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Research Article

Research on data acquisition and signal timing of single-point intersections based on millimeter wave radar

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Abstract With the accelerating urbanization in China, traffic congestion has become a major urban problem. In recent years, the continuous development of traffic information detection technology has made full use of the real-time data obtained by the new detection technology to dig out indicators that better reflect the dynamic characteristics of traffic flow, which is of great significance for intersection signal timing optimization. In this paper, we construct a short-term traffic flow combination prediction model based on Stacking, which is different from the traditional single prediction model. Based on the predicted traffic flow, we optimize the timing of the signal control scheme, calculate the optimized index values of the intersection for the next time period, and search to determine the optimal traffic cycle for the next time period before the actual traffic flow comes. Finally, the optimization model is solved for the case intersection and simulated using VISSIM to compare the average delay time and the average number of stops before and after optimization. The experimental results show that this method can optimize the intersection status quo and improve traffic operation efficiency.

Keywords Millimeter wave radar; Stacking prediction; Signal timing optimization

1. Introduction

Intersections play a crucial role in the entire road system, playing a key role in the articulation of roads and the evacuation of urban traffic flow, and the size of their capacity is largely related to the size of the capacity of the entire urban road network. With the increasing motorization level in recent years, traffic congestion has become a major urban problem.

The development of a reasonable traffic signal control timing scheme can reduce the delay time of vehicles at key nodes, the number of stops, improve the efficiency of vehicle traffic, is the key to improve the level of traffic management and control. With the continuous increase of motor vehicle ownership in China, the urban traffic system is becoming more and more complex, and it is difficult to obtain parameters that can accurately reflect the real-time status of traffic flow by traditional information detection means, and the optimization effect of signal timing needs to be improved.

The commonly used traffic information detection means include coils, video, microwave and other classical detection techniques. These fixed-point detection techniques have a small detection range, limited information type, low information update frequency, and cannot grasp the real-time information within the whole intersection, and the environmental adaptability of the equipment is weak and the data accuracy is low, which limits the effect of signal control timing optimization. Many new detection technologies, such as RFID and cell phone signaling, are still difficult to be applied on a large scale due to the market penetration and cost requirements [1]. In addition, urban traffic systems are highly stochastic and complex, and traditional signal timing optimization uses objective optimization to establish an accurate mathematical model to solve the optimal control scheme. A series of assumptions are often required in the modeling process, such as vehicle arrivals conforming to Poisson distribution or binomial distribution, which leads to the difficulty of the established model to realistically restore the whole complex and dynamic traffic system, and it is not easy to achieve good optimization results.

Therefore, for the development trend of urban traffic in China, new traffic information detection technologies need to be used to establish more effective traffic signal control systems [2], and single-point intersections, as the basis of signal control, need to be focused on research.In this paper, we address the problem that traditional traffic flow information detection parameters can hardly reflect the real-time characteristics of real traffic flow, combine millimeter wave radar, a new type of traffic information detection means, and study more effective signal timing control parameters to improve the effect of signal control timing optimization at single-point intersections based on the intersection's large-range and high-precision multiple information detection capability [3] [4] [5]. By fully exploiting the potential of intersection space-time resources utilization, we can improve intersection traffic efficiency, reduce average vehicle delays, and improve urban traffic management and control methods to achieve the purpose of enhancing urban economy and improving people's quality of life.

2. Data description

The original millimeter wave radar data time is from May 6 to June 3, 2021 (28 days), which can better reflect the data characteristics of different dates and different traffic states, and Figure 1 shows the output of millimeter wave radar for five minutes, and the description of the data in the figure is shown in Table 1.

```
[07:21:05.068] lane id: 1; Vehicle Cntr: 19; avgVel: 31.7 km/h; TOR: 3 %; SOR: 25 %; qLen: 0.0 m; status: 2;
[07:21:05.138] lane id: 2; Vehicle Cntr: 19; avgVel: 25.4 km/h; TOR: 4 %; SOR: 40 %; qLen: 0.0 m; status: 2;
[07:21:05.138] lane id: 3; Vehicle Cntr: 29; avgVel: 24.2 km/h; TOR: 7 %; SOR: 30 %; qLen: 0.0 m; status: 2;
[07:21:05.138] lane id: 4; Vehicle Cntr: 24; avgVel: 29.2 km/h; TOR: 5 %; SOR: 67 %; qLen: 0.0 m; status: 2;
[07:21:05.138] lane id: 5; Vehicle Cntr: 21; avgVel: 24.6 km/h; TOR: 5 %; SOR: 60 %; qLen: 0.0 m; status: 2;
[07:21:05.138] lane id: 6; Vehicle Cntr: 28; avgVel: 25.5 km/h; TOR: 7 %; SOR: 55 %; qLen: 0.0 m; status: 2;
[07:21:05.138] tick: 171594489
[07:21:05.389] lane amount: 6
[07:21:05.389] lane id: 7; Vehicle Cntr: 8; avgVel: 27.6 km/h; TOR: 1 %; SOR: 37 %; qLen: 0.0 m; status: 2;
[07:21:05.389] lane id: 8; Vehicle Cntr: 11; avgVel: 26.0 km/h; TOR: 2 %; SOR: 40 %; qLen: 0.0 m; status: 2;
[07:21:05.389] lane id: 9; Vehicle Cntr: 21; avgVel: 26.2 km/h; TOR: 5 %; SOR: 35 %; qLen: 0.0 m; status: 2;
[07:21:05.389] lane id: 10; Vehicle Cntr: 17; avgVel: 24.6 km/h; TOR: 4 %; SOR: 45 %; qLen: 0.0 m; status: 2;
[07:21:05.389] lane id: 11; Vehicle Cntr: 14; avgVel: 26.8 km/h; TOR: 3 %; SOR: 40 %; qLen: 0.0 m; status: 2;
[07:21:05.389] lane id: 12; Vehicle Cntr: 12; avgVel: 22.8 km/h; TOR: 6 %; SOR: 5 %; qLen: 0.0 m; status: 2;
```

Figure 1: Five-minute data output graph

Tabel 1: Data information

Data Key Information	Data Form	Description
Total number of vehicles	Vehicle cnter:19	Total number of vehicles entering the radar detection range in five minutes
Average vehicle speed	avgVel:26.0km/h	Average vehicle speed within five minutes
Congestion Index	TOR:1%	Conceptual index value to reflect the smoothness or congestion of the road
Time Occupancy Rate	SOR:40%	The ratio of time that traffic occupies the road
Elapsed time	07：17：09.295	The moment when the vehicle enters the radar detection range

3. Theory and Methods

3.1 Short-time traffic flow prediction method based on Stacking

The basic idea of the Stacking-based short-time traffic flow prediction model is to first obtain a large amount of historical traffic flow data, clean the historical data, perform data transformation and data normalization, extract feature values, and construct new feature values, and then use the Stacking integrated learning model to learn them [6][7]. More than ten models were validated in the previous study, and the selection was based on making a large difference among algorithmic models and encompassing different kinds of models so that they could learn as many features as possible in the traffic flow data. After excluding linear regression and stochastic gradient descent models that were not robust enough, Adaboost, Bayesian ridge regression, regression tree, Huber regression, passive aggressive regression, random forest, finally selected Support vector regression and XGBoost regression eight machine learning models as the first layer of learners for the processed data to obtain intermediate prediction values, and the XGBoost-based prediction model, which performs best in a single model, is used as the model in the output layer to learn the original data and the intermediate prediction values derived from the previous machine learning models [8][9][10], which is equivalent to more than the original data eight more feature values than the original data and gives the final prediction value.

3.2 Indicator Selection

Performance evaluation indexes in traffic signal control usually include average number of stops, average delay time, capacity, queue length, tailpipe emission, etc. In this paper, we consider the selection of evaluation indicators from two perspectives of travel cost and road utilization, and construct a multi-objective optimization model. The size of average number of stops and average delay time can affect the travel cost of traffic participants, and the capacity can affect the road utilization rate, so this paper selects the average number of stops, average delay time and capacity as constraints to optimize the timing scheme [11].

(1) Average number of stops

Usually drivers know that too many stops and starts are, first, wear and tear on car parts and, second, more energy consumption. Therefore it will be necessary to reduce the number of stops as a performance indicator for multi-objective optimization, and the average number of stops can be calculated by the following equation.

$$h_i = \frac{0.9T(1-\lambda_i)}{1-y_i}$$

Where: h_i is the average number of stops at phase i; T is the signal control period; y_i is the traffic intensity at phase i, i.e., the proportion of traffic in that phase to the saturation traffic, and λ_i is the green signal ratio at phase i. The average number of stops H for the whole intersection can be calculated by the following equation.

$$H = \frac{\sum_i^n h_i q_i}{\sum_i^n q_i}$$

where q_i is the value of the traffic flow in phase i.

(2) Average delay time

The impact of delay time on traffic is multifaceted, firstly, it makes more vehicles stranded in the traffic road network, secondly, long delays represent more tailpipe emissions, and reducing delay time is conducive to improving traffic system efficiency. Delay time is an important indicator to evaluate the level of road service. The average delay time calculation formula used in this paper is extended from the formula proposed by Webster and is calculated as follows.

$$d_i = \frac{T(1-\lambda_i)^2}{2(1-\lambda_i x_i)}$$

where T is the period of signal control; λ_i is the green signal ratio of phase i; and X_i is the road saturation of phase i. After calculating the delay time of each phase separately, the average delay D of all phases can be found by using the following equation.

$$D = \frac{\sum_i^n d_i q_i}{\sum_i^n q_i}$$

where D is the average delay time of all phases; d_i is the average delay time of the i-th phase.

(3) Capacity

The throughput capacity is also important in evaluating the intersection performance, which reflects the maximum capacity of the roadway. This algorithm optimizes the capacity of the road while delays and stops are reduced. The capacity Q_i for a given phase i is calculated as follows

$$Q_i = S_i \lambda_i = S_i \frac{y_i(T-L)}{TY}$$

Where Q_i is the capacity of phase i; S_i is the saturation flow of phase i; λ_i is the green signal ratio of phase i; y_i is the traffic intensity of phase i; Y is the sum of the maximum flow ratio of each phase; and T is the signal period. The total capacity Q of the intersection is calculated as follows.

$$Q = \sum_i^n Q_i$$

where Q is the total capacity of the intersection, Q_i is the capacity of phase i, and n is the total number of phases.

3.3 Weighting factor

The multi-objective timing optimization method based on traffic flow prediction proposed in this paper mainly uses the real-time dynamics of the predicted traffic flow, accompanied by a certain amount of advance, to improve the weight coefficients of each objective. When the traffic system is in a more congested state, with more vehicles and slower speed in the system, the primary objective should be to improve the capacity and give more weight to the capacity indicator; while when the traffic system is in an idle state, with fewer vehicles and faster speed in the system, the number of stops and delays should be given priority at this time, and the weight values of these two indicators in the optimization objective function should be increased. The weight coefficients of each evaluation indicator proposed in this paper are obtained by the following equation, which takes into account the current situation of the intersection (existing cycle T) and the future situation (the total predicted saturation Y).

$$\eta_1 = (1\text{-}Y)^2$$

$$\eta_2 = \frac{T(1-Y)}{1500}$$

$$\eta_3 = 2Y\sqrt{T}$$

where η_1 is the weight of the average number of stops among the three evaluation indicators; η_2 is the weight of the average delay time among the three evaluation indicators; η_3 is the weight of the capacity among the three evaluation indicators; Y is the total saturation of the intersection flow calculated using the traffic flow forecast value; and T is the traffic signal period.

3.4 Multi-objective optimization model

The multi-objective optimization model in this paper is based on the predicted traffic flow of the intersection, the predicted road conditions and evaluation indexes of the intersection in the next period, and the dynamic adjustment of the weights of the three optimization objectives in the model based on the real-time characteristics and improvement requirements of the traffic system at different times. The objectives of this optimization model are to improve the capacity of a single intersection, reduce the average delay time and decrease the average number of stops, so the average number of stops and delays are used as the numerator in the objective function, and the capacity is placed in the denominator. Therefore, the multi-objective optimization model for a single intersection in this paper is constructed as follows.

$$\min F(T, X_i) = \min[\eta_1 H(T, X_i), \eta_2 D(T, X_i), \eta_3 Q(T, X_i)^{-1}]$$

where H is the average number of stops; D is the average delay; Q is the capacity; and x_i is the saturation of the i -th phase.

After predicting the traffic flow by the constructed short-time traffic flow prediction model, the traffic condition of the intersection after five minutes is calculated, and the optimal period is calculated using this model and then timed to each phase.

3.5 Optimization model solving

Since the signal period is generally taken as an integer, the optimal period can be searched by a fixed-step parameter with a step size of one second, between the minimum period of 30s and the maximum period of 180s, while the minimum value of the objective function is calculated within the constraint of x_i, and the value of T and the value of the objective function are recorded, and the T value that minimizes the value of the objective function is taken as the optimal period. The process steps for searching the optimal period are shown in Figure 2 below.

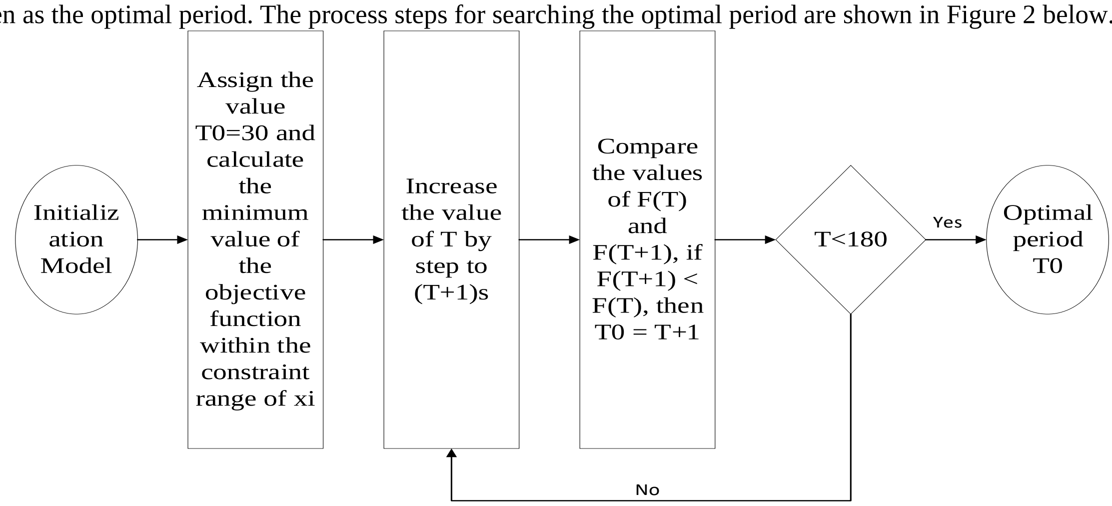

Figure 2: Optimal period fixed step search method

Based on the principle of equal saturation to find out the optimal period of the duration of each phase for the time allocation, so that the newly allocated signal duration for each phase of the flow of traffic to meet the same proportion as before the optimization, the calculation formula is as follows.

$$ge_i = \frac{Ge \cdot y_i}{Y}$$

$$G_e = T_0 - L$$

where ge_i is the green signal ratio of each phase; y_i is the i-th phase saturation; Ge is the total effective green time; Y is the total saturation; T_0 is the calculated optimal period; and L is the loss time.

4. Instance Verification

4.1 Intersection Status and Traffic Forecast

Using an intersection in a city of Shandong Province as a simulation example, the timing scheme optimization of the intersection is solved using a multi-objective optimization model. The figure below shows the intersection's drainage diagram.

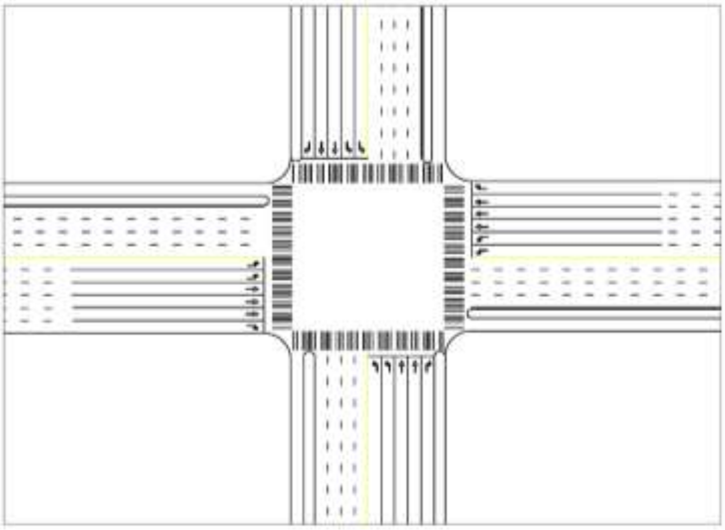

Figure 3: Intersection drainage map

The actual traffic data of the intersection from 7:00 am to 9:00 am on December 13, 2021 was obtained by millimeter wave radar, and after data processing, the flow rate of each direction of each inlet lane was obtained and the traffic flow was predicted, and the traffic flow is shown in Table 2 below, which was used as the main basis for traffic signal control timing optimization.

Table 2: Example of input traffic flow data

Traffic flow	Number of lanes	Real traffic pcu/5min	Predicted traffic pcu/5min
North import straight ahead	2	64	58
Left turn at the north entrance	2	34	36
East import straight ahead	3	144	139
East import left turn	2	68	67
South import left turn	2	42	43
South import straight	2	62	58
West import straight	3	132	138
West import turn left	2	144	137

4.2 Simulation evaluation of the intersection using VISSIM

Detectors were set at each inlet lane, where detectors 1 to 3 measured the left and right vehicle conditions at the west inlet, 4 to 6 measured the left and right vehicle conditions at the east inlet, 7 to 9 measured the left and right vehicle conditions at the north inlet, and 10 to 12 measured the left and right vehicle conditions at the south inlet. The signal schemes before and after optimization are placed in VISSIM and simulated. The main procedure of simulation using VISSIM is shown in Figure 4.

Figure 4: VISSIM simulation process

After the simulation, this paper will use multiple evaluations and summation to reduce the experimental error and count the experimental results. In order to reflect the innovation and algorithm superiority of this paper's research, the traditional optimization method (Webster's algorithm) is introduced in the simulation part for comparison. The improvement of intersections under different timing schemes is shown in Fig. 14, where the average delay and the average number of stops at different locations are compared. The numbers 1 to 12 in the horizontal coordinates correspond to the locations measured by the detectors in the VISSIM model, respectively.

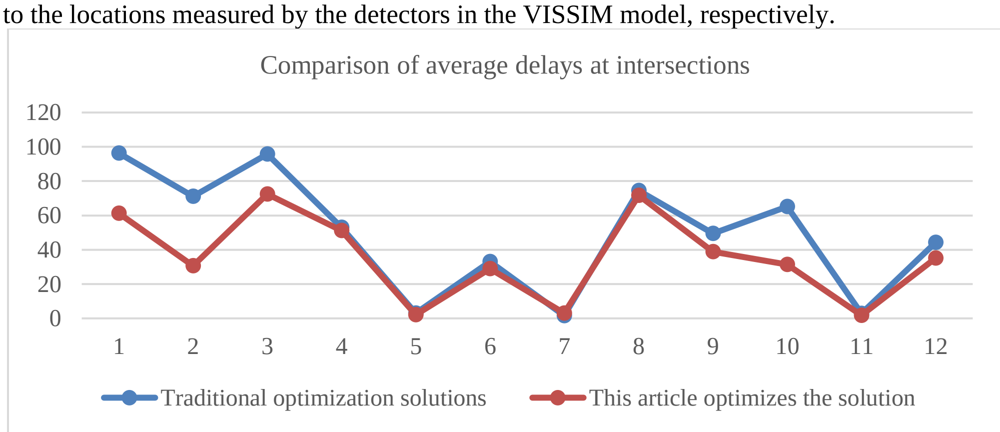

Figure 5: Comparison of average delays at intersections

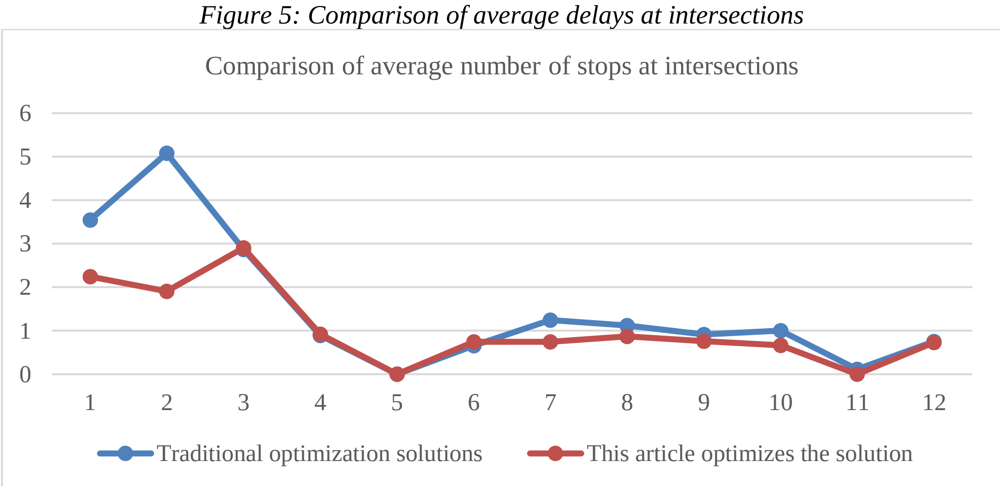

Figure 6: Comparison of average number of stops at intersections

It can be visually seen from the above figure that the results of the optimization scheme used are significantly better than the traditional optimization scheme, and the delay and number of stops generated at the intersection are effectively reduced under this timing scheme, which improves the current situation of roadway traffic. The experimental results of the optimized scheme in this paper are better than those of the traditional optimized scheme, and the total delays and stops are also smaller.

5. Conclusion

This paper focuses on the intersection signal optimization problem. By solving the optimization model using multi-objective signal timing optimization based on Stacking predicted traffic flow, a better signal timing scheme is obtained, which effectively reduces the number of intersection delays and stops and improves the traffic conditions at the target intersection. In the case study, the feasibility of the research direction of this paper in practical applications is demonstrated, and it is concluded that the improved signal timing scheme is significantly better than the traditional optimization scheme, which shows the relevance and superiority of the research on the artificial fish swarm algorithm to improve the traffic conditions at intersections. In terms of research prospect, the method can be continuously improved in the future to make it more suitable for solving the problem of improving road network capacity under different traffic flow conditions and realizing real-time adjustment of intersection green light timing, so that the road traffic system can operate conveniently, efficiently, smoothly, safely and environmentally friendly.

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