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Research Article

An Interactive Traffic Signal Optimization Approach with Dynamic Variable Guidance Lane Control

Fei Zhao,[1,2,3] Liping Fu,[1,2,4] Xiaofeng Pan,[1,2] Ming Zhong,[1,2] and Tae J. Kwon[3]

[1]*Intelligent Transportation Systems Research Center, Wuhan University of Technology, Wuhan 430063, China*
[2]*National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan 430063, Hubei, China*
[3]*Department of Civil & Environmental Engineering, Faculty of Engineering, University of Alberta, Canada*
[4]*Department of Civil & Environmental Engineering, University of Waterloo, Canada*

Correspondence should be addressed to Xiaofeng Pan; x.pan@whut.edu.cn

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The purpose of setting up variable guidance lanes is to ease the traffic pressure on lanes with more traffic under the condition of ensuring the traffic capacity of the intersection. This study proposes a bi-level model-interactive relationship between variable guidance lane design and signal control and carry out a case study for a road in Wuhan, China. The design plan for the goal, combined with the design plan of the variable guidance lane, optimizes the signal timing plan of the intersection. A real case is modeled in VISSIM to simulate the design scheme of variable guidance lanes to verify the reliability and effectiveness of the bi-level model. The results showed that the average vehicle delay at the intersection was reduced by 20.65% after the bi-level model was optimized. The average error between model calculation results and simulation results is 9.88%. Moreover, the influencing factors of the proposed model are also carried out. The results show that when the traffic flow is greater than 1,000 pcu/h, the optimization effect of the model is more significant. When the traffic capacity gradually increases, the average vehicle delay calculated by the model is smaller. The design scheme and signal timing scheme proposed by the bi-level model can ensure the overall traffic efficiency of the intersection, improve the traffic efficiency of the traffic-stressed lanes, and further promote the space-time resource utilization of the intersection, optimize the space-time resources of the road network, and provide a scientific basis and new ideas and methods.

1. Introduction

Traffic congestion is a traditional but lasting issue in front of transportation community. After the accumulation of knowledge, it is agreed that traffic congestion is actually related to various factors, such as inappropriate signal timing design in intersections or unlimited growth of car ownership. Recently, there is a phenomenon that traffic congestion has spread from large cities to small- and medium-sized cities, which is specifically significant in rapid developing areas or countries. In the rapid urbanization process of many small- and medium-sized cities, there has been a mismatch between urban layout and the activity of land use, in which often leads to the unbalanced traffic flow of intersections in specific directions, especially during the morning and evening rush hours.

On the other hand, it is widely acknowledged that keeping increasing the number of lanes is an impracticable approach to release the traffic pressure due to the limited land resources and potential travel demand variation. Meanwhile, it is also acknowledged that extending the traffic phases of signal lights without limits is also unbearable for drivers. For intersections, the signal control scheme can optimize the dynamic distribution of time resources;

however, it is often constrained by the fixed space resource. When the traffic demand changes, there may be a mismatch between the traffic demand and lane function setting, resulting in the imbalance of lane utilization at intersections, especially in peak hours, which often causes unnecessary traffic congestion. In this case, even if the signal control timing has been optimized, the corresponding improvement is still very limited. Therefore, the dynamic distribution of lane function provides conditions for further improving the utilization of space-time resources. In this sense, setting up variable guidance lanes at intersections becomes attractive, which could effectively combine signal timing and entrance lane functions to improve the utilization of time and space resources simultaneously.

This current paper tries to contribute studies about traffic congestion considering variable guidance lane as well as signal timing designs. Variable guidance lane refers to a lane whose traffic turn direction is changeable (normally it is changeable between left-turn and straight lanes) to satisfy the various traffic volumes [1]. Variable guidance lane is combined with the actual traffic flow characteristics, which makes the traffic direction of one or several lanes change with the variation of traffic flow. One thing should be noted is that the variable guidance lane is different from the tidal lane. The tidal lane can dissipate the traffic congestion in the main direction as soon as possible by using the opposite lane, which is used to solve the unbalanced problem of the opposite traffic flow, while the variable guidance lane is used to solve the unbalanced problem of different turning directions in the same entrance.

The variable guidance lane is to alleviate the uneven distribution of traffic flow in each direction at the entrance of the intersection, especially there is large gap of traffic volume between going straight and turning left direction, and this kind of lane that changes the driving direction of the vehicle is set at the entrance of the intersection. The setting and opening conditions of the lane are generally various in the different periods of a day. In the last century, some studies on variable lanes were carried out, and variable lane traffic management methods were proposed, which have been widely used to solve the problem of imbalanced traffic flow during daily commuting peaks [2].

This study aims to explore the interactive relationship between variable guide lane design and signal control by establishing a dynamic bi-level optimization model in order to mutually match between lane function setting and signal control and to improve the operation efficiency of the whole road network. Based on the above considerations, this study tries to contribute to the literature of traffic signal control by studying single intersection signal control and setting of variable guidance lance together. To this end, a signal timing strategy with the existence of dynamic variable guidance lanes is development through a bi-level model where the upper level is the design plan of dynamic variable guidance lanes and the lower level refers to an interactive traffic signal optimization model for single interaction (e.g., cycle length, green time). Using this proposed approach, we can extend the problem to combine both time and space, improving the efficient utilization of temporal and spatial resources, which can be treated the traffic demand in different time periods flexibly.

The remainder of the paper is organized as follows. Section 2 provides a literature review related to variable guidance lanes and signal control optimization. Section 3 briefly introduces the research objects and research methods. Section 4 presents the results of model and simulation. Section 5 is sensitivity analysis. The last section summarizes the paper.

2. Literature Review

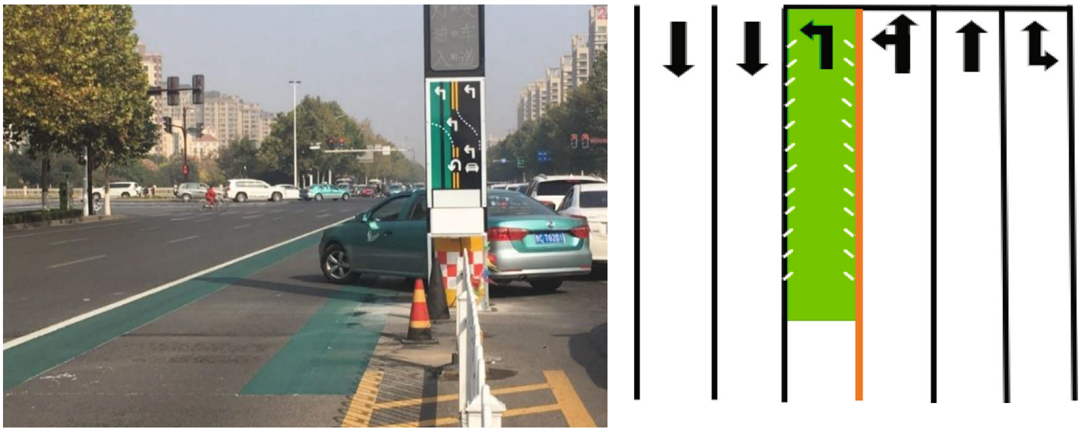
2.1. Variable Guidance Lane and Its History. It is acknowledged that the traffic flow fluctuates in different periods of time of a day. In a certain period (e.g., peak hour), there would be a traffic peak in certain flow directions, which leads to the uneven distribution of road traffic resources and forms a queue phenomenon. Therefore, in order to alleviate the pressure of congestion, practically a variable lane is normally considered during peak hours, and the function of the lane can be changed at different times.

The variable guidance lane is a lane whose movement direction of the vehicles can be changed according to the direction of dominated traffic flow. Normally, variable guidance lanes are adopted to deal with traffic congestion and the phenomenon caused by the separation of work and residence locations (see Figure 1 as an instance). In the last century, some researchers [3, 4] have carried out studies on variable guidance lanes and proposed corresponding traffic management methods, which have been used later and are mainly used to solve the problem of unbalanced traffic flow during a certain time period (e.g., morning peak hour), and to deal with influences of special important events, such as emergency evacuation, road construction, and particular traffic management.

Variable lanes can be divided into two categories according to applicable objects: reversible lanes (see Figure 1) and variable guidance lanes (see Figure 2). The former indicates that a lane of the opposite exit lane is used as the left-turn lane of the entrance lane during different periods. It is generally used to solve the problem of large left-turn traffic volume and improve the utilization rate of road resources. The latter indicates a lane that can change the vehicle turn direction of an interaction entrance at different periods (e.g., from going straight to turn left). This research mainly focuses on variable guidance lane at intersections.

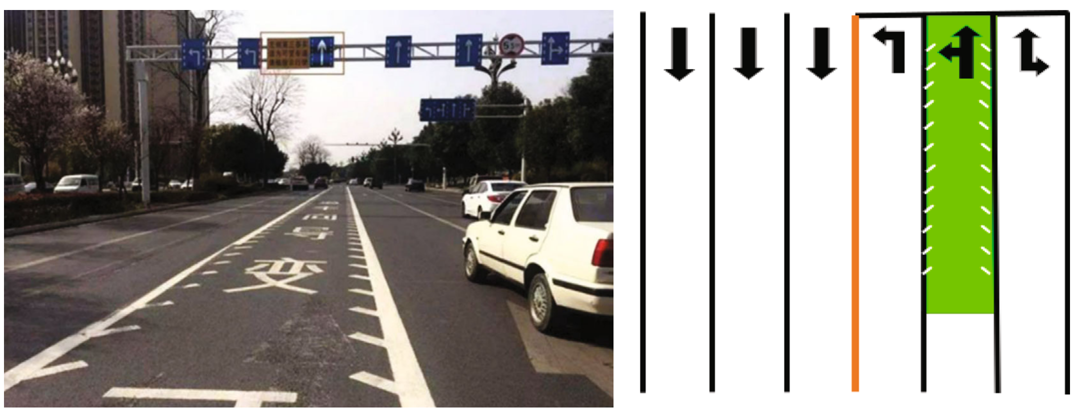
In the design of traffic channelization, in addition to turning left, going straight, turning right, and exclusive lanes, variable guidance lanes are often used. The variable guidance lane here refers to a traffic organization that changes the direction of traffic flow on certain lanes at different times [5]. Its characteristics are as follows: ① the left and straight traffic volume are not balanced; ② it changes with actual traffic flow; and ③ the variable number of lanes can be set according to the actual traffic flow.

In the literature, a series of optimization models have been developed and tested for variable lanes. Zhou [2] introduced the intelligent dynamic optimization model of the variable lane control system used in the George Massey



(a) (b)

Figure 1: Reversible lane.



(a) (b)

Figure 2: Variable guidance lane.

tunnel in southern Vancouver, and developed a program of the variable lane system that can more accurately estimate real-time traffic demand. Urbina [6] conducted research on emergency evacuation plans using variable lane technology in various states in the USA, focusing on the use of variable lane flow and the role of intelligent transportation systems in emergency evacuation plans. Tuydes and Ziliaskopoulos [7] developed a method for the lack of support of large-scaledecision-making tools in the current use of variable lanes in the road network. Stephen [8] conducted a study on the emergency management of evacuation in Charleston, South Carolina, when the hurricane came, and the results showed that delays during evacuating were significantly reduced after the implementation of variable lanes and the installation of new ramps.

In order to increase the road capacity and optimize the road network configuration, Afandizadeh [9] developed a road network optimization model, and the upper level problem is to minimize the total travel time of network users, while the lower level is a traffic assignment model. Nassiri [10] studied the real-time adjustment technology of variable lane. The offline scheme is used to adjust the variable lane through a logit model, and then, the lane direction is adjusted in real time. Turnquist [11] built an evacuation network optimization model based on variable lanes by integrating the strategy of eliminating conflicts between variable lanes and intersections. Based on the developments in automobile technology, Hausknecht [12] proposed the use of traffic sensors to record traffic conditions in real time, and then transmit the data to the traffic management department, which changes the direction of the road lanes in real time according to changes in traffic flow. The setting conditions of variable lanes are determined by analyzing the characteristics of traffic volume of one day [13]. Punith [14] analyzed the vehicle composition of urban arterial roads under mixed traffic conditions, developed a microscopic simulation model to evaluate the operation efficiency of variable lanes, and analyzed the impact of variable lanes on road capacity. Lígia [15] studied variable lanes in an autonomous vehicle context and used mixed integer nonlinear mathematical models to design a variable lane network and assign traffic flow. Song [16] provided a comprehensive overview of the state-of-the-art research on the surrounding vehicles' lane change maneuver prediction and detection. First, various driver behavior modeling and classification methods were reviewed and analyzed. Next, the primary sensing

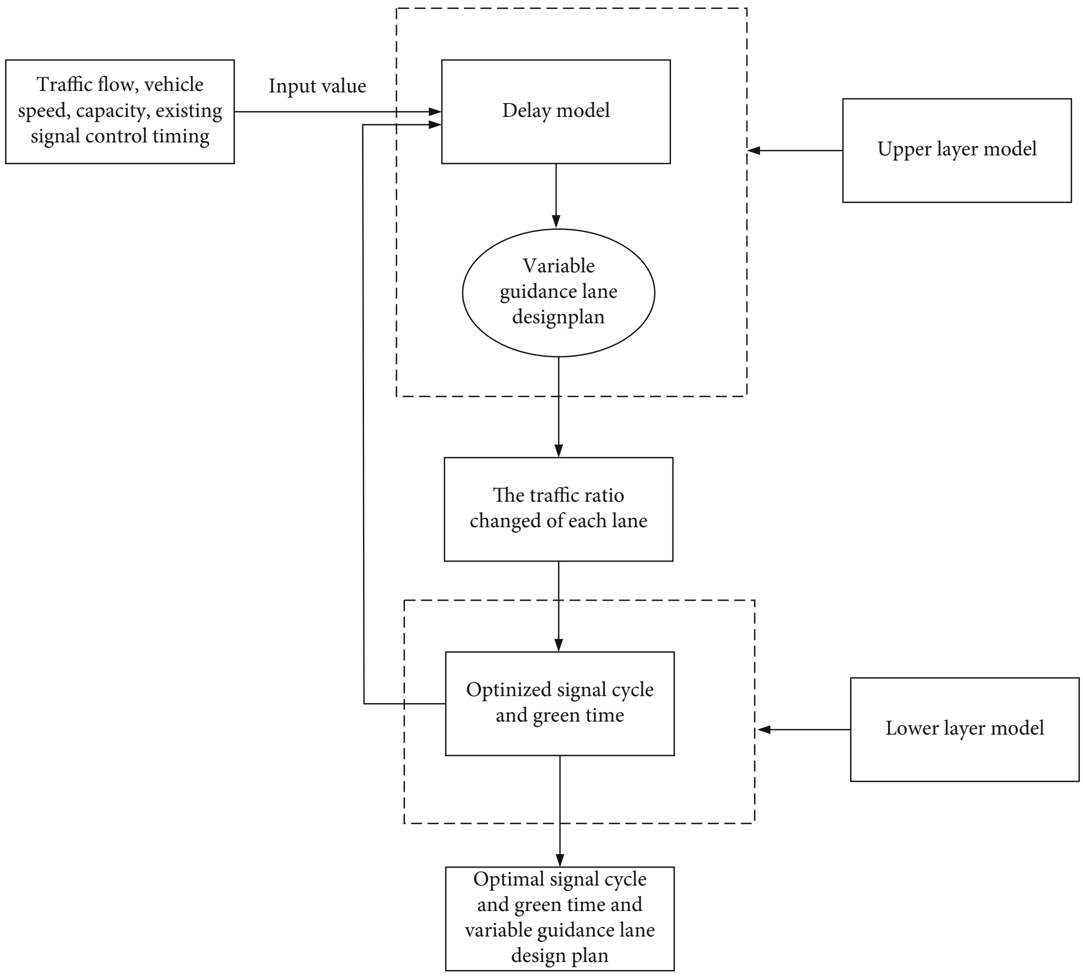


Figure 3: Detailed description of the model framework.

devices equipped on intelligent vehicles, and their impacts on lane change inference systems were discussed.

2.2. Research on Coordination of Lanes and Signal Timing at Intersections. The setting of variable lanes at intersections makes full use of the space resources of the entrance lanes and avoids the insufficient use of certain lanes during peak hours. From the middle of last century, transportation community has made many achievements in this topic. Webster [17], one of the first seminal studies about signal timing, took delay as a signal timing optimization target and proposed an intersection optimization model. After that, many researchers have applied Webster's delay timing method and make their own improvements. At this stage, signal timing mostly adopts multiobjective optimization models. Arthur [3] innovatively proposed a distributed signal control model to achieve the dynamic distribution of lane functions. Harvey [4] introduced the application of dynamic lane management in Houston, USA, and the distributed system that controls lane function dynamic signage. However, this study did not involve specific methods of dynamic lane management. William [18] established a hybrid linear integer model that optimizes the combination of lane functions and signal phases, but did not consider the dynamic switching of lane functions. Wolshon [19, 20] introduced the application of variable lane technology in the USA and pointed out that there is also a lack of operational variable lane design standards in the USA. Bade [21] designed a 3 km long variable guidance lane system in the Salt Lake City area. It was coordinated and controlled by traffic signals. It was also suitable for peak hour and special events and emergency traffic situation.

Wong [1] proposed an optimization model based on lane turn directions, aiming at maximum traffic capacity, minimum cycle length and minimum delay at intersections, using heuristic algorithms and case analysis to verify the feasibility of the model. Xuan [22] designed a presignal system and set the length of the waiting area reasonably, and the traffic capacity of the intersection can be significantly increased. Fu [23] used neural network control method to conduct the adaptive signal control method of lane change under dynamic flow based on actual traffic data. Zhao [24] demonstrated the application of microsimulation software in presignal-controlled intersections. Tian [25] proposed a traffic organization method of setting variable lanes at intersection exits. Zhao [26] proposed a special left-turn exit lane design algorithm for the large left-turn traffic flow. The intersections with left-turn exit lane were redesigned, and the signal control timing scheme was optimized. Dayi et al. [27] analyzed the main traffic flow according to the unbalance coefficient. A half-cycle green wave co-optimization strategy is proposed based on the characteristics of major traffic flows. Yi [28] proposed a traffic technology for changing lanes and turning functions within a single signal cycle. Alhajyaseen [29] developed a model that integrates the optimization of space allocation (dynamic lane grouping) with the optimization of signal timing parameters for the whole intersection in order to improve its mobility. Lee [30] developed a mathematical framework to estimate lane-based incremental queue accumulations with group-based variables and a predictive model of lane-based control delay. The objective is to establish the rolling horizon approach to lane-based control delay for group-based optimization of signal timings in adaptive traffic control systems. Khaled [31] proposed a comprehensive optimization model of time and space resources for an entrance lane based on the mutual restriction between dynamic lane allocation and travel time allocation. Yan [32] proposed a network-level multiband signal coordination (NMBSC) scheme to provide progression bands for major traffic streams extracted from vehicle trajectory data in urban road networks. A mixed-integer linear programming (MILP) formulation was proposed. Yao [33] proposed a new arterial coordination control model. Sum of the delays of all the sampled trajectories ever travelling on the mainline of the arterial is selected to be the optimization objective. Wu [34] conducted an operational performance analysis of the contraflow left-turn lane (CLL) design considering the influence of the upstream signalized intersection. An empirical optimization method was proposed to minimize the control delay by optimizing the length of contraflow lanes and the offset between adjacent intersections. Guo [35] developed a systematic method for determining the length of contraflow left-turn lane (CLL) and the signal timing plan for implementing CLL at signalized intersections.

As demonstrated in the literature review, signal control is still a popular topic of research. In the signal control strategy, the research objectives include minimization of vehicle delay and maximization of intersection capacity. In terms of variable guidance lanes, many existing studies aim to improve the performance of each individual intersection. Several studies have proposed different signal control optimization models for variable guidance lanes, which normally aim at the minimization of vehicle delay or queue length and the maximization of interaction capacity.

Nevertheless, there are significant limitations in the previous studies. First, the premise of the model is that the middle lane of each entrance at intersection can be variable guidance lane, rather than it can be set at only single entrance at a certain intersection depending on the manager experience. Second, although the topics of signal control and variable guidance lanes are of interest, the relationship between actually is not fully investigated.

2.3. Model of Queuing Length and Delay at Intersection. In the past few years, a number of lane and signal coordination strategy were conducted to demonstrate that this optimization could improve traffic mobility and reduce traffic delay. However, there are various optimization models based on microtraffic operation. Ahn [36] proposed a main road network signal control model that takes maximum capacity and control queue length to prevent backflow as the control objectives. However, this study only considers one-way optimal control. Lieberman [37] proposed a supersaturated real-time control model based on mixed integer linear planning, which takes maximum traffic capacity at intersections, effective use of lane space and service level as the optimization objective. Ban [38] used the travel time and dynamics model of the sampled vehicle to estimate the delay parameters of the signalized intersection. Cheng [39] used sampled vehicle trajectories and analyzed the estimation method of periodic queue length with the help of vehicle dynamics model. Hao [40] applied traffic flow theory to reconstruct the trajectory of vehicles at the entrance and extracted the queuing at signalized intersections. Wang [41] used the LWR model to obtain the queue length under the floating car and coil settings at the signalized intersection. Li [42] applied dynamic programming theory to establish a signal control optimization model for over-saturated intersections and deduced the average queue length state transition equation and the controller state transition equation. Walraevens [43] analyzes the delay experienced in a discrete-time priority queue with a train-arrival process. The lengths of the trains are traffic-class-dependent and generally distributed. Comert [44] presents a method for queue length estimation from connected vehicles equipped with range measurement sensors. Li [45] proposed a multiobjective optimization method for signal control design at intersections in urban traffic network. The cell transmission model was employed for macroscopic simulation of the traffic. Additional rules were introduced to model different route choices from origins to destinations. A multiobjective optimization problem (MOP) was formulated considering four measures in network traffic performance. Luca [46] proposed a network signal control method using daily traffic flows. Regarding the online traffic control, a hybrid approach combining the interacting-intersection optimization (i.e., optimizing the parameters such as the green time, the offsets and the phase sequences) and the link metering control was considered. The paper proposes a highly efficient approach traffic flow model to capture C-segment spillovers [47]. An optimization problem that takes C-segment spillovers into account is formulated as a nonlinear programming model, and it is solved by using a Markov chain Monte Carlo method.

In summary, many exiting studies have proposed different vehicle delay optimization models, which normally aim at the minimization of queue length or maximum traffic capacity at intersections, effective use of lane space and service level as the optimization objective. Although several studies were conducted into signal control optimization based on delay and queue length model, the signal control timings were designed for stationary sensors and detectors. And there is no mention of the application effect and feedback after using the optimized model.

However, there are two issues in those studies: (1) the specific setting of the variable guidance lane at an intersection and the period of changing driving direction have been fixed; (2) the optimization of signal cycle and phase green time does not consider the dynamic interaction with the variable guidance lane. To address the above defects, this paper puts forward a bi-level model considering the interactive relationship between variable guidance lane designs and signal timing. More specifically, the proposed model consists of three steps, and the total vehicle delay at the intersection is calculated based on the real-time queue length firstly. Next, the upper level model is proposed to calculate the optimal design scheme of variable guidance lane based on the minimum vehicle delay at an intersection. Finally, the signal cycle and green time of each phase are optimized based on the setting scheme of variable guidance.

3. Assumption

The turn direction of a lane in an entrance at an intersection is no longer just fixed as left-turn or go straight as usual. On the contrary, it depends on the real traffic volumes, so that the lanes can be fully utilized to improve the traffic capacity of the intersection [48]. Usually, the specific mark of the variable guidance lane is that there are multiple diagonal lines on the inside of the lane on the ground, and the corresponding arrow on the sign above the lane is the variable guidance arrow (Figure 2). The conditions for setting a variable guidance lane include as follows:

3.1. Intersection Channelization Requirements. The entrance of the interaction where the variable guidance lane is to be set up must have enough lanes to ensure that the straight-moving, right-turning, and left-turning vehicles can be released, and the turn directions of variable guidance lane can be changed. Otherwise, if the traffic volume of the entrance is large and the number of lanes is insufficient, setting a variable guidance lane will seriously prolong the delay of vehicles in other phases, thereby causing a negative impact. Under normal circumstances, if right-turning vehicles are released in advance through channelization or a straight-right lane is set up, the number of lanes for the entrance lane shall be at least 3, and if there is a dedicated right-turn lane, the number of lanes for the entrance lane shall be at least 4 in order to ensure the normal flow of traffic in all directions.

In addition, the entrance needs to have a dedicated left-turn lane for normal left-turn traffic. When the variable guidance lane changes its direction, it is necessary to ensure that at least one left-turn lane exists for left-turn vehicles.

3.2. Signal Timing Requirements. In addition to the channelization requirements, the setting of variable guidance lanes also has the following requirements for intersection signal timing:

(a) The entrance of signalized intersection has at least two phases

(b) There must be a left-turn dedicated phase to control left-turning vehicles

4. A Bi-Level Model

4.1. Model Description. In order to study the interaction between the variable guidance lane design and signal control timing, a bi-level model is established. Figure 3 shows the framework of the proposed bi-level model. The upper level model is a variable guidance lane design model with the minimum average vehicles delay (based on 2.3 section). The output of upper level model is the driving direction (left-turn or straight-move) of variable guidance lanes. The lower level model calculates the optimal signal cycle, and finally, the green time of each phase is calculated. Since the result of the upper level model will affect signal control timing of the lower level, the interaction between the two can improve the dynamic optimization of time and space resources.

In detail, the model first combines actual traffic flow data to determine the direction of variable guidance lanes. In this sense, the waiting time of left-turning traffic flow, straight-moving traffic flow at the stop line and the number of stops could be reduced. Finally, according to the design of variable guidance lanes, the model calculates the optimal signal control cycle and the green light time of each phase. The aim of the bi-level model is threefold: first, the vehicle delays are calculated based on the queuing length; second, the optimal design of the variable guidance lanes is determined; and finally, the optimal signal timing scheme for the intersection is calculated.

4.2. Objective Function. The traffic efficiency of each lane affects the service level of the entire intersection, so the objective function of the bi-level model is minimizing the average delay of cars in the k lane of the j entrance at the intersection D_{jk}, as shown in

$$\min \sum_j \sum_k D_{jk}. \tag{1}$$

The average vehicle delay D_{jk} is represented by the difference of the actual travel time and the theoretical travel time of a link entering an intersection, as shown in

$$D_{jk} = \frac{N_{jk}}{Q_{jk}} - \frac{N_{jk} \cdot J}{v_{jk}}, \tag{2}$$

where N_{jk} is the longest queue length in a signal cycle (unit: pcu); Q_{jk} is the capacity of the k lane of the j entrance at the intersection (unit: pcu/h); J is the length of each vehicle (unit: m); and v_{jk} is the average speed of vehicles in the k lane of the j entrance at the intersection (unit: m/s).

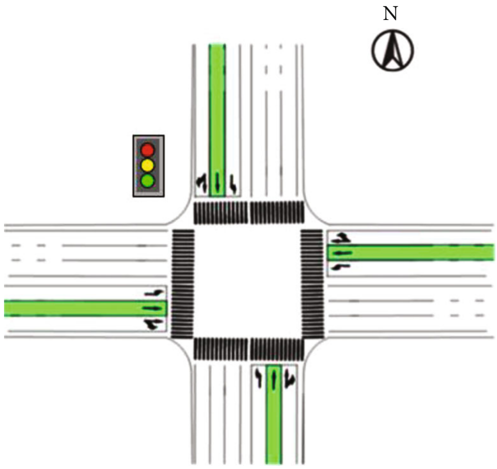


Figure 4: The distribution of each lane of the entrance lane of the intersection.

The average vehicle delay in this study is computed based on the length of the vehicle queue. The N_{jk} is the longest queue length in one signal cycle, and it is the queue length of vehicles waiting behind the parking line. The queue length N_{jk} includes the length of the uniform phase queue N_u and the length of the over-saturated queue N_0, and the length of each vehicle is J (m), so the actual length of the vehicles in the queue is $(N_u + N_0)^* J\,(m)$, and the average vehicle speed is v (m/s). The time is $(N_u + N_0)^* J/v\,(s)$, so the actual number of queued vehicles is calculated as shown in

$$N_{jk} = \frac{(N_u + N_o)\cdot q_{jk}}{1-(J/v_{jk})}, \tag{3}$$

where N_u is the uniform phase queue length (unit: pcu); N_0 is the over-saturated queue length (unit: pcu); and q_{jk} is the arrival rate of vehicles in the k lane of the j entrance at intersection (unit: pcu/s).

Formula (4) is the calculation method of the uniform phase queue length and depends on different saturation conditions:

$$N_u = \begin{cases} q_{jk}\times r_{ejk}, & x_{jk} < 1 \\ Q_{jk}\times r_{ejk}, & x_{jk}\ge 1 \end{cases} \tag{4}$$

where r_{ejk} is red light time of the k lane of the j entrance at intersection (unit: s) and x_{jk} is saturation of the k lane of the j entrance at intersection.

Formula (5) is the calculation method of the over-saturated queue length, which also depends on different saturation conditions. It is necessary to compare saturation with the initial saturation. Formula (6) is the calculation formula of initial saturation x_0:

$$N_o = \begin{cases} 0, & x_{jk}\le x_0 \\ \dfrac{Q_{jk}T}{4}\left[(x_{jk}-1)+\sqrt{(x_{jk}-1)^2+\dfrac{12(x_{jk}-x_0)}{Q_{jk}T}}\right], & x_{jk} > x_0 \end{cases} \tag{5}$$

$$x_0 = 0.67 + \left(\frac{S_{jk}g_{ejk}}{600}\right), \tag{6}$$

where T is the study period (unit: s); x_{jk} is saturation; x_0 is initial saturation of the over-saturated queue length; S_{jk} is saturated flow rate of the k lane of the j entrance at intersection (unit: pcu/s); and g_{ejk} is green light time of the k lane of the j entrance at intersection (unit: s).

Due to the different saturation x_{jk}, the calculation of the vehicle queue length in lanes varies:

(1) When $x_{jk}\le x_0\le 1$, combining with Formulas (4)–(6), the vehicle queue length is calculated as shown in Formula (7). The average delay is calculated as shown in

$$N_{jk} = q_{jk}\cdot r_{ejk}, \tag{7}$$

$$D_{jk} = \frac{{q_{jk}}^2\cdot r_{ejk}\cdot\left((1/Q_{jk})-(J/v_{jk})\right)}{\left(1-(J/v_{jk})\right)\cdot q_{jk}\cdot C}, \tag{8}$$

where C is the signal cycle of the intersection (unit: s).

(2) When $x_0\le x_{jk}\le 1$, combining with Formulas (4)–(6), the length of the vehicle queue is calculated as shown in Formula (9), and the average delay of vehicles is calculated as shown in

$$N_{jk} = \frac{q_{jk}\cdot r_{ejk} + (Q_{jk}T/4)\left[(x_{jk}-1)+\sqrt{(x_{jk}-1)^2+\left(12(x_{jk}-x_0)/Q_{jk}T\right)}\right]}{1-(J/v_{jk})}\cdot q_{jk}, \tag{9}$$

$$D_{jk} = \frac{q_{jk}\cdot r_{ejk} + (Q_{jk}T/4)\left[(x_{jk}-1)+\sqrt{(x_{jk}-1)^2+\left(12(x_{jk}-x_0)/Q_{jk}T\right)}\right]\cdot q_{ijk}\left((1/Q_{jk})-(J/v_{jk})\right)}{\left(1-(J/v_{jk})\right)\cdot q_{jk}\cdot C}. \tag{10}$$

(3) When $x_{jk} > x_0 > 1$, combining Formulas (4)–(6), the vehicle queue length is calculated as shown in Formula (11), and the average vehicle delay is calculated as shown in formula (12):

Table 1: Intersection signal timing scheme.

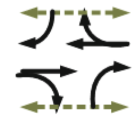
	Phase 1	Phase 2	Phase 3	Phase 4	Cycle
Phase					——
Time (s)	26	34	30	28	126

Table 2: Traffic flow data acquisition.

ID_Loop data	ID_Traffic source	ID_ link	ID_ lane	Create time	Vehicle count	Speed
145194829	LP100240_1	10088	1	2020-10-22 06 : 30 : 00	5	43
145207546	LP100240_1	10088	1	2020-10-22 06 : 50 : 00	10	43
145210726	LP100240_1	10088	1	2020-10-22 06 : 55 : 00	12	54
145213906	LP100240_1	10088	1	2020-10-22 07 : 00 : 00	10	90
145217086	LP100240_1	10088	1	2020-10-22 07 : 05 : 00	18	82
145220266	LP100240_1	10088	1	2020-10-22 07 : 10 : 00	27	61
145226626	LP100240_1	10088	1	2020-10-22 07 : 20 : 00	43	43
145229806	LP100240_1	10088	1	2020-10-22 07 : 25 : 00	25	57
145232983	LP100240_1	10088	1	2020-10-22 07 : 30 : 00	25	57
145236148	LP100240_1	10088	1	2020-10-22 07 : 35 : 00	22	50
145242494	LP100240_1	10068	2	2020-10-22 07 : 45 : 00	36	54
145245671	LP100240_1	10068	2	2020-10-22 07 : 50 : 00	23	68
145248848	LP100240_1	10068	2	2020-10-22 07 : 55 : 00	39	39
145255202	LP100240_1	10068	2	2020-10-22 08 : 05 : 00	36	46
145261536	LP100240_1	10068	2	2020-10-22 08 : 15 : 00	31	7
145271067	LP100240_1	10068	2	2020-10-22 08 : 30 : 00	30	43
145274244	LP100240_1	10068	3	2020-10-22 08 : 35 : 00	22	64
145277421	LP100240_1	10068	3	2020-10-22 08 : 40 : 00	18	82
145280598	LP100240_1	10068	3	2020-10-22 08 : 45 : 00	20	90
145286948	LP100240_1	10068	3	2020-10-22 08 : 55 : 00	15	68
145289776	LP100240_1	10068	3	2020-10-22 09 : 00 : 00	14	64
145292745	LP100240_1	10088	1	2020-10-22 09 : 05 : 00	15	68
145295922	LP100240_1	10088	1	2020-10-22 09 : 10 : 00	15	68
145299099	LP100240_1	10088	1	2020-10-22 09 : 15 : 00	12	54
145302276	LP100240_1	10088	1	2020-10-22 09 : 20 : 00	15	68
145305453	LP100240_1	10088	1	2020-10-22 09 : 25 : 00	23	68
145308605	LP100240_1	10088	1	2020-10-22 09 : 30 : 00	15	43
145311757	LP100240_1	10088	1	2020-10-22 09 : 35 : 00	14	64
145314909	LP100240_1	10088	1	2020-10-22 09 : 40 : 00	13	57

$$N_{jk} = \frac{Q_{jk} \cdot r_{ejk} + \left(Q_{jk} T/4\right)\left[\left(x_{jk} - 1\right) + \sqrt{\left(x_{jk} - 1\right)^2 + \left(12\left(x_{jk} - x_0\right)/Q_{jk} T\right)}\right]}{1 - \left(J/v_{jk}\right)} \cdot q_{jk}, \quad (11)$$

$$D_{jk} = \frac{Q_{jk} \cdot r_{ejk} + \left(Q_{jk} T/4\right)\left[\left(x_{jk} - 1\right) + \sqrt{\left(x_{jk} - 1\right)^2 + \left(12\left(x_{jk} - x_0\right)/Q_{jk} T\right)}\right] \cdot q_{jk}\left(\left(1/Q_{jk}\right) - \left(J/v_{jk}\right)\right)}{\left(1 - \left(J/v_{jk}\right)\right) \cdot q_{jk} \cdot C}. \quad (12)$$

Due to the setting of the variable guidance lane, the saturation of each turn direction of each entrance lane on the corresponding lane will change accordingly. The specific calculation is as follows:

$$x_{j-l} = \frac{q_{j-l}}{Q_{j-l}\left(1 + d_j\right)}, \quad (13)$$

$$x_{j-v} = \frac{q_{j-l} \cdot d_j + q_{j-s} \cdot \left(1 - d_j\right)}{2Q_{j-v}}, \quad (14)$$

Table 3: All-day traffic volume of each entrance at the intersection.

Time periods	South (pcu/h)		North (pcu/h)		West (pcu/h)		East (pcu/h)	
	Left	Straight	Left	Straight	Left	Straight	Left	Straight
0 : 00-6 : 00	96	193	207	102	85	175	217	103
6 : 00-9 : 00	270	734	465	595	450	541	276	532
9 : 00-16 : 00	207	425	305	215	240	247	392	247
16 : 00-19 : 00	476	589	283	767	534	386	362	614
19 : 00-0 : 00	150	92	165	97	124	204	139	118

$$x_{j-\mathrm{sr}} = \frac{q_{j-\mathrm{sr}}}{Q_{j-\mathrm{sr}}\left(2-d_j\right)}, \tag{15}$$

where x_{j-l} is the saturation of the left-turn lane of the j entrance at intersection; x_{j-v} is the saturation of the variable guidance lane of the j entrance at intersection; $x_{j-\mathrm{sr}}$ is the saturation of the straight-move and right-turn lane of the j entrance at intersection; q_{j-l} is the actual vehicle arrival rate of the left-turn lane of the j entrance at intersection (unit: pcu/s); q_{j-v} is the actual vehicle arrival rate of the variable guidance lane of the j entrance at intersection (unit: pcu/s); $q_{j-\mathrm{sr}}$ is the actual vehicle arrival rate of the straight and right-turn lane of the j entrance at intersection (unit: pcu/s); Q_{j-l} is the capacity of the left-turn lane of the j entrance at intersection (unit: pcu/s); Q_{j-v} is the capacity of the variable guidance lane of the j entrance at intersection (unit: pcu/s); $Q_{j-\mathrm{sr}}$ is the capacity of the straight and right-turn lane of the j entrance at intersection (unit: pcu/s); and d_j is the number of variable guide lane of the j entrance at intersection.

The capacity of each lane in Formulas (13)–(15) is shown in the following formulas:

$$Q_{j-l} = \frac{S_{j-l}\cdot(C-L)\cdot(y_i/Y)}{C}, \tag{16}$$

$$Q_{j-v} = \frac{S_{j-v}\cdot(C-L)\cdot\left(y_i\cdot\left(1-d_j\right)+y_{i+1}\cdot\left(1+d_j\right)/Y\right)}{C}, \tag{17}$$

$$Q_{j-\mathrm{sr}} = \frac{S_{j-\mathrm{sr}}\cdot(C-L)\cdot(y_{i+1}/Y)}{C}, \tag{18}$$

where S_{j-l} is the saturated flow rate of the left-turn lane of the j entrance at intersection (unit: pcu/s); S_{j-v} is the saturated flow rate of the variable guidance lane of the j entrance at intersection (unit: pcu/s); $S_{j-\mathrm{sr}}$ is the saturated flow rate of the straight-move and right-turn lane of the j entrance at intersection (unit: pcu/s); L is the total lost time of vehicles at intersection (unit: s); y_i is flow ratio of the i phase; and Y is the total flow ratio of the intersection.

The calculation of signal cycle C in Formulas (16)–(18) is shown in the following formulas:

$$C = \frac{1.5L+5}{1-Y}, \quad L = \sum_{i=1}^{n} l_i, \quad Y = \sum_{i=1}^{n} y_i, \tag{19}$$

where l_i is lost time of the i phase (unit: s) and y_i is flow ratio of the i phase.

$$y_i = \max\left\{y_{j-l}, y_{j-v}\right\} \text{or} \max\left\{y_{j-\mathrm{sr}}, y_{j-v}\right\}, \tag{20}$$

where y_{j-l} is the flow ratio of the left-turn lane of the j entrance at intersection; y_{j-v} is the flow ratio of the variable guidance lane of the j entrance at intersection; and $y_{j-\mathrm{sr}}$ is the flow ratio of the straight and right-turn lane of the j entrance at intersection.

The calculation of the flow ratio of each lane in each phase is shown in

$$y_{j-l} = \frac{q_{j-l}}{S_{j-l}\left(1+d_j\right)}, \quad y_{j-v} = \frac{q_{j-l}\cdot d_j + q_{j-s}\cdot\left(1-d_j\right)}{2S_{j-v}}, \quad y_{j-\mathrm{sr}} = \frac{q_{j-\mathrm{sr}}}{S_{j-\mathrm{sr}}\left(2-d_j\right)}. \tag{21}$$

After the model calculates the optimal signal cycle C, the effective green light time of each phase g_{ei} can be calculated according

$$g_{\mathrm{ei}} = (C-L)\times\frac{y_i}{Y}. \tag{22}$$

The assumption of previous research is that driving direction of the variable guidance lane and the period of changing direction have been determined. On this basis, the signal timing is further optimized. This model is different from the previous research methods of variable guidance lane in the following aspects. First, this study assumes that

Table 4: The bi-level model optimization results.

Entrance	South	North	West	East	Cycle(s)
Driving direction of variable guidance lane	d_1	d_2	d_3	d_4	C
0 : 00-6 : 00	0	0	0	0	94
6 : 00-9 : 00	0	1	1	0	136
9 : 00-16 : 00	0	0	0	1	112
16 : 00-19 : 00	1	0	1	1	144
19 : 00-0 : 00	0	0	0	0	104

Note: 0 means straight-move direction, and 1 means left-turn direction.

the middle lane of each entrance lane at the intersection is a variable guidance lane that can change the traffic direction. The minimum intersection delay is selected as the objective function. The upper level model calculated the driving direction of the lane when the delay was the minimum. Second, as the direction of the lane changes, the saturation of the lane and the flow ratio at each phase also change. The signal cycle of the intersection and the green time of each phase will be recalculated by lower level model.

Time resources and space resources interact to improve the dynamic optimization of both. The output results of the bi-level model are the design schemes of the variable guidance lane and the optimal signal timing scheme with the minimum vehicle delay.

5. Scenario

In order to verify the validity of the proposed model, an intersection in Wuhan, China, is selected as the research object, which could be abstracted as Figure 4 shows. The traffic volume in the morning and evening peaks at this intersection is very large. Due to the different nature and functions of the land use, the traffic flow of each turn direction is unevenly distributed. There is a large gap between the traffic flow of left-turning and straight movements. Generally, there will be the following situations: (1) There are many vehicles in the left-turn lane, and the queue length is increasing, while the left-turn phase is the red time. However, there are only a few vehicles in the straight-moving lane, while the straight phase is the green time. This phenomenon results in the waste of straight phase green time. (2) On the contrary, there are fewer vehicles in left-turn lane, while the left phase is green time. But the straight-moving lane is still in red time phase, and straight-moving vehicles will have to wait at the stop line. The increase of the queue length will further affect the service level at the upstream intersection. Therefore, the switching of lane driving direction at this intersection and the optimization of the signal timing scheme seem an effective approach to improving the overall service level of the intersection.

In this study, the four entrances of the intersection are the research objects. Each entrance includes a left-turn lane, a straight-moving lane, and a straight-moving and right-turn shared lane. The middle lane of the entrance is regarded as the variable guidance lane. At the same time, the signal control scheme of the intersection has four phases, which is shown in Table 1. The intersection is signal controlled by four phases, namely, turn left north-south; straight north-south; turn left east-west; and straight-move east-west. The green time of each phases are, respectively, 26 s, 34 s, 30s, and 28 s. The signal cycle is 128 s.

Table 5: Comparison of model result between before and after optimization.

Time periods	Before optimization (s)	After optimization (s)	Reduced average vehicle delays (%)
0 : 00-6 : 00	62.29	50.18	19.44%
6 : 00-9 : 00	127.51	100.05	21.53%
9 : 00-16 : 00	90.24	71.15	21.15%
16 : 00-19 : 00	157.1	125.78	19.93%
19 : 00-0 : 00	76.42	60.03	21.44%
Average			20.70%

In addition to signal timing plan of the intersection, other data needed in the research include traffic flow of each turn, length of entrance lane, vehicle speed, actual length of the vehicle, and the length of the entrance road. The traffic volume can be obtained by the geomagnetic detector. Details can be found in Tables 2 and 3. According to the traffic volume and the characteristics of the traffic flow, this study divides the whole day into five time periods: The time period of 0 : 00-6 : 00 is the free-flow period, during which the average traffic volume is the smallest; 6 : 00-9 : 00 is the morning peak period, during which the traffic flow rises to peak; 9 : 00-16 : 00 is the noon period, and the traffic volume is steady; 16 : 00-19 : 00 is the evening peak during which traffic volume is the largest; and the traffic volume of the period 19 : 00-0 : 00 is steady. Table 3 shows the statistics of travel volume of each entrance lane with different turns in the five periods.

6. Results and Analysis

6.1. Model Results. Table 4 shows the results of the bi-level model. It contains the design plan of variable guidance lane and the optimal signal cycle of intersection. These results are

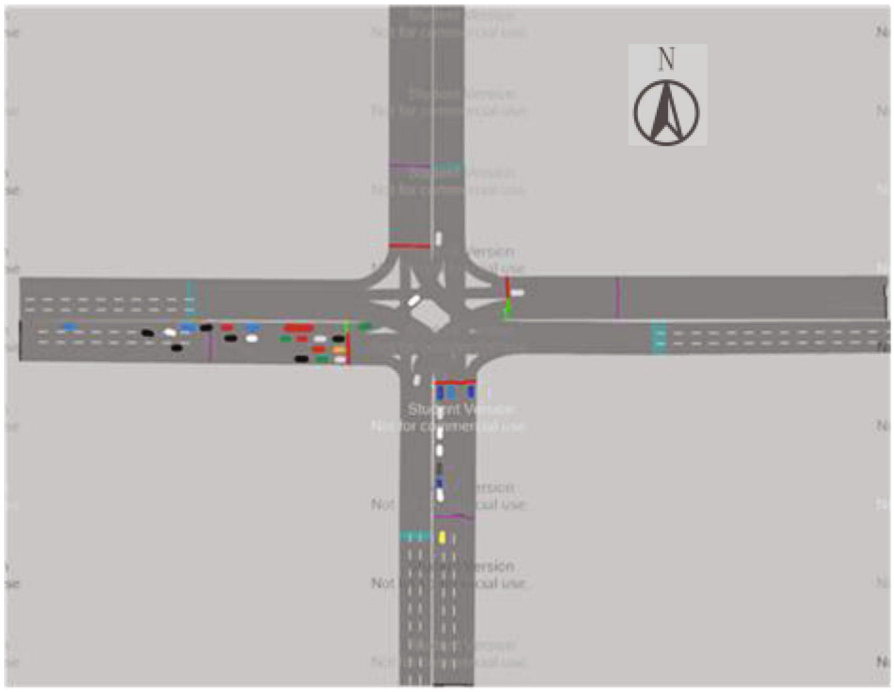


Figure 5: Screenshot of simulation.

Table 6: Simulation result before and after optimization.

Time periods	Comparison	South (s)	North (s)	West (s)	East (s)	Total delay (s)
0 : 00-6 : 00	Before	11.87	13.35	14.48	16.14	55.84
	After	9.98	10.39	12.11	13.17	45.65
6 : 00-9 : 00	Before	29.82	26.86	28.13	30.36	115.17
	After	25.33	19.57	21.3	23.96	90.16
9 : 00-16 : 00	Before	21.42	16.54	20.19	24.23	82.38
	After	17.7	13.27	16.21	18.33	65.51
16 : 00-19 : 00	Before	38.41	38.67	35.75	32.81	145.64
	After	30.95	29.02	28.15	25.66	113.78
19 : 00-0 : 00	Before	14.26	17.21	20.39	17.55	69.41
	After	11.25	14.62	16.23	12.78	54.88

Table 7: Comparison of simulation result between before and after optimization.

Time periods	Before optimization (s)	After optimization (s)	Reduced delays (%)
0 : 00-6 : 00	55.84	45.65	18.24%
6 : 00-9 : 00	115.17	90.16	21.71%
9 : 00-16 : 00	82.38	65.51	20.47%
16 : 00-19 : 00	145.64	113.78	21.87%
19 : 00-0 : 00	69.41	54.88	20.93%
Average			20.65%

calculated by the traffic flow data of each entrance lane with different movements.

It can be seen from Table 4 that due to the changes of traffic volume and the saturation of each driving direction during different time periods, the design plan of variable guidance lane and the optimal signal cycle for each time period output by the bi-level optimization model are also different, where 0 represents the lane driving direction is straight-moving and 1 represents the lane driving direction is left-turning. From 6 : 00 to 9 : 00, due to the increase of left-turning volume during the morning rush hour, the driving direction of the variable guidance lane of the north entrance and west entrance is switched to left, and the best signal cycle is 136 s. From 9 : 00 to 16 : 00, the driving direction of the variable guidance lane of the east entrance is switched to left, and the optimal signal cycle is 112 s. From 16 : 00 to 19 : 00, the variable guidance lane of the south entrance, west entrance, and east entrance are switched to left, and the optimal signal cycle is 144 s. During the other two periods, from 0 : 00 to 6 : 00 and from19 : 00 to 0 : 00, the sizes of traffic volume are smaller. So the driving direction of the variable guidance lane does not need to be switched. The driving direction remains straight-moving, and the optimal signal cycles are 94 s and 104 s, respectively.

The average vehicle delays that calculated by the bi-level model are shown in Table 5. It can be seen that (1) during the period from 0 : 00 to 6 : 00, the average vehicles delay is 62.29 s before optimization. It is dropped to 50.18 s. (2) During the period from 6 : 00 to 9 : 00, the average vehicles delay is from 127.51 s to 100.05 s, and it is reduced by 21.53% at morning peak hours. (3) From 9 : 00 to 16 : 00, the average

Table 8: Comparison of model calculation results and simulation results.

Time periods	Before optimization			After optimization		
	Simulation delay (s)	Model delay (s)	Error (%)	Simulation delay (s)	Model delay (s)	Error (%)
0 : 00-6 : 00	55.84	62.29	11.55%	45.65	50.18	9.92%
6 : 00-9 : 00	115.17	127.51	10.71%	90.16	100.05	10.96%
9 : 00-16 : 00	82.38	90.24	9.54%	65.51	71.15	8.60%
16 : 00-19 : 00	145.64	157.1	7.86%	113.78	125.78	10.54%
19 : 00-0 : 00	69.41	76.42	10.09%	54.88	60.03	9.38%
Average			9.95%			9.88%

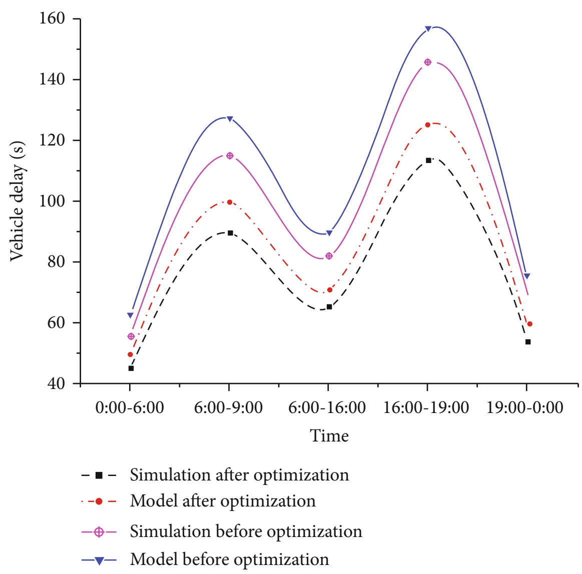


Figure 6: Comparison of model and simulation results.

Table 9: Comparison of the average vehicle delay of 16 schemes of variable guidance lane design.

Type	South	North	West	East	Simulation delay (s)	Model delay (s)
1	0	0	0	0	36.41	39.27
2	1	0	0	0	30.91	35.82
3	1	1	0	0	29.72	33.51
4	1	1	1	0	32.82	38.56
5	1	1	1	1	36.92	40.27
6	0	1	0	0	31.14	37.96
7	0	1	1	0	30.72	35.14
8	0	1	1	1	37.33	41.29
9	1	0	1	0	31.99	38.25
10	1	0	0	1	32.15	37.49
11	1	0	1	1	28.44	31.45
12	1	1	0	1	31.52	34.87
13	0	0	0	1	36.53	39.76
14	0	0	1	0	29.45	36.78
15	0	0	1	1	37.52	40.56
16	0	1	0	1	30.25	33.17

Note: 0 means straight-move direction, and 1 means left-turn direction.

vehicles delay is from 90.24 s to 71.15 s. (4) From 9 : 00 to 16 : 00, the average vehicles delay is from 157.1 s to 125.78 s, and it is reduced by 19.93%. (5) From 19 : 00 to 0 : 00, the average vehicles delay is from 76.42 s to 60.03 s. The average vehicle delay the can be reduced averagely by 20.70%.

To conclude, the proposed the bi-level model exhibits a better performance in reducing vehicle delay to further improve the level of service and operation efficiency of the intersection.

6.2. Simulation Results. To evaluate the effectiveness and accuracy of the proposed bi-level model, simulation is conducted for comparison using VISSIM (see Figure 5) on workstation running Windows 10. It takes 600 s for a simulation cycle. Key parameters used in this simulation are listed as follows:

(1) The lost time for each phase of all intersection is 2 s

(2) The rule of driving is on the right side

(3) The vehicle speed of road is 50 km/h, and the vehicle speed of crossing the intersection is no more than 30 km/h

(4) The vehicle delay is collected every 600 s

Table 6 shows the average vehicle delay of each entrance at the intersection, which are obtained by the VISSIM before optimization based on the traffic flow data (Table 3). It can be seen that the average vehicle delay is increased with increasing of the traffic flow.

The optimization results of the proposed bi-level model for VISSIM simulation are also listed in Table 6. It can be found that after the optimization, the average vehicle delay is still the largest in the morning and evening peak hours, but the average vehicle delay of each entrance lane has been significantly reduced as follows: (1) from 0 : 00 to 6 : 00, the average vehicle delay is reduced from 55.84 s to 45.65 s; (2) from 6 : 00 to 9 : 00, the average vehicle delay is reduced from 115.17 s to 90.16 s; (3) from 9 : 00 to 16 : 00, the average vehicle delay is reduced from 82.38 s to 65.51 s; (4) from 16 : 00 to 19 : 00, the average vehicle delay is reduced from 145.64 s to 113.78 s; and (5) from 19 : 00 to 0 : 00, the average vehicle delay is reduced from 69.41 s to 54.88 s.

Table 7 is a comparison of simulation before and after optimization. It can be seen that under the condition that

Table 10: The impact of traffic volume on vehicle average delay and signal cycle.

Traffic volume (%)	Before optimization vehicle delay (s)	After optimization vehicle delay (s)	Cycle (s)
10%	13.24	11.69	54
15%	14.38	12.35	56
20%	16.82	13.88	58
25%	18.69	15.66	60
30%	21.47	18.67	62
35%	23.75	20.69	63
40%	27.2	23.15	66
45%	29.16	24.9	69
50%	32.34	26.86	70
55%	34.33	28.96	72
60%	38.85	32.18	78
65%	41.70	33.49	80
70%	42.39	35.86	82
75%	44.15	36.59	86
80%	45.66	37.76	88
85%	46.73	38.26	94
90%	47.21	38.8	98
95%	47.79	39.76	102
100%	49.15	40.26	107
105%	50.66	40.8	110
110%	51.73	42.33	112
115%	52.21	43.84	120
120%	54.09	45.65	128
125%	55.25	45.28	130
130%	56.63	46.41	136
135%	57.87	45.59	140
140%	58.16	44.76	142
145%	59.34	44.85	138
150%	59.69	45.02	138

the traffic flow does not change during each time period. After implementing the design of variable guidance lanes from the bi-level interactive model for this intersection, the average delay of vehicles on each entrance is significantly reduced. The average delay of the vehicle decreased by 20.65%. It can be seen that the model can improve the service level and operating efficiency of the intersection.

6.3. Comparison of Model and Simulation Results. In order to further verify the effectiveness and accuracy of the bi-level model, Table 8 shows the comparison the simulation results with the model results. From the comparison in Table 8, it can be seen that under different traffic volume and different proportions of left-turning vehicles and straight-moving vehicles, the error between the results of the bi-level model and the simulation results is small, which are 9.95% and 9.88%, respectively.

The abscissa in Figure 6 is the five time periods of one day, and the ordinate is the total vehicle delay at the intersection. To illustrate the effectiveness and accuracy of the model, the model results and the simulation results before and after optimization are, respectively, compared. In detail, Figure 6 shows as follow. First, the proposed bi-level model can effectively reduce the average delay of each entrance lane at the intersection. Second, the error between the model result and the simulation results is very small before and after the optimization. In five time periods, the errors after the optimization are 9.92% 10.96%, 8.60%, 10.54%, and 9.38%, respectively, which indicates that the bi-level model has good feasibility and accuracy for improving the operation efficiency and service level of the intersection and reducing vehicle delay.

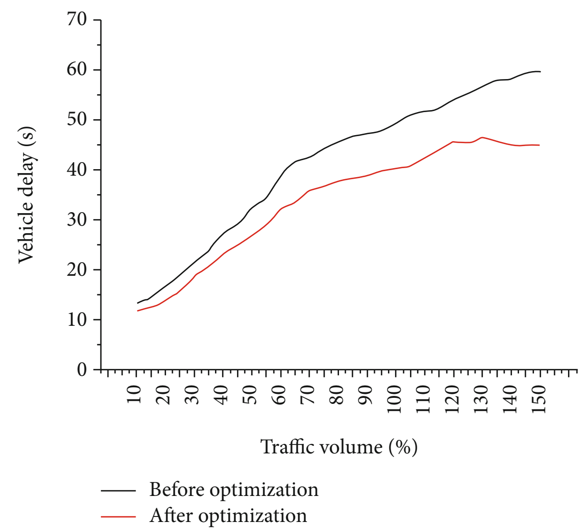


Figure 7: The impact of traffic volume on average vehicle delay.

In order to verify that the optimal variable guidance lane design scheme is given by the bi-level model based on the minimum vehicle delay at intersection, a detailed discussion is given below. In Table 9, the vehicle delays of all the design schemes (16 schemes) of variable guidance lanes at an intersection are summarized and displayed by model calculations and simulations.

The study data is during 16 : 00-19 : 00 from Table 3, and the signal control timing schemes adopted by these 16 schemes are also the same. Table 9 shows the simulation results and model results of these 16 schemes, where 0 means straight movement and 1 means left-turn movement. It can be seen that the first scheme is the initial state (that is the variable guidance lanes are default to straight-move lanes), and the other 15 schemes in each entrance are delayed compared with the initial state, and there are obvious changes. Some schemes (types 5, 8, 13, and 15) are higher than the initial state, and there are also some schemes (types 2, 3, 4, 6, 7, 9, 10, 11, 12, 14, and 16) lower than the initial state. At the same time, it can be found that the scheme with the lowest average vehicle delay (scheme 11) and the calculation result of the bi-level interaction model proposed in this study are consistent (Table 4). Importantly, the design scheme (type 11 in Table 9) variable guidance lane based on the minimum vehicle delay is consistent with the optimal scheme proposed by the bi-level model (from

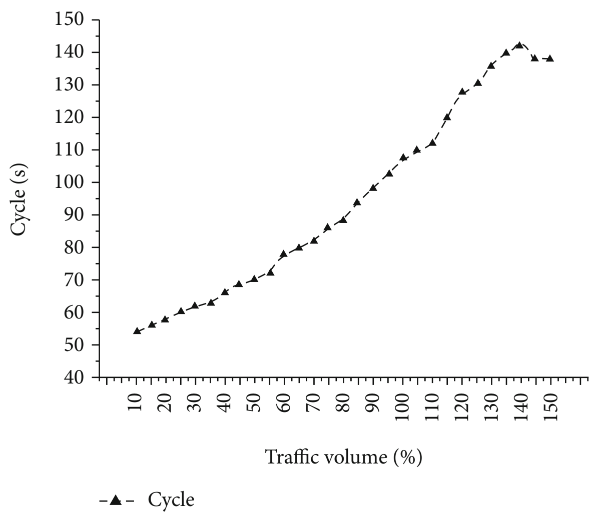


Figure 8: The impact of traffic volume on signal cycle.

16 : 00 to 19 : 00 in Table 4), which further confirms the accuracy of the bi-level model. In addition, Table 9 shows that in terms of different design schemes of variable guidance lanes, the average delays calculated by simulation and model are also different.

7. Sensitivity Analysis

In order to analyze the sensitivity of the traffic volume and capacity to the model, this study analyzes the results of different traffic volumes and road capacity on delays and signal cycles.

First, the traffic volume of each entrance is increased, from 10%, 15%, to 150% of the actual traffic volume. Using VISSIM constructs different simulation scenarios. The bi-level model calculates the vehicle delay and signal control cycle in the case of different traffic flows. The average vehicle delay and the optimal signal cycle before and after optimization in case of different traffic flows are collected by simulation as Table 10 shows.

Figure 7 shows the impact of traffic flow on average vehicle delay. It can be seen that when the flow is not saturated, the average vehicle delay is gradually increasing with the increase of traffic flow; however, when the traffic flow is increased to 130%, the increases of delay is relatively small. At the same time, the average vehicle delay before and after optimization is compared. It is found that the bi-level model proposed in this study can effectively reduce the average vehicle delay, especially when the traffic flow is increased to 60% of the original flow, the conclusion is more significant, which further illustrates the bi-level model has more significant improvement benefits under saturation and over saturation.

Figure 8 reveals the influence of different traffic flows on the optimal signal control cycle obtained by the bi-level model, from which conclusions can be made. First, as the flow increases, the signal control cycle also increases. Second, when the traffic flow is increased to 60% of the original flow, the increase is relatively large. Third, due to the increase of traffic flow, the red time of each phase will also be prolonged, which further causes delays to increase, so the increase is relatively small or even has a downward trend.

Table 11: The impact of capacity on vehicle average delay and signal cycle.

Capacity (pcu/h)	Vehicle delay (s)	Cycle (s)
200	36.33	86
300	35.42	88
400	34.5	90
500	33.34	92
600	32.67	94
700	31.76	96
800	28.84	98
900	26.92	104
1000	25.99	112
1100	24.07	118
1200	22.14	124
1300	21.2	130
1400	23.26	135
1500	26.32	137
1600	29.36	138
1700	32.48	140
1800	33.41	142

Next, the road capacity is also changed from 200, 300, to 1800 (unit:pcu/h). The impact of different road capacity on vehicle delay and signal cycle is analyzed during the analysis period. It can be seen from Table 11 that under the condition that the traffic flow does not change, the greater the capacity of the lane, the smaller the delay. However, as traffic capacity increases, traffic flow will be redistributed, signal timing plans will also change, and average vehicle delays will slowly increase (Figure 9). Figure 9 shows the impact of south entrance middle lane capacity on the signal cycle. It can be found that as the road capacity increases, the signal cycle will increase. But when the capacity is more than 1,400 pcu/h, the lane is saturated or oversaturated. In order to ensure that the average delay of vehicles is minimized in this case, the signal cycle will not increase significantly.

8. Conclusions, Limitations, and Future Research

Variable guidance lanes are an effective solution to improve the traffic capacity of urban road intersections, which can optimize the space-time resources distribution of each lane at the intersection. Therefore, this research aims to improve the utilization of time and space resources at intersections using a bi-level model which analyzes the interactive relationship between designs of the variable guidance lane and the intersection signal timing.

The bi-level model considers the difference of traffic flow in different period, where traffic flow of each turn direction could be unevenness (such as morning peak hour). The

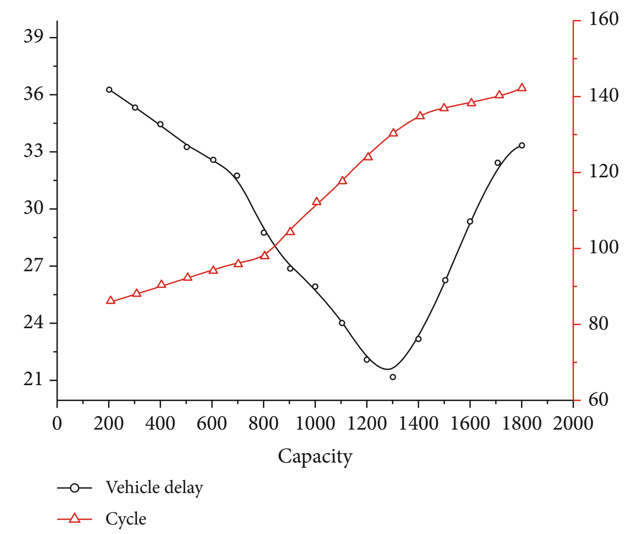


Figure 9: The impact of capacity on signal cycle.

proposed model is very different from the previous method of setting variable guidance lanes regarding the following aspects. First, the premise of the model is that the middle lane of each entrance at a certain intersection can be variable guide lane, rather than it can be set at only single entrance lane. Second, with the objective of minimizing the average vehicle delay, the model answers the question that which direction the variable guidance lanes should be. Third, the optimal the variable guidance lane design scheme of each entrance at the intersection is proposed, and the signal control cycle and the green light time of each phase are optimized. At last, according to the results of the model, this study uses VISSIM to verify the effectiveness of the model. The relationship between the vehicle driving direction of the variable guidance lanes and the signal cycle promotes the dynamic interaction and further improves the dynamic optimization of time and space resources.

Furthermore, a final result analysis is as follows. First, the average vehicle delay at the intersection has been significantly reduced, and the delay be reduced by 20.65%. Second, VISSIM is used to conduct a microscopic traffic simulation to verify the applicability and accuracy of the bi-level model under the same traffic context. The simulation results show that the error of the bi-level model is acceptable (e.g., 9.88% comparing to the results from simulation). Third, all the variable guidance lane schemes are also listed at a certain intersection, and the model and simulation results are compared and analyzed. It is found that the average vehicle delay varies widely under different schemes. The most important is that the average vehicle delay of the optimized design scheme proposed in this study is the minimum delay. Finally, we design some scenarios to analyze the impact of traffic volume and lane capacity on the model. The results show that the average delay and signal cycle calculated by the model are positive with traffic volume. Conversely, the lane capacity is negatively correlated with vehicle average delay, but it is positive with signal control cycle.

Some problems related to the bi-level model need to be further studied and resolved [45, 47]. In particular, the method proposed in this study is based on a single intersection. In practical applications, it may be necessary to collect the traffic flow of the road network. The characteristics of traffic flow at the upstream and downstream intersections are also analyzed. The relationship between the signal control of the network and the variable guidance lane will also be investigated and studied. In addition, the bi-level model proposed in this study is only verified on the entrance lanes of intersections in specific scenarios. At the same time, it is also necessary to use bi-level model on other intersections to verify the optimization effect of the model in different scenarios. As deep learning and artificial intelligence are now becoming more and more practical, they can be trained to capture the relationship between traffic flow of various lane distribution types and vehicle delay for numerous roads simultaneously.

Data Availability

The traffic flow data used to support the findings of this study have not been made available in public because these data relate to personal privacy and there is a data confidentiality agreement with the data provider.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

The authors confirm contribution to the paper as follows: (i) Fei Zhao, Xiaofeng Pan, and Liping Fu have contributed to the study conception and design; (ii) Fei Zhao has contributed to the data collection; (iii) Fei Zhao has contributed to the analysis and interpretation of results. (iv) Fei Zhao, Xiaofeng Pan, Liping Fu, Ming Zhong, and Tae J Kwon have contributed to the preparation and drafting of the manuscript. (v) All authors reviewed the results and approved the final version of the manuscript.

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