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Research Article

Dynamic Allocation Model for Reversible Lanes in the Intelligent Vehicle Infrastructure Cooperative System

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The real-time dynamic control of reversible lanes is an effective measure to alleviate the traffic congestion caused by the directional imbalance of the traffic flow and improve the utilization rate of urban road resources. This paper proposes a dynamic allocation model for reversible lanes for road sections and intersections in the intelligent vehicle infrastructure cooperative system (IVICS). The dynamic lane allocation model for the road sections is constructed based on the Bureau of Public Road (BPR) function, in which the 24 hours of the day are divided into stages, the traffic volume and road impedance of each stage are obtained, and their product is integrated over time. Finally, the plan with the least delay in each stage is selected as the optimal solution. The dynamic lane control model for intersections is built according to the Highway Capacity Manual 2000 (HCM2000) delay model. With the minimum average delay of vehicles at the intersection as the objective function, the average delay of different lane combinations under different traffic conditions is analyzed to find the optimal combination of reversible lanes and ordinary lanes. The model is verified by case analysis and MATLAB calculations. The results show that the reversible lane dynamic control model can effectively allocate road resources and reduce driving delays.

1. Introduction

Unbalanced two-way traffic flow on urban roads causes traffic congestion [1]. Occasional traffic accidents or major event gatherings lead to one-way congestion. It is difficult to use the current reversible lane control method for scheduled road segments to solve this kind of congestion problem.

The study of reversible lanes on road sections is mainly for traffic management and evaluation. Wolshom and Lambert [2] analyzed the implementation cases of various reversible lane schemes, focused on introducing and summarizing the implementation conditions and applicable scope of reversible lanes, identified the effect of setting reversible lanes, and discussed how to solve the drawbacks of setting reversible lanes in practical applications. Meng and Khoo [3] constructed a bilevel programming model based on dynamic lane optimization. The first-layer model was based on the minimum travel time as the objective function, and the second-layer model was the simulation model for selecting the optimal path using the genetic algorithm. They conducted a case study to examine whether the model was feasible. Glickman considered the service demand and reversible lane allocation decision, established a mathematical model based on the minimum vehicle delay and maximum capacity, and applied it to bridges and tunnels [4–7]. Later, they extended the research to adaptive control algorithms and considered the random arrival. Mao et al. [8] proposed a reversible lane switching scheme and a safety control model in IVICS. Analysis through numerical examples showed that the real-time dynamic lane switching mode can effectively reduce vehicle delays. Sun [9] established the objective function of the lane allocation optimization model based on the BPR road resistance function and used MATLAB to calculate the state variables to obtain the optimal plan. The reversible lane allocation schemes at different periods were given, and the allocation model was found to be reasonable. Fu et al. [10–14] proposed an adaptive control method that can dynamically adjust the number of lanes with the real-time traffic flow changes by analyzing the influencing factors of reversible lanes and verified its feasibility through the PARAMICS simulation. Chen and Huo [15] used Shuxi Road in Chengdu as the survey area, worked out the design scheme of reversible lanes by analyzing their traffic characteristics and road conditions, and carried out the effect simulation using software. The experiment showed that the design scheme was used to improve the road service level and had a significant effect. Wu et al. [16, 17] investigated the lane-reservation problem in an existing transportation network for special transport tasks with given deadlines. The objectives were minimizing the total negative impact on normal traffic and maximizing the robustness of the lane-reservation solution. An improved integer linear program solved by a fast and effective quantum-inspired evolutionary algorithm and a biobjective mixed-integer linear program solved by an improved exact-constraint and a cut-and-solve combined method were proposed.

Much research has focused on the investigation of control methods and dynamic control with signals. Wong and Wong [18] proposed an integrated design method of the intersection and signal configuration based on lane optimization, constructed a binary integer nonlinear programming model, and verified its feasibility, safety, and effectiveness. Wang and Deng [19] studied the capacity of the reversible lanes and analyzed the factors to be considered during the introducing of reversible lanes through a two-layer optimization model, such as the intersection signal configuration and lane number allocation. The genetic algorithm was adopted to calculate the capacity of a double-layer network. Hausknecht et al. [20] proposed a reversible lane optimization model under the premise of the continuous improvement of intelligent vehicle infrastructure cooperative system and autonomous driving technology. This model can dynamically adjust the lane direction according to real-time road traffic conditions, and integer linear programming and double-level planning were used to calculate the optimal lane configuration. Experiments were conducted to verify that the introduction of reversible lanes can improve traffic efficiency. Gu [21] investigated and analyzed the attributes of intersection-oriented lanes with unbalanced steering characteristics, proposed conditions suitable for lane function conversion, and then compared and analyzed the average delays of the vehicles under different lane combinations with varying traffic flow conditions. Cao [22] studied the optimal control method of reversible lanes based on the characteristics of the tidal traffic flow. The authors combined three reversible lanes and guided the reversible lanes and signal timing to achieve coordinated control. The research results provide a feasible approach for reversible lane dynamic control. To realize the optimal allocation of space-time resources of reversible lanes at signal intersections, Ding [23] established objective functions and constraints under different levels of phase control and optimized reversible lane sections under various road conditions. Through simulation of the alternative safety evaluation model, the safety of the intersection was compared and analyzed, and the safety impact of the installation of reversible lanes at the intersection was investigated. Yao et al. [24] coordinated the reversible lanes and signal timing of intersections in a coordinated manner, using MATLAB and VISSIM to compare the delays of the ordinary and reversible lanes. The experimental results show that the reversible lanes can improve the efficiency of the intersection traffic and have a positive effect on reducing delays.

There is significant research on the setting of reversible lanes in China, but there are still the following problems: the reversible lane attributes of road sections have not been fully developed, and they are limited to solving the phenomenon of the tidal traffic flow in the morning and evening peak period, which is ineffective for some sudden situations on the road guidance; the domestic reversible lane switching mode basically relies on manual control, which is subjective; and the study of dynamic lane allocation schemes for reversible lanes and intersections is fragmented, making quantitative analysis difficult. The innovation of this article is to realize the dynamic lane allocation of reversible lanes at sections and intersections. The combination scheme of the real-time allocation of lanes according to road traffic conditions can be applied to urban traffic congestion caused by tidal traffic and occasional traffic accidents. The conditions are controlled to ensure the smooth operation of the reversible lanes.

The development of intelligent transportation is an important direction for the transportation industry. Intelligent transportation relies on the comprehensive perception of the roadways and the cooperation between people, vehicles, and roads for information transmission, processing, and optimal decision-making. Tanimoto et al. [25–27] combined traffic flow analysis with game theory to quantify the impact of a driver's cooperative behavior and defect behavior on the traffic flow, introduced a new lane-changing protocol with the support of intelligent transportation systems to improve traffic flow, and then (based on the revised S-NFS model) built a cellular automata model to simulate the propagation of this behavior. The development of 5G technology has made information interaction more efficient, and the future development of reversible lane schemes in the intelligent vehicle infrastructure cooperative system appears positive. The objective of this paper is to discuss the dynamic control strategy of reversible lanes under such a background. The intelligent vehicle infrastructure cooperative system can transmit road traffic information in real time, make reversible lane allocation decisions quickly and safely, and truly realize low-latency and efficient dynamic reversible lane control.

2. Dynamic Lane Allocation Model for Road Sections

2.1. Objective Function. The reversible lanes studied in this paper were built in an intelligent vehicle infrastructure cooperative system, which not only functioned during the morning and evening peak hours, but also enabled real-time operation throughout the day and dynamically adjusted the lane allocation. Suppose that the upstream traffic direction is r and the downstream traffic direction is r'. The capacity of each lane is c, and there are n lanes in each direction of the road section. The capacity of the one-way section is nc. Let i be the number of lanes that could be switched for reversible lanes. When introducing the reversible lanes, the capacity of the lanes in the original direction and in the opposite direction will decrease and increase $\pm ic$. In short, the setting of reversible lanes does not affect the total capacity of the road. The total capacity is still $2nc$. The road impedance BPR function from the American Road Capacity Manual was chosen for the analysis, and we recalibrated the parameters in the formula to adapt them to urban road conditions. The road impedance is the time impedance of a road section, which is shown in the following formula (1) for the upward lane:

$$t_r = t_0\left[1 + \alpha\left(\frac{x_r}{c_r}\right)^{\beta}\right], \tag{1}$$

where t_r represents the actual time required to pass the road section; α and β are parameters that need to be determined by a thorough traffic investigation; t_0 is the free flow travel time on the road segment; x_r is the traffic flow in the direction r of the upward lane, and the unit is pcu/h; and c_r is the capacity in the direction r of the upward lane, and the unit is pcu/h.

The dynamic allocation model constructed in this paper multiplies the road impedance and the traffic volume and integrates them in time to minimize the total impedance of all vehicles traveling in the direction of the upward and downward lanes [28]. When the upward lane direction r is the direction of heavy traffic flow, then ic is added to increase the capacity of heavy traffic direction, while the capacity in the direction of the light traffic decreases correspondingly. When the upward lane direction r is the direction of the light traffic flow, then ic is subtracted from that value.

In a certain period of time, if we sum up the impedance of the upstream traffic direction and downstream traffic direction, then the total impedance of the entire road segment can be obtained. The objective function of the model minimizes the total impedance on the road:

$$\min: \int_{t_1}^{t_2} t_0\left[1 + \alpha\left(x_r/(nc + ic)\right)^{\beta}\right]x_r d_t + \int_{t_1}^{t_2} t_0\left[1 + \alpha\left(x_r'/(nc - ic)\right)^{\beta}\right]x_r' d_t + T_i, \tag{2}$$

where t_1 is the reversible lane opening time, t_2 is the reversible lane closing time, and T_i is the transition time of each stage.

To achieve a real-time changing of the number of reversible lanes according to the real-time traffic volume, a specific period of time is divided into k stages, each stage lasts for h hours, and the optimal number of reversible lanes under each lane allocation combination of each stage is calculated. There are many factors to consider for the transition time T_i between stages. When a certain stage is completed, and the next stage is opened, sufficient emptying time should be reserved to ensure driving safety. The calculation of the clearing time includes the driving away time, the color change time of the road stud light, and the safety reservation time, which is not described in detail here.

The next step involves investigating the traffic volume at each stage and calculating the road impedance at each stage, and then multiplying the two parts and integrating them over time. The equation can be expressed as P_k:

$$P_k = \int_{t_k}^{t_k+h} t_0\left[1 + \alpha\left(x_r/(nc + i_k c)\right)^{\beta}\right]x_r d_t + \int_{t_k}^{t_k+h} t_0\left[1 + \alpha\left(x_r'/(nc - i_k c)\right)^{\beta}\right]x_r' d_t + T_i, \quad 0 \le i_k < n, \tag{3}$$

where t_k represents the start time of the kth stage, i_k represents the number of lanes in the kth stage, P_k represents the state variable of the kth stage, and $W_k(P_k)$ represents the state variable of the kth stage (it is the accumulation of the state variables in the previous stage). The expression of the decision variable $W_k(P_k)$ is shown as follows:

$$W_k(P_k) = \sum_{i=1}^{k-1}\left\{\int_{t_k}^{t_k+h} t_0\left[1 + \alpha\left(x_r/(nc + i_k c)\right)^{\beta}\right]x_r d_t + \int_{t_k}^{t_k+h} t_0\left[1 + \alpha\left(x_r'/(nc - i_k c)\right)^{\beta}\right]x_r' d_t + T_i\right\}. \tag{4}$$

The state transition function refers to the process in which each state is known in the decision-making process, and the previous state is transformed into the next state. Assuming that the state variable P_k of the k^{th} stage and the decision variable $W_k(P_k)$ of this stage are given, the value of the state variable P_{k+1} of the $k^{+1\text{th}}$ stage can also be determined. Therefore, the state transition equation $E_k(W_k, P_k)$ is shown as follows:

$$E_k(W_k, P_k) = P_k + W_k(P_k). \tag{5}$$

2.2. Constraints

2.2.1. Delay Difference (ΔM) Optimization Constraint. ΔM refers to the difference between the average vehicle delays of the road segment between the original lane combination scheme and the adjusted lane combination scheme [29]. To make the optimization effect of the lane combination from the previous stage to the next stage significant, the vehicle's potential safety hazards due to frequent lane changes must be considered. Therefore, the delay difference optimization value is set as a limiting constraint. The value of the delay optimization difference of this model is at least greater than the delay time cost of the vehicle during the phase switching process. When the difference between the delays of the two stages exceeds the time cost of the transition process, the next stage of transition is performed. The difference between the delays in this stage does not exceed the delay difference optimization value, and then we continue to implement the current lane combination plan. The delay optimization difference expression is as follows:

$$P(i_k) - P(i_{k+1}) > \Delta M, \tag{6}$$

where $P(i_k)$ represents the average delay of vehicles in the lane plan implemented in the k-phase of the heavy traffic flow direction (the unit is seconds) and $P(i_{k+1})$ represents the average delay of vehicles in the lane plan implemented in the $k+1$ stage of the heavy traffic flow direction (the unit is seconds).

2.2.2. Time Interval Constraints. In the morning and evening rush hour, the traffic flow shows dynamic periodic changes. The determination of the switching interval depends on the dynamic periodic change in the traffic flow. If the interval is too short, not only will no effect be seen, but it will also cause confusion to the drivers. The determination of the interval time must be greater than the average travel time of the vehicle through the reversible lane segment under steady flow conditions:

$$T > T_{\min}, \tag{7}$$

where T represents the duration of the current lane combination scheme (the unit is minutes) and $T_{\min}$ represents the minimum time interval for the lane combination scheme switching (the unit is minutes).

2.2.3. Lane Number Constraint. The value of i is the number of reversible lanes, so

$$0 \le i < n. \tag{8}$$

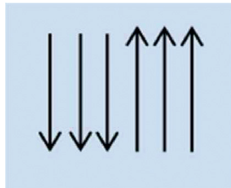
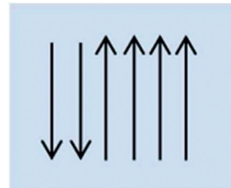
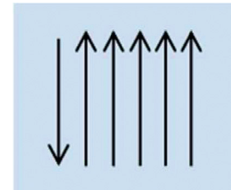
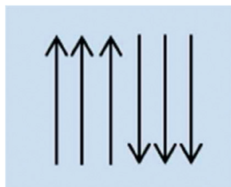
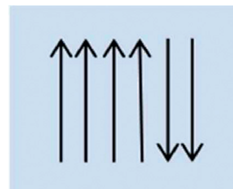
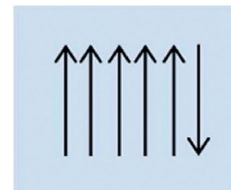
The reversible lane control model is studied on the basis of two-way six lanes, and $0 \le i < 3$.

2.3. Lane Combination Plan. The enumeration method is used to solve the model. All possible lane allocation schemes are set as the solution space of the model, which is shown in Table 1. As can be seen from Table 1, for two-way traffic in six lanes, there are five-lane allocation schemes, namely, 3-3, 4-2, 5-1, 2-4, and 1-5. When the traffic is running smoothly, $i = 0$, both directions should maintain three lanes, and there is no need to change the number of lanes. When there is an obvious two-way traffic flow imbalance on the road, $i = 1$, the direction of a lane in the light traffic direction will become the reversible lane serving the direction of the heavy traffic flow. When the two-way traffic flow on the road is unbalanced, and there is serious congestion, $i = 2$, the two lanes in the heavy traffic flow direction are converted into the reversible lanes serving for the heavy traffic flow. This article does not consider the case of $i = 3$.

The specific flowchart of the reversible lane allocation model operation is shown in Figure 1.

2.4. Case Analysis. The calibration of the road resistance function was determined by a large number of traffic surveys. Using a parameter calibration method of the two-level traffic travel time model based on microlevel fitting and macrolevel checking [30], the value of $\alpha = 1.5$, $\beta = 3$ was selected; this was set while assuming that the vehicle travel time in the initial free flow state was 60 seconds, that is, $t_0 = 60s$. For the traffic volume data, the option for the two-way traffic in six lanes was selected, that is, $n = 3$. Assuming the capacity of a single lane is 1200 pcu/h, no matter how many lanes are converted into reversible lanes, the capacity of the entire road segment is a constant of 7200 pcu/h. We set the value of ΔM in this case as 60 seconds for the demonstration analysis. If the delay difference of the two stages is within 1 minute, the reversible lane introduction (converting normal lanes into reversible lanes) was not considered. If the delay difference of the two stages was greater than 1 minute, the lane switching was carried out.

Table 1: Lane combination plans of reversible lanes.

Traffic flow direction	$i = 0$	$i = 1$	$i = 2$
Light/heavy			
Heavy/light			

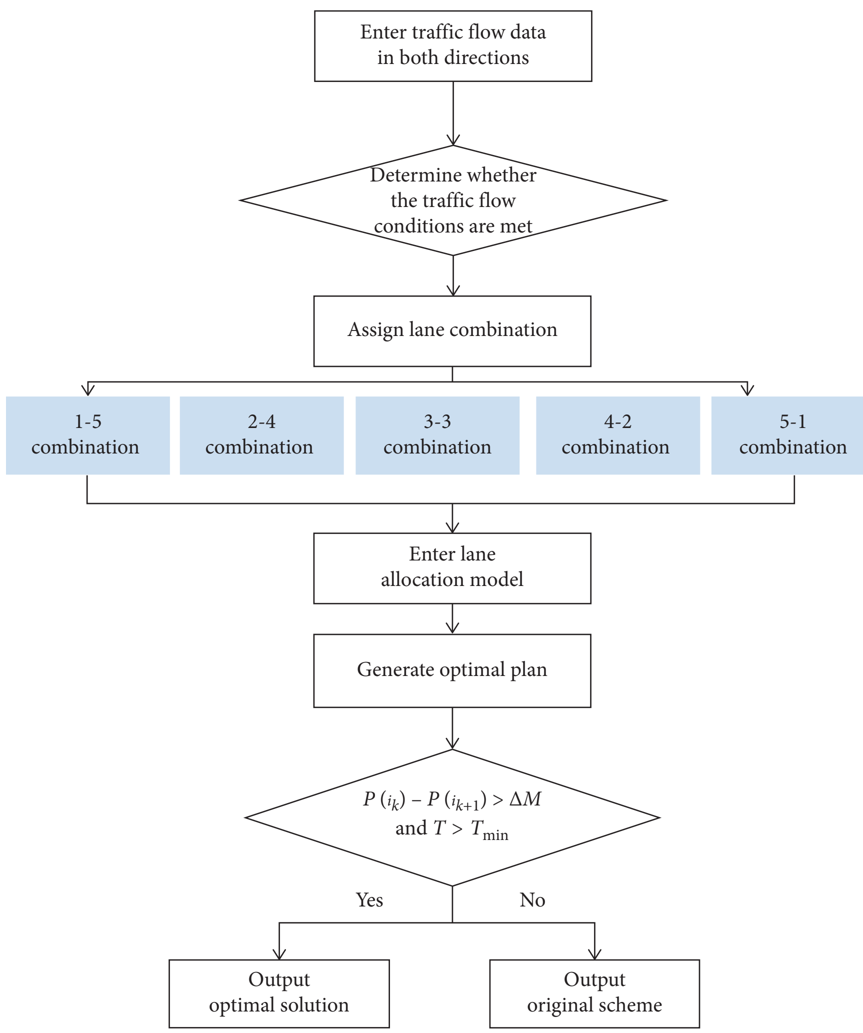


Figure 1: Flowchart of the reversible lane allocation model of the road section.

The traffic volume data of the tide section of Lihu Avenue from 7:00 to 19:00 was collected, and the traffic volume was determined every 15 minutes. A total of 48 sets of data were examined, as shown in Figure 2.

After calibrating the unknown variables and parameters, and selecting 15 minutes as the switching interval, the objective function becomes

$$S_k = \int_{t_k}^{t_k+0.25} 60 \times \left[1 + 1.5\left(\frac{V_a}{3600 + i_k \times 1200}\right)^3\right] V_a d_t + \int_{t_k}^{t_k+0.25} 60 \times \left[1 + 1.5\left(\frac{V'_a}{3600 - i_k \times 1200}\right)^3\right] V'_a d_t. \quad (9)$$

The reversible lane allocation model builds an integration function that takes the road resistance function as the main body. MATLAB can be used to write the integral calculation codes, convert the above variables into codes, and obtain the data in Figure 3 by calculation.

It can be seen from Figure 3 that the delay between the lane combinations is obviously different. The lane control and optimal decision-making tend to be stable as time increases. Moreover, a lane scheme is often presented within a period of time to avoid frequent lane changes caused by short-term traffic accidents. However, through calculation, it was found that the delay of the 1:5 lane combination of 18:15–18:30 is the smallest compared to other lane combinations of the same period, but the delay difference between the 1:5 and 2:4 lane combination schemes was not significant. The delay difference was less than the delay difference optimization value, and thus, there was no need to switch lane schemes. Only the 2:4 lane combination scheme of the previous stage continued to be implemented to ensure control safety.

The dynamic lane allocation model of the road segment can allocate reversible lanes according to the traffic flow in real time based on the minimum vehicle delay, so that the total delay of all vehicles on the road segment is minimized. The model also considers the instability of the traffic flow of the road segment and chooses the delay optimization difference ΔM as a controllable factor. When the difference between the two stages is within the range of the delay difference optimization value, no lane change is performed to meet its safety requirements. Therefore, this model was found to be reasonable, scientific, and effective after being verified by the calculation examples.

3. Dynamic Lane Assignment Model of Intersections

The uneven distribution of lane functions at intersections can easily lead to long queue lengths at intersection entrances and increased vehicle delays. The intersection dynamic lane allocation model can dynamically change the lane combination according to the traffic flow of each turn of the entrance lane. The model can quickly identify the delay of different lane combinations under different traffic conditions and choose the optimal combination of entrance lanes.

3.1. Objective Function. The most common problem at intersections is that vehicles line up at the entrance for too long, resulting in vehicle delays. How to minimize the delay of all vehicles passing through the intersection is one of the purposes of this model study. The dynamic lane allocation model of intersection uses the delay estimation formula of the HCM 2000 version to construct the objective function. Regardless of the initial queuing situation, only the two parts of uniform delay and incremental delay are used. The constructed functions are as follows:

$$\min D = \frac{\sum_i \sum_j d_{ij} q_{ij} n_{ij}}{\sum_i \sum_j q_{ij} n_{ij}}, \quad (10)$$

where n_{ij} is the number of lanes corresponding to the jth traffic on the ith entrance lane, q_{ij} is the actual traffic volume of the jth lane group on the ith entrance lane, and d_{ij} is the cars in the jth lane on the ith entrance lane that are delayed.

3.2. Constraints. At the intersection, the traffic operation of each entrance depends on the space-time configuration of the intersection. This includes the cycle length, signal timing, and minimum green light time. This also includes the number of lanes and road saturation. The constraints of the relevant variables in the model and the objective function constitute a complete nonlinear objective function.

3.2.1. Saturation Constraint. "Intersection saturation" refers to the ratio of the actual traffic volume of each lane to the saturated capacity of the lane and is an important indicator reflecting the service level of the intersection. It is also a key parameter for the application of the reversible lane change model.

It is necessary to clarify the congestion situation of each entrance lane before switching lanes. The saturation of the entrance lane is usually used to determine the degree of congestion at the intersection. The criteria for the congestion situation are given in Table 2.

Table 2 shows that when the saturation is greater than 0.9, the entrance lane is severely congested. The traffic flow at the intersection will show large fluctuations with time. The amount of traffic on the subarterial road will be less than that of the arterial road, and the saturation of the subarterial road will also decrease. At this time, it is necessary to reduce the traffic volume of the arterial road in a timely manner to protect the right of way of the traffic on the arterial road.

The saturation constraints are as follows:

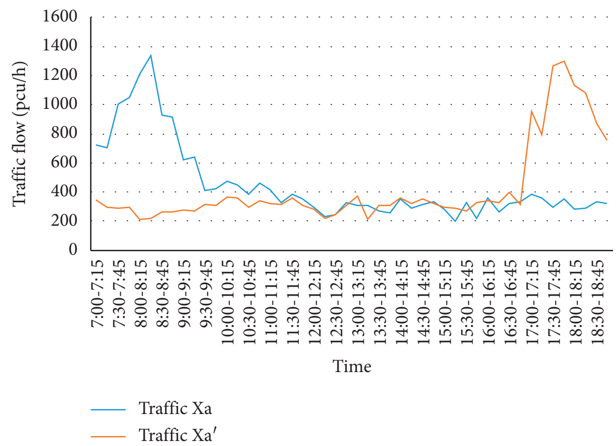


Figure 2: Traffic volume of the Lihu Avenue tidal section.

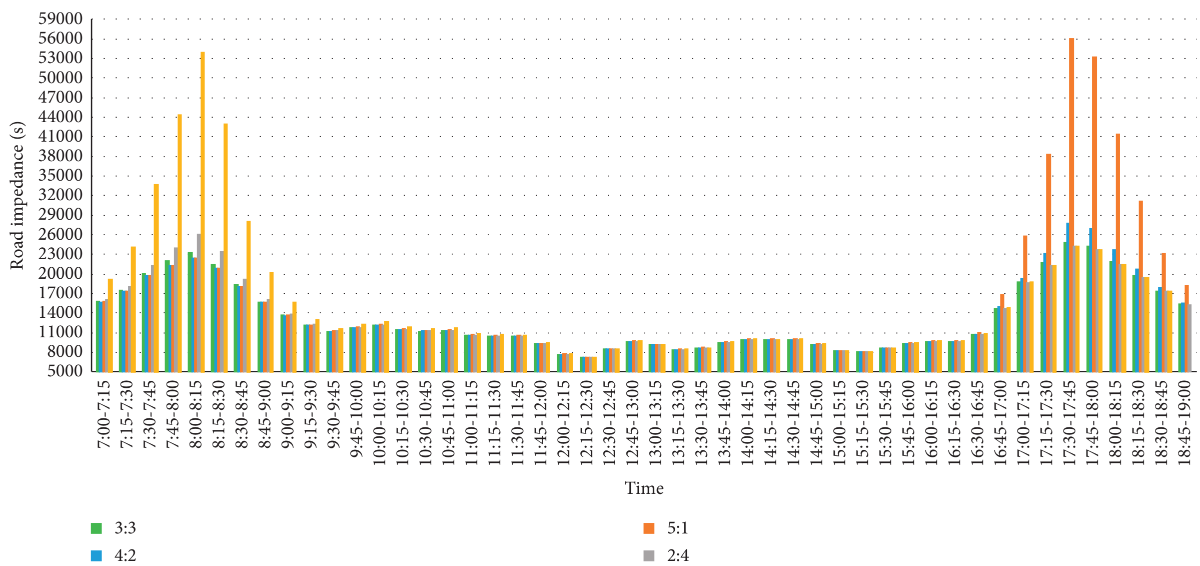


Figure 3: Delay analysis of different lane combination schemes.

Table 2: Criteria of the congestion degree of the entrance lanes at intersections.

Degree of congestion in steering lane	Very high	High	Low	No congestion
Criteria	X ≥ 0.95	0.9 < X < 0.95	0.85 < X ≤ 0.90	X ≤ 0.85

$$x_{ij} = \frac{q_{ij}}{\mathrm{CAP}_{ij}} = \frac{q_{ij}}{S_{ij}\lambda_{ij}n_{ij}} \leq 0.9, \quad (11)$$

where x_{ij} is the saturation of the jth lane group on the ith entrance lane, q_{ij} is the actual traffic volume of the jth lane group on the ith entrance lane, CAP_{ij} is the capacity of the jth lane group on the ith entrance lane, S_{ij} is the saturated flow rate of the jth lane group on the ith entrance lane, and $\lambda_{ij}$is the green signal ratio of the phase of the signal belonging to the jth lane group on the ith entrance lane.

3.2.2. Minimum Green Light Time Constraint. Each phase has a minimum green light time, which represents the minimum transit time given at the beginning of the phase to ensure that vehicles in line from the parking line to the vehicle detector can all pass through the parking line.

$$G_{\min k} \leq g_k, \quad (12)$$

where $k = \{1, 2, 3, 4\}$ represent four different phases, $G_{\min k}$ is the minimum green light time of the signal phase k that is generally 10 seconds, and g_k is the effective green time of the signal phase k.

3.2.3. Signal Period Duration Constraint. The signal period refers to the time required for the signal light color to display one cycle; it is represented by C and expressed in seconds. There are certain constraints on the cycle time of the signal period. Increasing the value of C when necessary can help improve the traffic efficiency at the intersection, but it is only temporary. A longer cycle time is beneficial to improve the capacity of intersections and reduce the average number of stops. However, it will lead to an increase in the average vehicle delay at intersections. On the contrary, a shorter signal cycle is beneficial to reduce the average vehicle delay, but it will increase the signal loss and lead to the decrease of the traffic capacity.

$$C_{\min} \leq C = \sum_{K=1}^{4} g_k + L \leq C_{\max}, \tag{13}$$

where g_k is the effective green time of the signal phase k, C is the signal cycle length that is 120 seconds in this paper, and L is the total loss time within a signal period.

3.2.4. Lane Number Constraint. In this paper, it is assumed that the original entrance lane has three lanes. When the reversible lane is introduced, the number of entrance lanes of the intersection also changes, but at most, two of the lanes in the opposite direction could be occupied. This means that when n reversible lanes are introduced, the entrance lanes at the intersection also increase n lanes. When the reversible lanes of the road section are not introduced, the appropriate entrance traffic volume at the intersection determines whether to introduce the intersection entrance reversible lane alone.

$$\sum_{j=1}^{3} n_{ij} = N_i, \tag{14}$$

where n_{ij} is the number of lanes corresponding to the jth traffic on the ith entrance lane and N_i is the total number of lanes at the ith entrance lane.

3.3. Operating Efficiency Analysis of Different Entrance Lane Configurations. The dynamic lane allocation model for intersections is used to explore the relationship between the intersection traffic conditions and vehicle delays. The analysis is based on the change in unidirectional traffic flow and the change in left-turn and straight-through traffic flow. Cars are subject to a comparative analysis of delays to calculate which lane configuration is better under the same traffic conditions, with fewer delays.

This paper divides the entrance lane of the intersection into three situations, namely, three lanes, four lanes, and five lanes. The lane allocations of the entry lanes are shown in Figures 4–6. The layout of the intersections follows the design specifications of the intersections, and various lane combinations are also allocated based on the traffic volume.

In view of the fact that the current IVICS is not perfect, it is difficult to collect valid data. The traffic flow of the entrance lanes in different lane combinations was simulated for experimental analysis, and the right-turn traffic was ignored to simplify the study.

3.3.1. Straight Flow Change Analysis. For the straight flow change analysis, the left-turn traffic volume is set as a fixed value. Considering that the actual traffic volume of the road section where intersections with less entrances are located is also smaller, the left-turn traffic volume is set to be 250 pcu/h for the three-lane intersection, and 300 pcu/h for the four-lane and five-lane intersections.

For an intersection with three-lane entrances, the left-turn traffic volume is determined as 250 pcu/h; when the value of the straight-through traffic is changed, and the delay variation of the vehicles with the straight-through traffic can be observed. Figure 7 shows that when the straight traffic flow is less than 400 pcu/h, the difference between the delays of the two-lane combinations is extremely small, but with the increase of the straight traffic flow, the delay of the two-lane combination vehicles also increases. Overall, the delay of the "left 1 straight 2" lane combination is smaller compared to that of the "left 2 straight 1" lane combination.

For an intersection with four lane entrances, the left-turn traffic volume is 300 pcu/h, and the value of the straight-through traffic is changed. We can observe the change in the delay of vehicles with the straight-through traffic. Figure 8 shows that, before the straight-through traffic volume reaches 600 pcu/h, the delays of the three-lane combinations have not changed much, but as the straight-through traffic continues to increase, the delays of the "left 3 straight 1" vehicles have risen linearly, and the "left 2 straight 2" and the "left 1 straight 3 vehicles" both experienced slow growth. In general, before the straight-through traffic is 800 pcu/h, the delay of the "left 2 straight 2" lane combination is the smallest; and after 800 pcu/h, the "left 1 straight 3" lane combination has the smallest delay.

For an intersection with five lane entrances, the left-turn traffic volume is 300 pcu/h, and the value of the straight-through traffic is changed. Observe how the delay of the vehicles varies with the straight-through traffic. Figure 9 shows that the delay of the "left 4 straight 1" lane combination is much larger than that of the other three-lane combinations, and it continues to rise with the growth of straight traffic. Before, the straight traffic is 1000 pcu/h. The delays of the combination of the "left 1 straight 4," "left 2 straight 3," and "left 3 straight 2" lanes are basically the same, with little change. After 1000 pcu/h, the delay of the "left 1 straight 4 lane" combination is the smallest, and the delays of the "left 2 straight 3" and "left 3 straight and 2" lane combinations show a slow upward trend.

By analyzing the combination of the above three entrance lanes, the following two conclusions can be drawn. The first is that no matter what changes are made in the left-turn and straight-through traffic, as long as the traffic flow at the intersection increases, the average vehicle delay will also increase, and the delays of the different lane combinations are different. The second is that although the number of lanes for each entrance lane is different, the lane combination also varies; however, for different traffic combinations, there is always an optimal lane combination for each

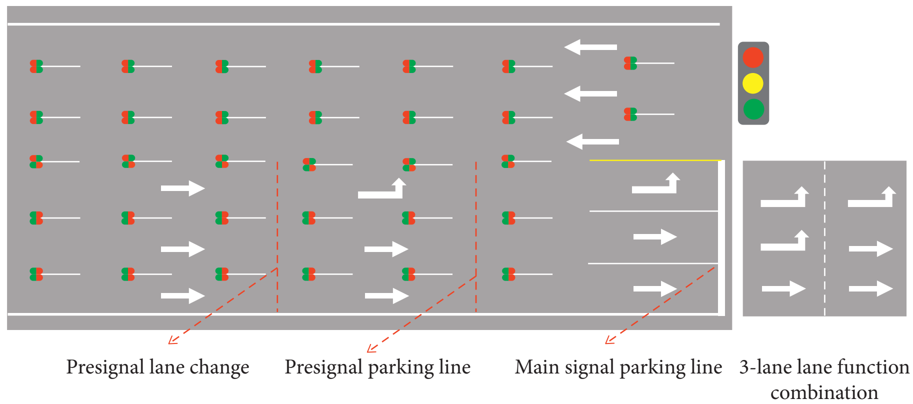


Figure 4: Illustration of the three-entrance-lane configuration.

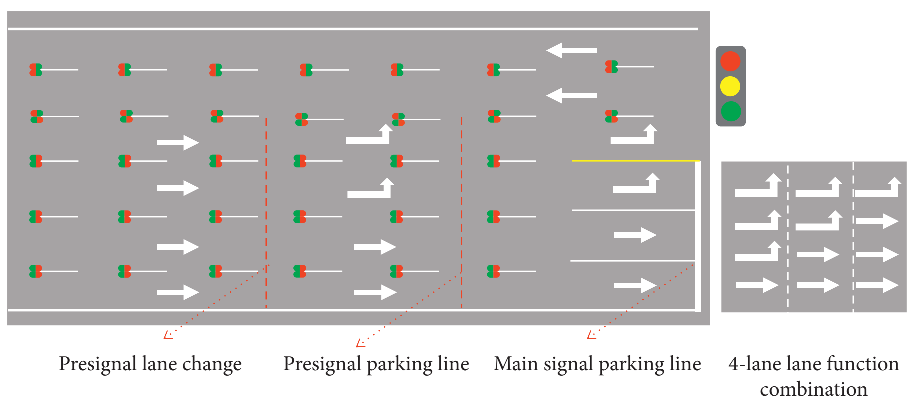


Figure 5: Illustration of the four-entrance-lane configuration.

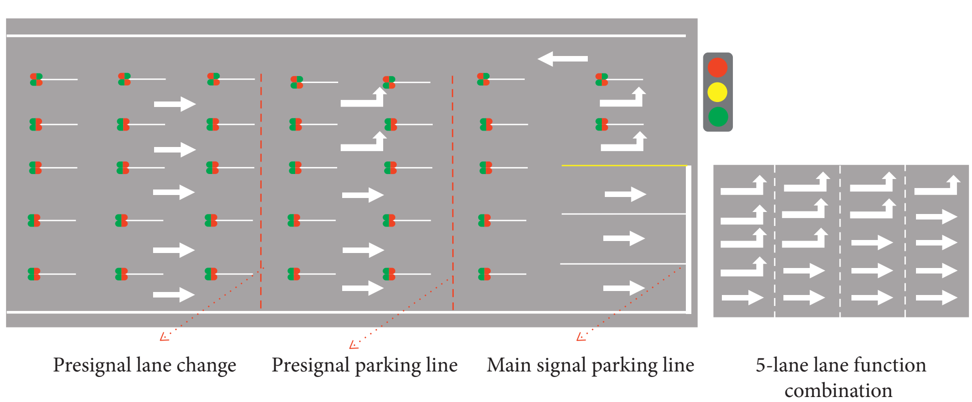


Figure 6: Illustration of the five-entrance-lane configuration.

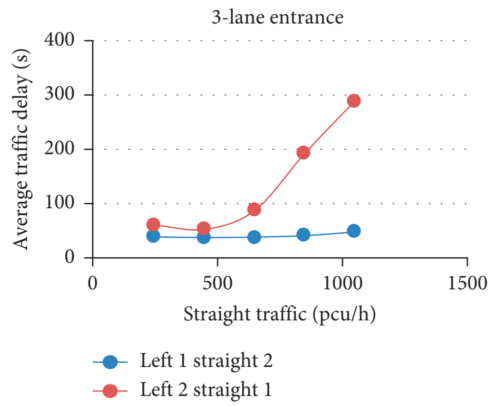


Figure 7: Change chart of the straight direction delay under different combinations of lanes on three entrance lanes.

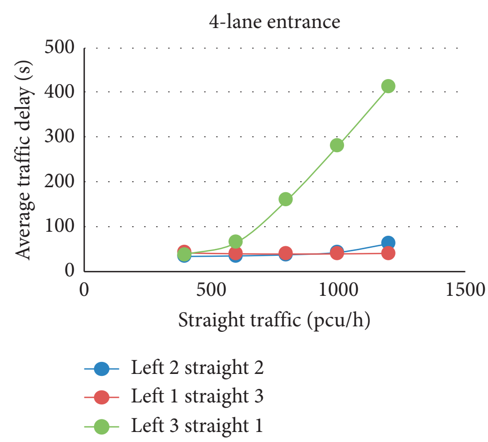


Figure 8: Change chart of the straight direction delay under different combinations of lanes on four entrance lanes.

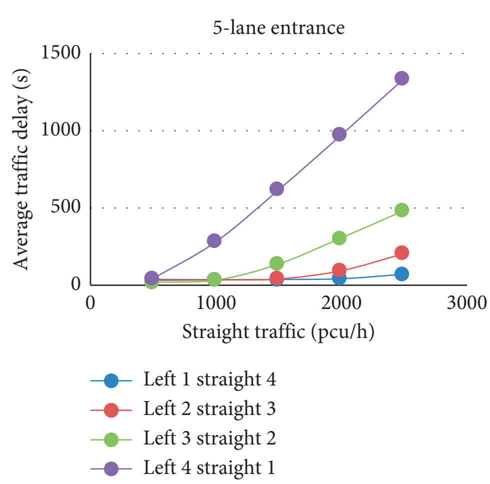


Figure 9: Change in the straight direction delay under different combinations of lanes on five entrance lanes.

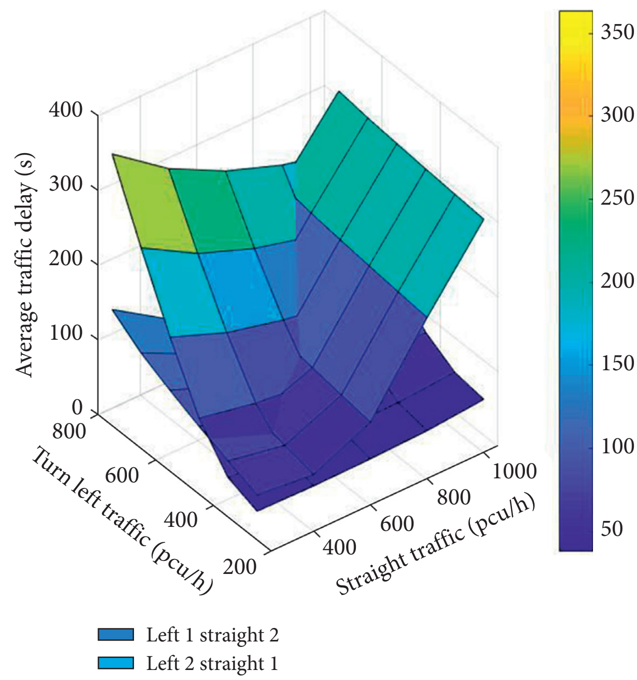


Figure 10: Change in the two-way delay under different lane combinations on three entrance lanes.

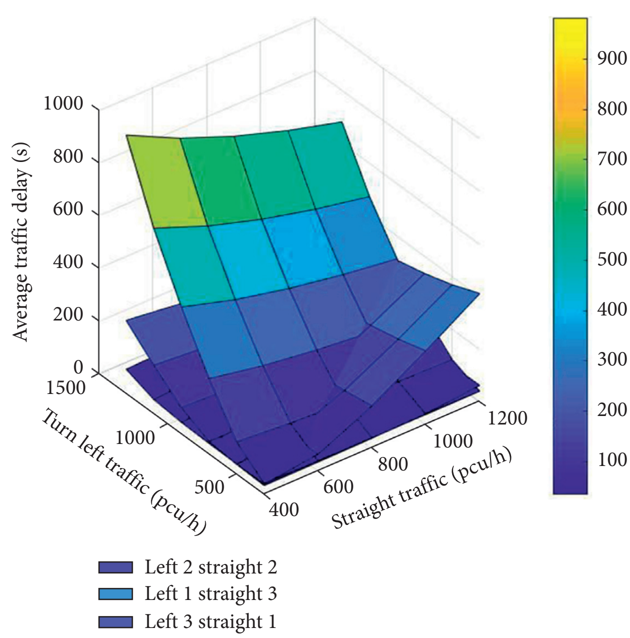


Figure 11: Change in the two-way delay under different lane combinations on four entrance lanes.

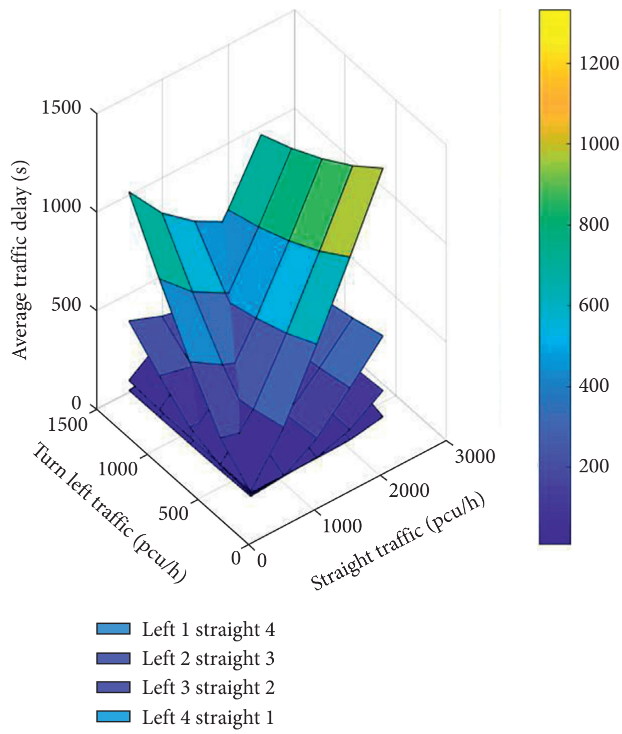


Figure 12: Change in the two-way delay under different lane combinations on five entrance lanes.

entrance lane to match so that the delay of the traffic is minimized.

3.3.2. Analysis of Changes in Left-Turn and Straight-Through Traffic. If the straight-through and left-turn traffic both change, how will the delay of vehicles at the intersection change? Figures 10–12 show the delays of the three-lane entrance lanes, the four-lane entrance lanes, and the five-lane entrance lanes under different traffic flow conditions.

A three-dimensional map using MATLAB was created to intuitively show the difference in the delay errors of different lane combinations. From the three-dimensional map shown in Figure 12, the following conclusions can be drawn:

(1) There are certain left-turn and straight-through traffic thresholds that make the delays of cars in different lane combinations the same.

(2) For different numbers of entrance lanes and different entrance flows, there will always be a lane combination to match it, so that the delay of traffic at the intersection is minimized.

(3) When the degree of saturation of each entrance lane is high, the delay of the combined vehicles of different lanes is obvious. At this time, it can be clearly seen which of the combination of lanes has the smallest average delay. The conditions for setting reversible lanes at intersections are that the traffic flow of each entrance lane is large and oversaturated.

4. Conclusion

This paper proposes the construction of a reversible lane dynamic allocation model in the intelligent vehicle infrastructure cooperative system based on previous studies. The proposed model is based on a data analysis of real-time traffic information in such an environment, and a dynamic lane allocation model is constructed to allocate the lanes. Intelligent road stud lights installed on the pavement are used as lane markings to guide the entire lane-changing process. This enabled us to realize dynamic and reversible lane control, improved the efficiency of road resource utilization, and eased traffic congestion.

Although the proposed model was proven to be feasible, there are still some shortcomings to this work. The road lane allocation model was established in an ideal state, and the errors caused by the convergence of various stages were not fully considered. During the calibration of vehicle average delay model parameters, other various influencing factors on the road are not fully considered, and these require more detailed optimization later. In the future, the dynamic allocation model needs to be applied to actual roads for verification.

The control and management of reversible lanes involve all aspects of the system and are a significant system problem. Only the lane allocation of the reversible lanes is partially explained, and the depth and breadth of the research need to be improved. Future work should include more detailed research on the safety control of reversible lanes and emergency rescue on road accidents, and it should expand the application range of the reversible lanes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Lina Mao conceived and designed the study; Lina Mao and Guiliang Zhou wrote the manuscript; Huimin Cao and Pengsen Hu conducted the model and collected traffic data; Huimin Cao and Xu Bao analysed the simulation results.

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