

Research Article

Design of Real-Time Dynamic Reversible Lane in Intelligent Cooperative Vehicle Infrastructure System

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The rapidly growing traffic demand and the slowly increasing traffic supply have produced an mounting contradiction, which is mainly manifested in cities as road congestion and unbalanced bidirectional traffic flow. Most of the reversible lanes are implemented on fixed sections and fixed times and are mainly guided by ground markings, road signs, railings, and traffic police officer. It requires a lot of human and material costs. And, the control effect is lagging and inaccurate. Aiming at these problems, a real-time dynamic reversible lane scheme in the Intelligent Cooperative Vehicle Infrastructure System (CVIS) was proposed. Traffic information was collected in real time through the CVIS, and a reversible lane scheme was established based on the real-time service level V/C and BRP functions. A lane change control model was applied to determine the number of lanes and the timing of lane changes. Then, the reversible lanes were managed in real time through intelligent road stud lights and light curtain walls. Buffer sections and no-entry sections were set to ensure reversible lanes operating safely and efficiently. VISSIM simulation was used for case analysis, and the results showed that compared with the traditional time-controlled reversible lane scheme, the real-time dynamic reversible lane scheme could reduce the average vehicle delay by 27.4% and decrease the vehicle VOC, CO and NO_x emissions by 13.5%.

1. Introduction

By the end of 2018, China's car ownership had reached 240 million units, an increase of 22.85 million units over 2017. The national highway mileage reached 4,486,500 km, an increase of 73,100 km and 1.53% over the previous year. The rapidly increasing transportation demand and the slowly increasing transportation supply have produced increasing contradictions between supply and demand [1, 2]. Some urban roads have serious congestion and unbalanced bidirectional traffic flow. In 2017, the number of connected vehicles in China reached 17.8 million. With the integration and innovation of big data, cloud computing, and other technologies, the penetration rate of connected vehicles will continue to accelerate in the future [3–6].

Intelligent road stud light is currently mainly used for underground parking lot vehicle indication, detection, and lane keeping reminder and has not been used as a signal indicating device on the road. In the proposed reversible lane scheme, intelligent solar road stud lights were used, which were controlled in real time under connected vehicle environment, to achieve the same indication function as road traffic lights.

A huge amount of study has been carried out on reversible lanes. Brian Wolshon and Laurence Lambert studied the application status, control and management measures, and evaluation methods of reversible lanes, and found that although there was no unified planning and well-established standards, the introducing of reversible lanes still achieved the expected goals and were accepted by the public [7]; Matthew and Peter et al. established a linear programming

model to calculate the optimal configuration of variable lanes and used the information collected by traffic sensors to determine the direction of reversible lanes on the road. The direction was dynamically changed, and the results showed that the road capacity can be effectively improved by introducing the dynamic reversible lane scheme [8]; Golub et al. put forward suggestions from the perspective of economic benefits and traffic benefits from the design of reversible lanes, marking, and management [9]; Yu and Tian studied the setting conditions of the reversible lanes and established a two-level planning model based on the road network. The upper layer of the model integrates and optimizes the lane allocation, and the lower layer is a network equilibrium model for predicting the driver's response to lane allocation [10]; Cui and Liu investigated the possibility and necessity of introducing reversible lane schemes based on field survey and put forward solutions to manufacturing-related hidden traffic hazards of the reversible lane schemes [11]; Sun established an optimization model for the allocation of reversible lanes, dividing 24 hours of a day into several continuous time sections, which were used to allocate the number of tidal lanes in different sections according to the traffic flow characteristics of different time sections [12–14];

Dai et al. analyzed the current status of reversible lane schemes in foreign countries, proposed three steps for setting reversible lane schemes, and verified the effect of introducing reversible lane schemes through simulation [15, 16].

Reversible lanes have been studied by scholars all over the world, and they have been widely used in urban roads, but most of them are fixed time and fixed lanes, which require manual operation depending on the traffic situation. At present, no intelligent lane-combined technology with road studs has been achieved for the dynamic control of reversible lanes [17–20]. Where road information in CVIS was collected, the control model was used to allocate reversible lanes and intelligent road studs were used to guide traffic [21, 22]. Compared with the existing reversible lane control methods, the biggest advantage is that reversible lane allocation can be dynamically changed according to the traffic volume of the road, no manual operation is needed, and energy conservation and environmental protection are achieved, thereby achieving optimal use of road resources.

2. Design Principles and Schemes of Real-Time Dynamic Reversible Lanes

2.1. Reversible Lane Scheme Implementation Conditions. According to the reversible lane implementing conditions recommended by the American Society of Transportation Engineers, the road condition, road capacity, and traffic volume are generally considered. In this paper, the road conditions and traffic conditions for opening the reversible lane schemes were investigated.

2.1.1. Road Conditions

- ① Lane setting conditions: for the introduce of variable lanes, the number of original road lanes must be at

least three in both directions. In cities with large traffic flow, the number of lanes on the road should be greater than 6 or no less than 5 to ensure the room for reversible lanes.

- ② Traffic facility conditions: city roads with reversible lanes generally should not equip immovable facilities such as central separation zone or trolley tracks.

2.1.2. Traffic Conditions

- ① Traffic directions: stable traffic flow is the primary condition to ensure the implementation of reversible lane scheme, and the traffic flow with obvious traffic imbalance phenomenon is the premise to set the reversible lane. It is required that the directional distribution coefficient below 2/3, so as to ensure the benefits of implementing of the variable lane.
- ② Traffic capacity: after the reversible lane is introduced, the capacity of the road should still meet the original traffic demand.

2.2. Dynamic Lane Changing Criteria

2.2.1. Determination of Traffic Conditions. In CVIS, wireless sensors are used to obtain real-time traffic volume information V and the traffic capacity C which is used to calculate the service level V/C in both directions of the road. The traffic conditions are divided into five levels according to its service level for 5 states as shown in Table 1.

2.2.2. Determination of the Number of Lanes Based on the Minimum Travel Time. Among the influencing factors of travel behavior, time is the most valued factor by travelers. For the study of travel time on the road, the BPR model is most frequently used, and the road resistance function is as follows:

$$t = t_0 \{1 + \alpha (V/C)^\beta\}, \quad (1)$$

where t is the travel time, t_0 is the travel time for free flow, V is the traffic volume, C is the traffic capacity, and α and β are parameters equal to 0.15 and 4, respectively.

Based on the minimum impedance, the path resistance function model is as follows:

$$\min f(x, i) = t_0 \left\{ \left[1 + \alpha \left(\frac{V_1}{mC} \right)^\beta \right] + \left[1 + \alpha \left(\frac{V_2}{nC} \right)^\beta \right] \right\},$$

$$t_0 = \frac{K_o L}{(V_s \cdot \gamma \cdot \eta)},$$

$$i = |m - n|,$$

(2)

where V_1 and m refer to the traffic volume and number of lanes in one direction, V_2 and n refer to the traffic volume and number of lanes in the other direction, C represents the traffic capacity, I is the number of reversible lanes, K_o is the delay coefficient ranging from 1 to 1.2, L is the length of reversible lane, V_s is the design speed of the road, r is a parameter, if the nonmotorized lane and motor lane are

TABLE 1: Road conditions and corresponding service levels.

Service levels	State 1	State 2	State 3	State 4	State 5
V_1/C_1	0~0.6	0~0.8 (0.6~0.8)	0~0.8	≥ 0.8	≥ 0.8
V_2/C_2	0~0.6	0.6~0.8 (0~0.8)	≥ 0.8	0~0.8	≥ 0.8

V_1/C_1 represents the service level of the traffic in one direction; V_2/C_2 represents the service level of the traffic in the other direction. State 1 is the best state, and state 5 the worse state.

separated, r equals to, otherwise r equals to 0.8, and η equals to 1 if the width of lanes is 3.5 meters.

2.2.3. Determination of the Two-Way Traffic Conditions after the Lane Change Based on the Adjusted Service Level.

$$\begin{aligned}
 V_1 &= \sum_{i=1}^m V_i = m \cdot v_1, \\
 V_2 &= \sum_{i=1}^n V_i = n \cdot v_2, \\
 V_1/C &= \frac{V_1}{m \cdot c} = \frac{m \cdot v_1}{m \cdot c} = \frac{v_1}{c}, \\
 V_2/C &= \frac{V_2}{n \cdot c} = \frac{n \cdot v_2}{n \cdot c} = \frac{v_2}{c}.
 \end{aligned} \tag{3}$$

Let $V_M = \max(V_1, V_2)$ and $V_N = \min(V_1, V_2)$, then the congestion service level can be calculated as follows:

$$V_M/C = \frac{V_M}{(M+i) \cdot c} = \frac{M \cdot v_M}{(M+i) \cdot c}. \tag{4}$$

The adjusted service level of the uncongested segment is not lower than the service level of the congested segment, then we have the critical state:

$$\frac{N \cdot v_N}{(N-i) \cdot c} \geq \frac{M \cdot v_M}{(M+i) \cdot c}, \tag{5}$$

$$V_N \geq \frac{N-i}{M+i} V_M.$$

2.2.4. Establishment of Dynamic Control Model of Lane Change. The lane change dynamic control model obtains road traffic information in CVIS and evaluates the road traffic flow conditions based on the service level of the road. Then, the corresponding control module is used to solve the optimal switching scheme and determine whether the scheme meets the preset conditions. If it is satisfied, the optimal solution is executed; if it is not satisfied, the existing solution is maintained. The flow chart of dynamic control model is shown in Figure 1.

2.3. Road Signaling. The intelligent road stud is used as a road signal indicating device to dynamically change the lane allocation and guide the vehicle throughout the road. The intelligent road stud light uses lithium battery and solar battery to power. It can work continuously for 36 days under

the supply of lithium battery power. It uses 6 2000 mcd LED lights to meet the signal indication requirements under different conditions. Through LoRa's new generation of IoT communication technology, point-to-point and point-to-center ultra-long-distance communication is realized at the same time. The road stud light adopts cast aluminum housing, with IP68 waterproof feature, and the working temperature range is -40° to 85° ; it can withstand 20 tons of static pressure, which can meet the requirements of different scenarios and different roads.

The Intelligent road stud has three light colors, red, yellow, and green, and can be displayed in flashing. Red flashing means reminding to leave the lane and prohibiting traffic; green flashing means the lane is about to open and allowing traffic; the yellow light indicates the buffer section, which means to drive away as soon as possible and warn drivers that there is a no-entry section ahead. There are six patterns for road stud lights, as shown in Figure 2. The road management agency can change the color of the lights through the remote communication function to achieve the indication of different road traffic conditions. The remote instructions of the road stud lights are encrypted by RSA to achieve the security of traffic infrastructure control.

In combination with the existing laser projection technology, a virtual wall curtain idea formed by light projection was proposed. A light curtain wall was provided with a small projection device in a stud light to project light onto a reversible lane to form a virtual wall curtain; the brightness and color of the wall curtain are consistent with the stud lights. The light curtain wall can cooperate with road stud lights to provide instructions and reminders to ensure that vehicles can safely change lanes and drive. At present, the light curtain wall technology does not meet the requirements for practical application to roads. According to technical research and experimental analysis, light curtain wall technology can be applied to roads as a traffic signal indicator in the future.

2.4. Traffic Safety Analysis

2.4.1. Conflict Zones. A conflict zone of the reversible lane is divided into a starting conflict zone and an ending conflict zone. The objective of setting conflict zones is to make the vehicles in both directions change lanes smoothly and avoid conflicts. The starting conflict zone consists of a no-entry section. The ending conflict zone consists of two buffer sections and a no-entry section. The vehicle can complete the lane change or stay for a while waiting for a lane change in the buffer section. During the operation of the variable lane, the traffic is allowed to enter the no-entry section, forming a spatial separation zone for traffic flow to avoid oncoming conflicts.

When setting a conflict zone on a city road, the location should be as far away as possible from intersections, bus stops, and other places where traffic flow will be disturbed. If the reversible lane is at the beginning or end of the intersection, it is not necessary to set a conflict zone. The intersection is an effective area to avoid oncoming conflict.

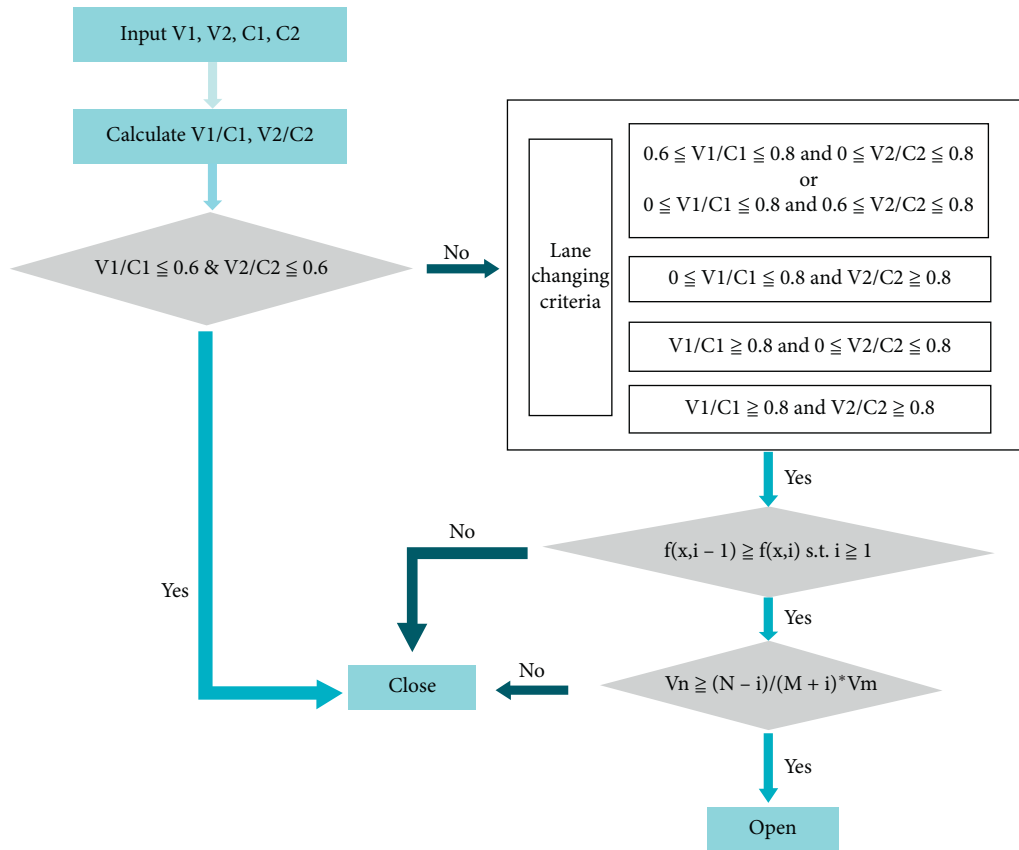


FIGURE 1: Dynamic control model flow chart, where V_m and m are traffic volume and number of lanes in the congested direction, respectively, V_n and n are traffic volume and number of lanes in the opposite direction, i refers to number of reversible lanes, and when $f(x, i - 1) \geq f(x, i)$, the number of reversible lanes equals to i .

Road stud light patterns	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Pattern 6
Color						

FIGURE 2: Different patterns of intelligent road stud light.

Therefore, when the distance between the start or end of the reversible lane of the road section and the center of the intersection is within 300 m and the intersection satisfies the conditions of introducing the reversible lane, the reversible lane should be directly extended to the intersection. When the intersection does not meet the requirements for setting a reversible lane, the reversible lane should be shortened to ensure that the distance from the conflict zone to the intersection is more than 300 m. Because the reversible lane extending to the intersection does not need to set the conflict zone, we will only discuss the corresponding setting parameters for setting the conflict zone far away from the intersections. The starting conflict zone of the reversible lane is relatively simple to set. There is no direct oncoming conflict for two-way traffics in starting conflict zone, so we only need to avoid conflicts happen in the lane change process. The distance of the starting conflict zone depends on the vehicle’s safe following distance and road stud laying interval which is generally 5–10 m.

In order to alleviate traffic congestion of eastbound traffic, vehicles in the eastbound traffic can borrow a part of the middle lane of the westbound traffic. Figure 3 shows the starting conflict area of the reversible lane. Vehicles in the eastbound traffic can choose to merge left to enter the reversible lane in the starting conflict area, and vehicles in the westbound traffic can merge left to get back to its original lane after the starting conflict zone. In Figure 4, the ending conflict area is the end area of the lane occupancy for vehicles in the eastbound traffic and the starting area of lane occupancy by the eastbound traffic for vehicles in the westbound traffic. Therefore, vehicles in the eastbound traffic must drive back to the original lane, and vehicles in the westbound traffic must drive into other lanes in the eastbound direction to avoid oncoming conflicts.

2.4.2. Design of No-Entry Section. The no-entry section is the isolated area of the vehicle during the operation of the reversible lane. It is set at the beginning and end of the reversible lane where the two-way traffic conflicts. In order to ensure the safety of reversible lane operation, the longer the distance of the no-entry section is, the better. However, in the perspective of utilization of road resources, the shorter no-entry section is preferred. Therefore, it is necessary to make the distance of the no-entry section as small as possible while ensuring the safety operation of the traffic. The length

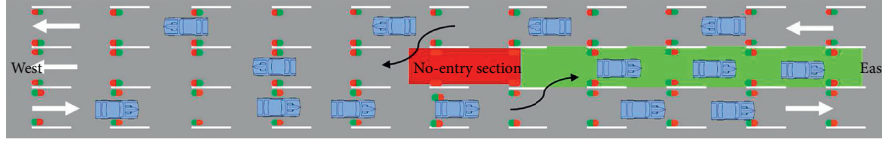


FIGURE 3: Configuration of starting conflict zone.

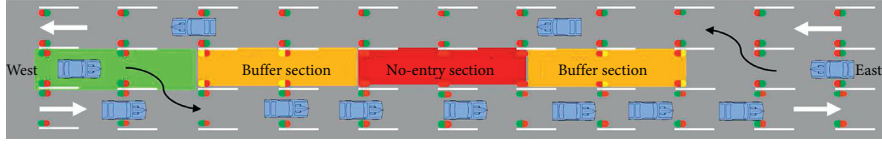


FIGURE 4: Configuration of ending conflict zone.

of the starting no-entry zone is the length of the starting conflict zone, and it is the safety following distance between vehicles. Generally, it is 5–10 m. The parameters of the ending on-entry zone are discussed below.

If a driver in one direction enters the end of the no-entry section, then they must be able to make a complete stop before the end of the no-entry section; if two drivers from opposite directions have entered the no-entry section, they must have sufficient space to stop cars to avoid a collision. Therefore, the length of the no-entry section must meet the sight distance of the vehicle and ensure the safe braking distance. The shortest length is determined by the reaction distance (l_{r1}, l_{r2}), breaking distance (l_{b1}, l_{b2}), and safety following distance (l_0) of two opposite traveling drivers as shown in Figure 5.

Assume the vehicle braking performance and response time of drivers are the same, then

$$l_1 = l_2 = \frac{V_0}{3.6}t, \quad (6)$$

$$l_{b1} = l_{b2} = \frac{V_0^2}{2g\varphi \times 3.6^2},$$

$$S = l_{r1} + l_{r2} + l_{b1} + l_{b2} + l_0,$$

where t is the reaction time ranging from 1 to 2.5 seconds, V_0 is the vehicle speed before braking, g is the gravity, and φ is the coefficient of adhesion of wheels.

2.4.3. Design of Buffer Section. If one is driving in the buffer section of a reversible lane, one should wait for the opportunity to change lanes and leave the reversible lane when one sees the yellow light on the road stud. If one reaches the buffer section and has not found the opportunity to leave the reversible lane, one should immediately brake and stop, waiting for the time to leave the reversible lane. If the one is forced to change lanes here, one should change lanes before running into a no-entry section. Therefore, the distance of the buffer section of a reversible lane must meet the maximum braking distance of the driver at the beginning the buffer section and the maximum length of the lane change forced by the driver at this point.

A vehicle will be guided to compulsory lane change at the beginning of a buffer section. According to the critical distance model of compulsory lane change, the deceleration of vehicle braking during is a and the initial driving speed is v , taking into account the degree of caution of the driver, the traffic density of the target lane, and the number of interval lanes between the current lane and the target lane. The formula for calculating the distance traveled by a vehicle during a lane change is

$$D_c = \frac{v^2}{2a} + \theta \left(\alpha_1 \frac{\rho}{\rho_{jam}} \right) + \alpha_2 n, \quad (7)$$

where θ is the cautious coefficient of drivers ranging from 0 to 1, the larger the number, the more cautious the driver is, α_1 and α_2 are parameters depends on traffic condition and number of interval lanes between the current lane and the target lane, ρ is the traffic density, ρ_{jam} is the traffic congestion density, and n is the number of reversible lanes.

Vehicle braking deceleration is related to the driver's judgment of the braking distance and is also related to the driver's driving habits, road conditions, and vehicle speed on the road. From the perspective of the braking capacity of a car, the maximum deceleration of the car during emergency braking is generally $7.5 \sim 8 \text{ m/s}^2$. For a normal braking, the average deceleration of the car should be $3 \sim 4 \text{ m/s}^2$. However, in real situation, except for emergency situations, the braking deceleration should normally be $1.5 \sim 2.5 \text{ m/s}^2$. Thus, a value of 2 m/s^2 of deceleration is used in this paper.

If the driver takes breaks at the beginning of the buffer section, the braking distance of the vehicle is calculated based on the vehicle's speed, braking performance, and road friction coefficient. The driver's reaction time from making a braking decision to force the brake is called the driver's reaction time t_0 . The time interval from when the brake is forced to when the brake is in effect is called the driver's operating time, which is represented by t_1 . Assume total the reaction time $t = t_0 + t_1$, and define t_2 is the time interval from when brake is in effect to when the car completely stops. The total braking distance of the vehicle could be calculated as follows:

$$D_b = \frac{V_0}{3.6}t + \frac{1}{2}t_2 \frac{V_0}{3.6} + \frac{V_0^2}{2g\varphi \times 3.6^2}. \quad (8)$$

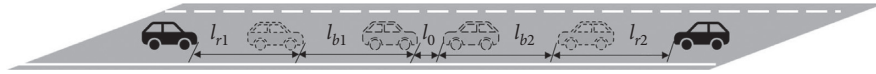


FIGURE 5: Configuration of a no-entry section.

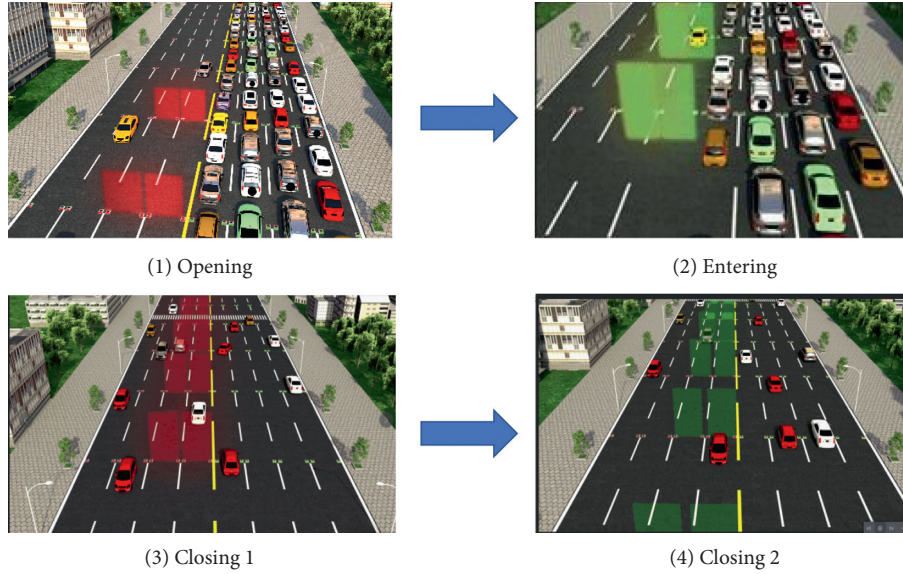


FIGURE 6: Illustrations of the real-time dynamic reversible lane operation process.

Let $t = 2.5$ s, and t_2 is negligible so the second term drops out. The reaction distance S_1 and breaking distance S_2 can be calculated as follows:

$$S_1 = \frac{V_0}{3.6} t = 0.694V_0,$$

$$S_2 = \frac{V_0^2}{2g\phi \times 3.6^2} = 0.00394 \frac{V_0^2}{\phi}, \quad (9)$$

$$D_b = S_1 + S_2 = 0.694V_0 + 0.00394 \frac{V_0^2}{\phi}.$$

The length of a buffer section is

$$L_{\text{buffer}} = \text{Max}(D_c, D_b) + l_0. \quad (10)$$

3. Simulation and Data Analysis

3.1. Simulation. In CVIS, real-time traffic information is obtained and lanes in the direction of light traffic flow are selectively cleared based on real-time traffic volume. Taking an eight-lane road as an example, the two lanes on the inner side of the light traffic flow direction are cleared, and the real-time dynamic reversible lane operation process is demonstrated through animation simulation.

- (1) *Opening.* When the reversible lane opening conditions are reached, the real-time dynamic reversible lane will be open. In the direction of light traffic, the red studs on two lanes are flashing first and the light curtain wall flashing red, indicating that the vehicles

in these lanes should leave as soon as possible. No traffic is allowed on these lanes, supplemented by a voice prompt in the car: "Please leave these lanes," as shown in Figure 6(1).

- (2) *Entering.* After the target lanes are cleared, vehicles in heavy traffic flow can merge onto the cleared lanes. First, the stud light and the light curtain wall flash green, indicating that the target lanes are about to open, and then the stud light and the light curtain wall stay constant green, indicating that the target lanes have been opened and allow entrance, as shown in Figure 6(2).
- (3) *Closing.* In the direction of the original heavy traffic, the stud lights on two lanes are first flashing red and light curtain walls flashing red, indicating that the vehicles in the lanes should leave the lane as soon as possible. Then, the stud lights and light curtain walls are in constant red, indicating that vehicles in the heavy traffic are not allowed on these two lanes and supplemented by a voice prompt in the car: "Reversible lane is closed, please drive away from these lanes," as shown in Figure 6(3). In the direction of the light traffic flow, stud lights are first flashing green and the light curtain wall flashing green as well, which indicates that the lanes are about to be reopened to light traffic. Then, the stud light and the light curtain wall are in constant green, indicating that the target lanes have been reopened to vehicles in the light traffic, as shown in Figure 6(4).

TABLE 2: Traffic flow data.

T	18:05	18:10	18:15	18:20	18:25	18:30	18:35	18:40	18:45	18:50	18:55	19:00
V_M	2560	2670	2840	3000	3260	3500	3730	3900	4000	4200	4350	4460
V_N	2100	2150	1980	1870	1740	1620	1580	1390	1280	1200	1170	1050

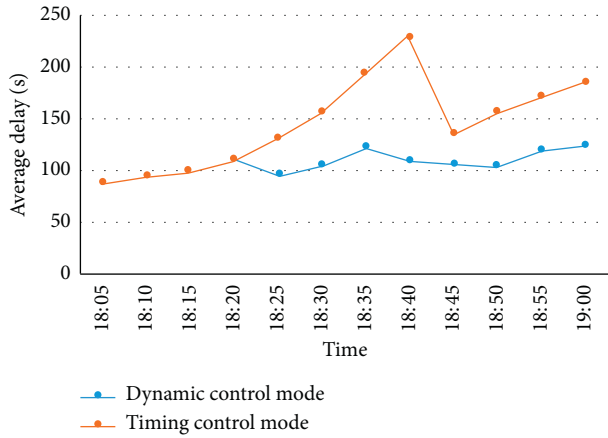


FIGURE 7: Comparison of average delay of dynamic control mode and timing control mode.

3.2. Data Analysis. A survey was conducted to collect traffic flow data from 18:00 to 19:00 of an 8-lane highway in Huai'an city, as shown in Table 2. The microscopic simulation software VISSIM and its secondary development are used to simulate and evaluate the vehicle running effect of the road in timing control mode and dynamic control mode. The timing control mode is controlled by the traffic police officer according to the traffic conditions of the road. It was turned on at 18:40 in the simulation. The dynamic control mode is controlled using the lane change control model of the proposed scheme.

Through the analysis of simulation data, with the continuous increase of road traffic, the average delay of vehicles in the dynamic control mode is relatively slow (Figure 7), the overall average delay of vehicles is reduced by 27.4%, and the vehicle VOC, CO, and NO_x emissions are reduced by 13.5%. Therefore, the dynamic control mode has better effects in improving traffic efficiency and environmental protection.

4. Conclusions

This paper proposed a real-time dynamic reversible lane scheme in CVIS. Compared with the traditional time-controlled lane change mode, the proposed scheme can reduce the average delay of vehicles by 27.4% and reduce vehicle VOC, CO, and NO_x emissions. The volume reduction of 13.5% effectively improves the imbalance of traffic flow and alleviates road congestion, improves road traffic efficiency, reduces energy consumption, and provides a new solution for the promotion of new energy-saving and environmentally friendly reversible lane designs. With the continuous development and application of urban traffic guidance system and vehicle-road collaboration technology,

combining it with this solution can more effectively optimize road resource allocation and improve vehicle traffic efficiency. The proposed dynamic signal control mode with intelligent road stud lights can guide urban roads in different road conditions. The combination with bus priority can effectively improve the utilization of existing bus lanes and other facilities. Adhering to the concept of energy saving and environmental protection, optimizing road resources, and innovating signal control modes, a new solution for the optimization of smart city transportation systems was proposed.

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 paper; Wenquan Li conducted the model and simulation; Lina Mao and Pengsen Hu wrote the paper; Guiliang Zhou designed the real-time dynamic reversible laneschemes; Huiting Zhang analyzed the simulation results, Jin Dai collected traffic data.

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