Research on Traffic Signal Control Optimization Based on Time Period Division and Traffic Flow Prediction

Chengchao Yin [1,*], Kun Wang [1], Gaoshuai Ren [1], Jiayu Wang [2], Tianyu Zhao [1]

[1] Xi'an Mingde Institute of Technology, Xi'an, China, 710124

[2] Qinhuangdao Vocational and Technical College, Qinhuangdao, China, 066102

* Corresponding Author Email: ycc200472520@163.com

Abstract. With the acceleration of urbanization, the surge in traffic flow makes traffic signal optimization a key issue, and the traditional fixed-time control method is difficult to cope with the dynamically changing traffic flow, which urgently needs to be optimized and adjusted based on actual data. Specifically, for traffic flow analysis, this study first preprocesses the dataset, extracts the records of the longitudinal middle road - latitudinal middle road, and divides the data from 1 April to 6 May 2024 into weekdays, double holidays, and holidays. By the equidistant binning method, the day is divided into four time periods, and the steering rate is introduced for traffic flow estimation. Next, the traffic signal period, maximum number of passing vehicles and delay time are calculated, and a nonlinear planning model is established to minimize the delay. In contrast, the optimization of the traffic signal configuration by applying the SLSQP algorithm yields an average speed of 60km/h for the low peak, 50km/h for the flat peak, and 40km/h for the peak, which improves the average speed.

Keywords: Steering Rate, Binning, Nonlinear Programming, Slsqp Algorithm.

1. Introduction

The rapid pace of urbanization has led to a sharp increase in urban traffic volume, resulting in traffic congestion becoming one of the primary challenges confronting modern cities. Traffic congestion not only leads to increased travel times and higher fuel consumption but also escalates environmental pollution, thereby affecting the sustainable development of cities. Effective traffic management and optimization measures are crucial for alleviating congestion and improving road utilization efficiency.

Traffic signal control is a pivotal component of urban traffic management, directly influencing the capacity of intersections and the average delay time for vehicles. Traditional traffic signal control methods, such as fixed-time signal control and simple adaptive control, often struggle to cope with complex and varying traffic conditions. This is especially true during peak hours and holidays when traffic volumes and flow directions fluctuate more dramatically. With the advancement of big data and artificial intelligence technologies, data-driven traffic signal optimization methods have gradually become a research hotspot. By analyzing and processing large volumes of traffic data, it is possible to more accurately predict traffic flow trends and formulate more scientific and reasonable signal control strategies, thereby enhancing the efficiency and effectiveness of traffic management.

The main objective of this study is to construct a flexible and efficient traffic signal control optimization strategy based on real-time traffic flow data, in order to adapt to different time periods and special traffic conditions, and to ensure a smoother overall operation of the traffic system. The existing fixed-time control mode methods cannot be flexibly adjusted and are inefficient. In order to break through the limitations of traditional signal control methods, non-linear planning models and advanced optimization algorithms (e.g. SLSQP) are used to optimize traffic signal configurations, which not only take into account the dynamic changes in traffic flow, but also make the signal configurations more flexible to cope with the complex traffic conditions by providing a detailed division of the traffic conditions on different dates and time periods. In addition, the combination of traffic flow prediction and real-time data will provide a scientific basis for the dynamic adjustment of traffic management measures. In conclusion, this study aims to provide new ideas and methods for future urban traffic management and to promote the safe, efficient and sustainable development of urban traffic systems.

2. Traffic Flow and Turning Behavior Modeling

2.1. Isometric binning period

Binning is a mathematical algorithm commonly used in data preprocessing and analysis, mainly for converting continuous data into discrete data, thus facilitating subsequent data processing and analysis. The data for this study was obtained from https://www.mcm.edu.cn/.

Firstly, the string variables of the time column in the dataset were converted into timestamps, and 8590720 data were left over from the 8844996 data in which the license plate number was listed as a police car, cadet car, no license plate, and unnnwk, and then the longitudinal and middle roads were extracted. A total of 1093310 and 1135930 data from the mid-warp road and 1135930 data from the May Day Golden Week, and finally the data from 1 April to 6 May 2024, divided into three parts: weekdays, double holidays and holidays (May Day Golden Week) [4]. The hourly traffic flow of the time columns of the extracted data of Longitudinal Middle Road - Latitudinal Middle Road is merged, and then the hourly traffic flow is counted by hour, and the average traffic flow of 24 hours a day is calculated and found that the traffic flow increases gradually at 6:00 and decreases gradually at 19:00. Therefore, according to the 24-hour water flow division interval: 32% below corresponds to the peak, 32%-50% corresponds to the flat peak, more than 50% corresponds to the peak.

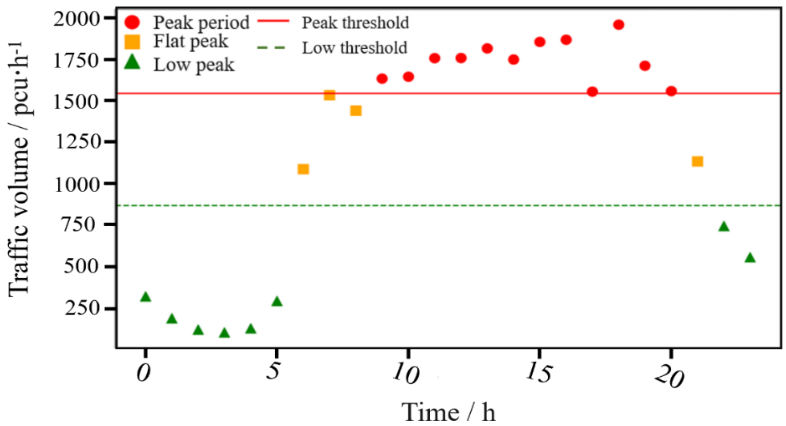

Figure 1 Traffic flow analysis results

As shown in Figure 1, weekdays have a low peak at 22-6, a flat 6-9 with 21-22, and a peak at 9-21; double holidays have a low peak at 23-7, a flat 7-8 with 20-23, and a peak at 8-20.

2.2. Determination of traffic flow

Firstly the trajectory of each vehicle is analysed one by one by segmenting the data by each plate number. Secondly traversing each set of vehicle data [5], checking whether a specific time difference condition is satisfied (whether the steering occurs within the 60s), and finally calculating the probability of different steering in each direction.

$$P_{d,z} = \frac{C_{dz}}{Z_{total}} \tag{1}$$

Counting the volume of traffic for each period and direction.

$$L = \sum_{n=1}^{N} \delta \tag{2}$$

The total traffic volume (sum of traffic in all directions and turns) for each period is:

$$L_{total} = \sum_{c=1}^{4} \sum_{z\in\{st,l,r\}} tl \tag{3}$$

The percentage of total traffic for each period, direction, and turn is:

$$P_{(c,\,z)} = \frac{L_{total}(c,z)}{L_{total}} \tag{4}$$

Based on the above equations, the total traffic flow and the traffic flow for straight, left, and right turns for the three different periods of weekdays, double days, and holidays were estimated as shown in Tables 1 - 3:

Table 1: Estimation of weekday traffic flow

Time slot		22-6				6-9				9-21				21-22			
Traffic flow		2558				4026				20278				1081			
Each phase		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Direction	Straight travel	332	361	187	721	510	491	441	993	2370	2968	1815	5469	144	141	82	304
	Turn left	325	45	242	43	500	61	571	59	2322	368	2350	326	141	18	106	18
	Turn right	121	85	2	94	186	117	4	128	862	704	15	708	52	33	1	39

Table 2: Estimation of traffic flow on weekends

Time slot		23-7				7-8				8-20				20-23			
Traffic flow		3256				1581				22288				3518			
Each phase		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Direction	Straight travel	640	655	546	937	344	218	365	416	4531	4042	4146	6264	739	657	497	1095
	Turn left	167	31	39	51	89	10	26	23	1180	190	296	343	192	31	36	60
	Turn right	76	31	16	66	41	10	10	30	540	190	119	445	88	31	14	78

As can be seen in the data in Tables 1-3, there is a significant difference in the volume of traffic in each of the phases on weekdays, bi-weekdays, and holidays. Specifically, flows per phase were generally higher on double days and holidays than on weekdays. In terms of the specific distribution of traffic flow, the flow of straight vehicles generally exceeds that of turning vehicles. In particular, during the straight-ahead hours, the traffic volume of all four phases exceeded that of phases 1, 2, and 3. For left-turning and right-turning vehicles, the flow in phase 1 significantly exceeds that in phases 2, 3, and 4, while the flow in phases 2, 3, and 4 is roughly equal.

Table 3: Estimation of holiday traffic volume

Time slot		23-7				7-8				8-20				20-23			
Traffic flow		3256				1581				22289				3518			
Each phase		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Direction	Straight travel	683	660	545	937	366	219	363	416	4843	4066	4131	6262	788	661	495	1095
	Turn left	125	32	42	55	67	10	28	24	888	194	320	363	145	31	38	63
	Turn right	75	27	14	64	40	9	10	28	530	163	109	427	86	27	13	75

3. Signal Configuration Optimization and Delay Analysis

3.1. Delay analysis

The traffic signal cycle length is determined by the green time in both directions and the phase switching loss time (the amount of time a vehicle waits while the phase switches).

$$C = t_{Green1} + t_{Green2} + 2 \times t_h \tag{5}$$

Capacity is the maximum number of vehicles that can pass through a traffic signal per unit of time and depends on the green time, cycle length, and phase switching loss time [6-7].

$$C_r = \frac{S_b}{3600} \times \left(\frac{t_{Green}}{C} - \frac{t_x}{C}\right) \tag{6}$$

Traffic flow delays are calculated to measure the average delay time for vehicles that are abnormally delayed because they are waiting at a red light under the current signal cycle configuration.

$$D = 0.5 \times C \times \frac{\left(1 - \frac{t_{Green}}{C}\right)^2}{1 - \min\left(1, \frac{v/c}{t_{Green}/C}\right)} \tag{7}$$

3.2. Nonlinear programming

The objective function is the core of the optimization problem, This function is the same as measuring the advantages and disadvantages of the current traffic configuration and finding the optimal signal configuration by minimizing the value of this function, the objective function has a delay time and a penalty term composition, this paper to minimize the delay time response to the maximum average speed.

$$M = \sum_{i=1}^{n} D_i \times f + p_e \tag{8}$$

The penalty term is used to ensure that the stoplight time and red-light time satisfy the constraints.

$$\begin{aligned} p_e = 1000 \times \Big(& max\left(0, min\_t_{\mathrm{Green}} - t_{\mathrm{Green}}\right)^2 \\ & + max\left(0, C - t_{\mathrm{Green}} - max\_t_{\mathrm{Red}}\right)^2 \Big) \end{aligned} \tag{9}$$

A constraint is defined to ensure that the sum of the green time and phase switching loss time in both directions does not exceed the total cycle length.

$$t_{Green1} + t_{Green2} + 2 \times t_x = C \tag{10}$$

In summary, a nonlinear planning model with the sum of the green time plus phase switching loss time in both directions not exceeding the cycle length as a constraint and minimizing the delay time and penalty term as an objective function is established [6].

$$\begin{aligned} & \min\left(\sum_{i=1}^{n} 0.5 \times C \times \frac{\left(1 - \frac{t_{Green}}{C}\right)^2}{1 - \min\left(1, \frac{v/c}{t_{Green}/C}\right)} \times f\right) \\ & + 1000 \times \Big(max\left(0, min\_t_{Green} - t_{Green}\right)^2 \\ & + max\left(0, C - t_{Green} - max\_t_{\mathrm{Red}}\right)^2 \Big) \end{aligned} \tag{11}$$

3.3. Optimisation based on SLSQP algorithm

SLSQP is an optimization algorithm based on Sequential Quadratic Programming, which solves nonlinear optimization problems by constructing quadratic approximations in each step. This method allows to deal with nonlinear objective functions and linear/nonlinear constraints and is a suitable choice for such optimization problems. Setting 40km/h as the speed in the peak period based on the SLSQP algorithm traversing all the traffic signals gives the optimal configurations for weekdays, bi-weekdays, and holidays and the maximum average speeds for the low, flat, and peak periods [7].

Table 4: Optimization configuration of intersections on weekdays (Part)

Traffic light direction		East West Direction				North South Direction			
Time slot		22-6	6-9	9-21	21-22	22-6	6-9	9-21	21-22
Jingzhong -Huanbei Road	Red	70	65	60	65	24	29	34	29
	Green	20	25	30	25	66	61	56	61
Jingzhong - Weiyi Road	Red	31	65	60	65	63	29	34	29
	Green	59	25	30	25	27	61	56	61
Jingzhong - Weizhong Road	Red	24	65	60	29	70	29	34	65
	Green	20	25	30	61	66	61	56	25
Jingzhong - Huannan Road	Red	24	29	34	65	70	65	60	29
	Green	66	61	56	25	20	25	30	61
Huanxi -Weizhong Road	Red	24	29	34	29	70	65	60	65
	Green	66	61	56	61	20	25	30	25
Jingyi - Weizhong Road	Red	24	29	34	29	70	65	60	65
	Green	66	61	56	61	20	25	30	25
Jing'er - Weizhong Road	Red	24	29	34	29	84	84	67	70
	Green	80	80	63	66	20	25	30	25
Jingsan - Weizhong Road	Red	24	29	34	29	70	65	60	65
	Green	66	61	56	61	20	25	30	25
Jingzhong - Scenic Area Entrance and Exit	Red	24	29	34	29	84	65	60	65
	Green	80	61	56	61	20	25	30	25

Table 4 shows the optimized configuration of the traffic signals based on Python simulations, considering different periods and traffic flows. Specifically, the optimized configurations were analyzed differently for weekdays, fortnights, and holidays based on the assumption of a peak period speed of 40 km/h. The optimized configurations include maximum average speeds for the low, level, and peak periods, which are 60 km/h for the low peak, 50 km/h for the level, and 40 km/h for the peak. For the weekdays and holidays, the periods were divided in the same way due to the similarity of the traffic conditions, which include: 23:00-07:00, 07:00-08:00, 08:00-20:00, 20:00-23:00 four time periods. Therefore, the optimal allocation scheme is the same for both types of dates. As for weekdays, the periods are divided into four time periods: 22:00-06:00, 06:00-09:00, 09:00-21:00, and 21:00-22:00. Finally, the optimization algorithm calculates the optimal signal configurations for the 12 intersections on weekdays. As a result, it can be seen that the signal configurations on holidays and double holidays are different from those on weekdays, mainly due to the differences in the division of periods caused by changes in traffic flow [8-10].

4. Conclusions

In this paper, the pre-dataset is used to divide April 1 to May 6, 2024, by weekdays, bi-weekdays, and holidays, and the traffic flow periods are subdivided using the equidistant binning method. Steering rates are introduced to assist in traffic flow estimation, and steering rates are analyzed and estimated for each intersection. By calculating the signal period and the maximum number of passing vehicles, a nonlinear planning model is established to minimize the delay time, and finally, the SLSQP algorithm is applied to optimize the signal configurations, which proves the feasibility of this method in the field of traffic flow control.

In this paper, This paper not only presents an innovative research idea and framework designed to be applied to the complex field of traffic flow control but also fully demonstrates the feasibility and effectiveness of the methodology through practical exercises and data analysis. This presentation of research results aims to highlight the potential of the methodology and framework This research has been adopted to be applicable in traffic flow management practices, further reinforcing their practical application value in enhancing traffic efficiency and optimizing road use. The future research direction can be to improve the model adaptability by introducing fuzzy logic and machine learning algorithms to consider the impact of unexpected traffic situations and complex environments on the traffic flow, followed by integrating real-time traffic data and utilizing ITS and Telematics to realize real-time response to the signal control strategy. In addition, exploring more efficient optimization algorithms, such as genetic algorithm and particle swarm optimization, can avoid the problem of locally optimal solutions, thus improving the effect of signal configuration. At the same time, attention should also be paid to the coordinated control of multiple intersections to improve the overall traffic smoothness.

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