly focuses on the study of optimization models, in which the optimization objectives include passenger delay or traffic participant delay minimization, vehicle-weighted delay minimization, and emission reduction. The existing passive priority studies have taken the intersection as a whole as the optimization objective for signal timing, and have not considered the impact of bus priority on non-priority phases, especially on their stopping times. **Related studies have shown that frequent start-stop not only increases the psychological load of drivers and affects traffic safety, but also further aggravates the pollution of the environment** [17,18]. **Based on this, this paper takes the number of stops in non-priority phases as an entry point to improve the passenger delay minimization model, with the aim of obtaining a relatively balanced transit priority scheme.**

II. INTERSECTION PASSENGER DELAY MINIMUM MODEL

The basic principle of the passenger delay minimization model is that because bus vehicles carry a larger number of passengers, the number of passengers in their phase is relatively larger when the bus traffic is relatively larger. When allocating green lights to each phase of an intersection, the phases with higher passenger counts are often given more weight and time to pass, thus achieving the effect of bus priority.

Passenger delay is closely related to vehicle delay, and is typically obtained by multiplying the number of vehicles by the average vehicle delay by the average number of passengers carried. The traditional passenger delay minimum model usually calculates bus vehicle and social vehicle delays separately, and further calculates the respective passenger delays. The general assumptions of the model are:

(1) Each cycle intersection is in unsaturated state, i.e., random delays and oversaturation delays are not considered.

(2) There are n phases at the intersection with m traffic streams, and vehicles arrive at the intersection at a constant arrival rate q_{ij} (i ∈ n, j ∈ m).

According to the Webster delay model, the average vehicle delay of the jth traffic stream at phase i in unit hour is：

$$d_{ij} = \frac{Cq_{ij}(1-\lambda_i)^2}{2(1-y_{ij})} \tag{1}$$

where:

d_{ij}—average delay of the jth traffic of phase i in unit hour, s;

C—signal cycle duration, s;

λ_i—Green signal ratio of phase i;

y_{ij}—Lane flow ratio of the jth traffic of phase i.

The passenger delay of a social vehicle per unit hour is then equal to its total delay times the number of passengers per social vehicle, which can be expressed as:

$$d_a = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{Cq_{aij}\overline{o_a}(1-\lambda_i)^2}{2(1-y_{ij})} \tag{2}$$

where:

d_a—Total delay of passengers of social vehicles at the intersection per unit hour, s;

q_{aij}—social vehicle flow of phase i jth traffic in unit hour, pcu/h;

$\overline{o_a}$—average passenger load of social vehicles, per/pcu.

Similarly, the passenger delays of bus vehicles in unit hours are:

$$d_b = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{Cq_{bij}\overline{o_b}(1-\lambda_i)^2}{2(1-y_{ij})} \tag{3}$$

where:

d_b—passenger delay of intersection bus vehicles per unit hour, s;

q_{bij}—bus vehicle flow of the jth traffic of phase i in a unit hour, bus/h;

$\overline{o_b}$—average passenger capacity of bus vehicles, per/bus.

According to equations (2) and (3), the total intersection passenger delay can be expressed as：

$$D_p = d_a + d_b \tag{4}$$

Then the intersection passenger delay minimum model is:

$$\min D_p = \sum_i^n \sum_j^m \left(q_{aij}\overline{o_a} + q_{bij}\overline{o_b}\right)\frac{C\left(1-\lambda_i\right)^2}{2\left(1-y_{ij}\right)} \tag{5}$$

$$s.t.\begin{cases} \dfrac{q_{ij}}{s_{ij}} \le \lambda_i, \forall i, j \\ \sum_{i=1}^{n}\lambda_i + \dfrac{L}{C} = 1 \\ g_{i\min} \le \lambda_i C \le g_{i\max} \end{cases} \tag{6}$$

where:

D_p—total intersection passenger delay per unit hour, s;

s_{ij}—saturation flow rate of the jth traffic stream of phase i, pcu/h;

L—Total cycle loss time, s;

$g_{i\min}$—minimum green light time for phase i, s;

$g_{i\max}$—maximum green light time for phase i, s.

III. IMPROVED OPTIMIZATION MODEL

A. Basic Ideas

The objective of the passenger delay minimization model is often to achieve transit priority by allocating more green time to the phase with greater passenger delay, i.e., the transit priority phase, to enable more transit vehicles to pass per unit of time given the constraints. Although the overall intersection passenger delay decreases, it may cause an increase in the number of vehicle stops for non-priority phases.

This paper provides a new idea: on the basis of the minimum overall delay of intersection passengers, the delay is appropriately increased by a certain range, thus determining the set of schemes for bus priority signal timing, and then selecting the scheme with the minimum number of stops for non-priority phases from the set of schemes, so as to reduce the impact of the signal control scheme of bus priority on vehicles of non-priority phases, thus obtaining a comprehensive optimization scheme that is relatively satisfactory for all phases.

Improving the model can be divided into two steps:

① Using the intersection passenger delay as the control objective, the passenger delay minimization model is used to find the minimum passenger delay at the intersection.

$$D_p^* = \min\left(D_p\right) \tag{7}$$

② Let the acceptable degree of delay increase based on the minimum passenger delay be δ, then the acceptable passenger delay D_δ is

$$D_\delta = D_p^*(1+\delta) \tag{8}$$

There are various signal timing schemes $p_1, p_2, \dots p_u$ (u is the number of timing schemes) between D_p^* and D_δ, and a scheme p_r^* that minimizes the number of non-priority phase stops can be found among them.

B. Model improvements

According to the steady-state theory, the average number of stops for the tth flow of phase k can be calculated by the following equation.

$$h_{kt} = \frac{1-\lambda_k}{1-y_{kt}} \tag{9}$$

where:

h_{kt} —average number of stops for the tth traffic flow of phase k.

Let the number of priority phases be b(b=1,2,...,n-1), and there are l (l=1,2,...,m-1) traffic flows; then the number of non-priority phases is (n-b), and there are (m-l) traffic flows. The average number of stops H_r (r=1,2,...,u) for non-priority phases can be calculated by the following formulas:

$$H_r = \frac{\sum_{k=1}^{n\text{-}b}\sum_{t=1}^{m\text{-}l} q_{kt}h_{kt}}{\sum_{k=1}^{n\text{-}b}\sum_{t=1}^{m\text{-}l} q_{kt}} \tag{10}$$

Where:

H_r —average number of stops per unit hour for non-priority phases;

q_{kt} —The vehicle arrival rate of the tth traffic flow in the kth phase, pcu/h.

Therefore, the set of stopping times corresponding to u signal timing schemes between D_p^* and D_δ is $\{H_1, H_2,..., H_u\}$, and the stopping times corresponding to scheme p_r^* is H_r^*.

In summary, the improved optimization model can be described as:

$$H_r^* = \min\{H_1, H_2,..., H_u\} \tag{11}$$

$$s.t.\begin{cases} D_p^* \le D_r^* \le D_\delta, \quad r=1,2,...,u \\ H_r = \dfrac{\sum_{k=1}^{n\text{-}b}\sum_{t=1}^{m\text{-}l} q_{kt}h_{kt}}{\sum_{k=1}^{n\text{-}b}\sum_{t=1}^{m\text{-}l} q_{kt}}, \quad r=1,2,...,u \\ h_{kt} = \dfrac{1-\lambda_k}{1-y_{kt}} \end{cases} \tag{12}$$

Where:

H_r^*—Minimum value of the number of non-priority phase stops in u scenarios per unit hour;

D_r^* —The total intersection passenger delay value corresponding to the minimum number of non-priority phase stops per unit hour, s.

IV. MODEL SOLVING

A. Theoretical Foundations of Particle Swarm Algorithms

From equations (11) and (12), it can be seen that the improved optimization model is a nonlinear programming problem. In general, the complexity of nonlinear planning problems lies in the fact that they involve nonlinear mathematical functions in their objective functions and constraints [19]. These functions are usually characterized by the fact that they cannot be simply derived or solved analytically and usually require an iterative approach for numerical optimization solutions. Therefore, the model can be solved with the help of MATLAB and intelligent algorithms.

When it comes to solving linear programming problems, the available algorithms include gradient descent, conjugate gradient, genetic algorithm and particle swarm algorithm. Compared with other algorithms, the particle swarm algorithm has the advantages of fewer parameters, high accuracy and fast convergence. Therefore, in this paper, the particle swarm algorithm is chosen to solve the model in order to make full use of the characteristics of this algorithm and hopefully to obtain better solution results.

Particle swarm algorithm (PSO) is a kind of stochastic search algorithm based on group collaboration, which is named by simulating the foraging behavior of a flock of birds and belongs to swarm intelligence algorithm. It has excellent global search capability and is suitable for solving extreme value problems of continuous functions as well as nonlinear, multi-peaked problems.

The specific steps of the particle swarm algorithm are shown below:

step1: Initialize, set the population size N, and assign the initial position and velocity to each particle randomly.

step2: Determine the fitness function and calculate the fitness values of individuals.

step3: Find the individual best fitness value. For each particle, compare the fitness value between its current position and the best position of the individual, and update the best position of the individual.

step4: Find the population best fitness value. Compare the fitness values of all particles, find the best position of the group and record it.

step5: Update the particle position and velocity. Update the velocity and position of each particle according to equations (13) and (14).

$$v_i^d = wv_i^{d-1} + c_1 r_1 \left(pbest_i^d - x_i^d \right) + c_2 r_2 \left(gbest^d - x_i^d \right) \quad (13)$$

$$x_i^{d+1} = x_i^d + v_i^d \quad (14)$$

where v_i^d denotes the velocity of the ith particle at the dth iteration;

x_i^d denotes the position of the ith particle at the dth iteration;

w is the inertia weight;

c_1、c_2 is the acceleration constant;

$pbest_i^d$ denotes the best position of the ith particle up to the dth iteration;

$gbest^d$ denotes the best position of all particles up to the dth iteration;

r_1、r_2 are random numbers from 0 to 1, in order to make the process random.

step6: Check whether the termination condition is satisfied, such as reaching the maximum number of iterations or reaching the target fitness threshold. If it is not satisfied, return to step2 to continue iteration; if it is satisfied, the algorithm ends and the optimal solution is output.

B. Intersection passenger delay minimum model solving process

Programming is performed using MARLAB R2020b software, and the program is divided into three main parts: the objective function, the particle swarm algorithm, and the main function.

(1) Objective function: It is used to define the model variables and the related calculation formulae.

① Definition and coding of variables: intersection green light duration g_i and period C are defined as variables in the population, and 8-bit binary is used to code these variables.

② Preparation of calculation formula: Input formulae (5) and (6), and use the total passenger delay D_p as the objective function.

③ Setting of constraint conditions:

a. For the unsaturated state constraint, it can be converted to the phase maximum flow ratio is smaller than the phase green letter ratio;

b. For the period constraint, it can be determined according to equation (2.3).

④ Select the length, period, and total passenger delay of each phase green as the output result.

(2) Particle swarm algorithm: for the writing of the algorithm program, determination of the fitness function, and the specific iterative process, see 3.1.

① Initialize the population: give the particle a random initial position, the particle initial velocity v_0=randn(size(x)), that is, the velocity size is random, in line with the normal distribution.

② Determine the fitness function: take fit= D_p as the fitness function.

③ Iteration process: Let $x_i = [g_{1i}, g_{2i} \cdots g_{ni}, C_i]$, $\min y = \min fit = \min D_p$.

a.Calculate the fitness value of N particles using the fitness function

$$for\ i=1:N$$

$$fit[i] = y\left(x_i\right)$$

c. Compare the fitness value corresponding to the current position of each particle with the historical best fitness value, and the position corresponding to the better value is the current individual best position x_p, and record the fitness value y_p of the individual best position.

d.Compare the fitness value corresponding to the current position of all particles with the historical best fitness value, and the position corresponding to the better value is the current population best position x_g, and record the fitness value y_g of the population best position.

e.Update the particle position and velocity according to equations (13) and (14).

f. Judge whether the requirements are met.

(3) Main function: Its main purpose is to store the basic data such as the investigated to traffic flow and the average number of passengers carried by the vehicle, set the range of variables in the model, algorithm parameters, etc. After all data input is completed, running the main function can get the iterative results of the objective function and variables.

① Basic data storage and variable setting in the model: the traffic ratio y_ij for each lane at the intersection, the range of cycle C variation, the range of green light g_i for each phase, the average number of passengers carried by vehicles $\overline{o_a}$, $\overline{o_b}$ and other data can be stored in a 1×n order matrix.

② Algorithm parameters setting: the number of populations N, the maximum number of iterations N_0, acceleration constants c_1、c_2, and the value of inertia weight w.

③ Output results: When the iteration is completed, the optimal solutions of the variables and the corresponding objective function values are given in the command window of MATLAB.

C. Solving process of the Improved optimization model

After getting the minimum passenger delay value, multiply (1+δ) on its basis to get the value of D_δ. Then, in the main function screen, do the following:

(1) Add a for loop so that each iteration of the signal timing scheme is displayed in the command window.

(2) Create a temporary variable temp whose value is equal to the phase green light time increment for each iteration.

(3) Update the green light time by adding the temp variable after the minimum green light of each phase, with the purpose of making the minimum green light time increase evenly.

(4) Output the current green light time, select the signal timing schemes that meet the delay range, and then bring the non-priority phase green light times of these schemes into equation (11) respectively to get the scheme with the minimum number of stops p_r^*.

V. Simulation Verification

In order to verify the effectiveness of the improved optimization model, the intersection of Huanghe Road-Guangping Street in Dalian, Liaoning Province, is selected as an example study, and the investigation time is the evening peak (17:30~18:30) on June 20, 2022. Its each inlet channelization scheme is shown in Figure 1, and the flow rate is shown in Table 1. The intersection is a cross intersection, and the east-west direction is the bus priority direction. The proportion of east-west direct bus traffic obtained from the field survey is 6.4% and 7.1%, respectively. The average number of passengers carried by bus vehicles at this intersection is 35 per/pcu, and the average number of passengers carried by social vehicles is 2 per/bus during the peak period taken from the survey statistics.

The intersection adopts a two-phase control scheme with a cycle time of 144 s. The first phase is for straight east-west traffic and left turn east-west, with a green light duration of 82 s. The second phase is for straight north-south traffic and left turn north-south, with a green light duration of 52 s. Both phases have a yellow light of 3 s. The basic timing scheme (Option 1), the minimum passenger delay model timing scheme (Option 2), and the improved optimal model timing Option 3 (taking δ=20%) are used to time the intersection respectively. Then the timing results are input into VISSIM simulation software to compare the simulation results of delays and stopping times under the three scenarios.

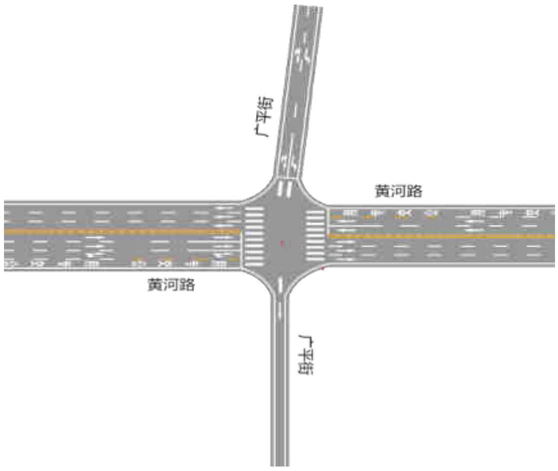

Figure 2 Intersection drainage

Table 1 Traffic flow of intersections (veh/h)

Type	West entrance	East entrance	North entrance
Left	0	0	204
Straight	1162	1434	228
Right	0	0	96

Each phase of the green light needs to meet the minimum green light time for pedestrians crossing the street in the same direction, and the maximum green light exceeds the minimum green light by at least 10 s. The range of values for each variable is as follows (unit (s)):

$$g_1 \in [60,70],\quad g_2 \in [42,52],\quad C \in [108,128]$$

Regarding the values of the parameters of the particle swarm algorithm, after a more detailed study done by previous authors, it is found that the population size N should not be too large, the inertia weight w is taken at [0.2,0.7], and the learning factors c_1、c_2 are better when they are taken as 2 [20]-[22]. Then the particle swarm parameters in this paper are taken as follows:

$$N = 50,\quad N_0 = 100,\quad c_1 = c_2 = 2,\quad w = 0.5$$

The results of solving the passenger delay minimum model are:

$$g_1 = 70s,\quad g_2 = 42s,\quad C = 118s$$

The solution results of the improved optimization model are:

$$g_1 = 70s,\quad g_2 = 49s,\quad C = 125s$$

The simulation results of the delays under the three Options are shown in Figure 2, and the simulation results of the average number of non-priority phase stops are shown in Table 2.

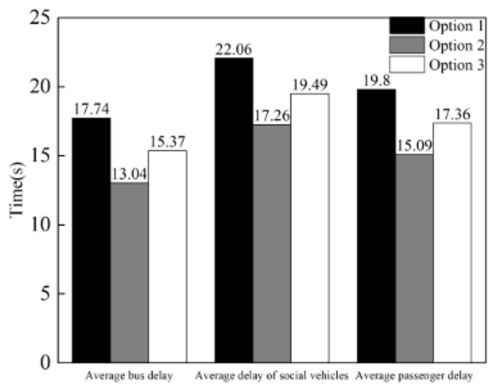

Figure 3 Comparison of delayed error results

Table 2 Comparison of the average number of stops in non-priority phases

Option	Average number of stops (times)
2	0.66
3	0.63

(1) Compared with Option 1, Option 3 reduces intersection transit delays by 13.4%, which is 17.9% higher than Option 2. It shows that the improved optimization model can effectively reduce the intersection transit delay.

(2) Compared with Option 1, Option 3 reduces intersection social vehicle delays by 11.7%, which is 12.9% higher than Option 2. This indicates that the improved model can improve the efficiency of social vehicles at intersections.

(3) Compared with Option 1, Option 3 reduces the intersection passenger delay by 12.3%. The passenger delay under Option 3 matching time is 15% higher than that of scenario 2, which is less than 20% within the acceptable range.

(4) From Table 2, it can be seen that Option 3 reduces the average number of stops at non-priority phases by 4.5% compared to Option 2.

In summary, it can be seen that the improved optimization model is able to achieve transit priority and reduce the stopping rate of non-priority phases within an acceptable range of increased passenger delay compared to the minimum passenger delay model.

VI. Conclusion

(1) In this paper, we take unsaturated intersections as the object of study and improve the traditional passive bus priority method with the objective of "minimum passenger delay", which may cause an increase in the number of non-priority phase stops. The specific idea of improvement is proposed, and the improved optimization model is established.

(2) The results of the simulation show that the improved model can achieve bus priority and reduce the number of stops in non-priority phases without significantly increasing passenger delays compared to the passenger delay minimization model.

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