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Research Article

Research on HOV Lane Priority Dynamic Control under Connected Vehicle Environment

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The optimization of high-occupancy vehicle (HOV) lane management can better improve the efficiency of road resources. This paper first summarized the current research on HOV lane implementation and analyzed and identifies the threshold of setting road HOV lane dynamic control under the connected vehicle environment. Then, the HOV lane priority dynamic control process was determined, and the operating efficiency and energy consumption evaluation method was proposed. Moreover, a case study in Wuxi City, China, was carried out. The results showed that, after implementing the HOV lane priority dynamic control, the total mileage of road network vehicles was saved by 4.93%, the average travel time per capita was reduced by 4.27%, and the total energy-saving rate of road network travel was 21.96%.

1. Introduction

The setting of the HOV lane can provide more space resources for high-occupancy vehicles to improve traffic operation efficiency. However, it met with great controversy at the beginning [1–3] because when the HOV lane was not fully utilized at the time, road space resources were wasted [4]; Pravin and Han [5] made a comprehensive comparison between the HOV lane and the ordinary lane set in California in the United States. After investigating the HOV lane capacity, traffic operating condition, and carpooling percentage, it was believed that, under the appropriate road and traffic conditions, HOV lanes can serve to improve the traffic capacity, but when a certain saturation is reached, frequent lane changes may cause a decline in capacity. Dahlgren [6] claimed that the HOV lane setting has a significant effect on reducing carbon dioxide and other greenhouse gas emissions. Gutierrez et al. [7–10] made a detailed comparative analysis of the implementation effects of toll lanes and HOV lanes and concluded different applicable conditions for toll lanes and HOV lanes. Chen [11] discussed the experience and lessons of HOV priority planning and application worldwide in detail and proposed the necessity and feasibility of introducing HOV priority into urban transportation planning in China. The conclusion shows that the development level and urban residential characteristics of intelligent transportation technology in China have provided the necessary conditions for the implementation of HOV lanes.

Wang [12] put forward conceptual plans for carpooling priority based on the design experience of HOV schemes and pointed out that road, traffic, and urban land use functions are the key influencing factors of HOV lane setting in large cities. Bi [13] conducted an in-depth study on the carpooling rate model after the HOV lanes were set up and clarified the change law of the carpooling rate under the conditions of different passenger numbers for buses and HOV vehicles, thus proving the necessity and feasibility of setting HOV lanes in urban cities. Wu and Pan [14] analyzed and studied the relationship between the BRT lanes and

HOV lanes on urban roads and the implementation strategy; some scholars also studied aspects such as operating efficiency and traffic conditions. The feasibility of HOV lane setting has been systematically studied [15–21], which provides a theoretical basis for the scientific and rational setting of HOV lanes. In summary, most of the previous studies focused on the feasibility of HOV lane setting, road conditions, and HOV lane static management. However, the dynamic control of HOV lanes based on real-time data is ignored. With the rapid development and improvement of information technology and Internet of Vehicles (IoV) technology, it is feasible to realize HOV lane dynamic control using real-time data for carpooling priority.

2. Threshold Determination for Setting HOV Lanes Priority Dynamic Control under Connected Vehicle Environment

HOV lanes provide the right of way for high-occupancy vehicles. It improves the operating efficiency of highways and attracts more people to carpool, thus reducing the number of trips by private cars with low occupancy, and alleviates the urban traffic congestion. At present, the use of HOV lanes mostly adopts the fixed scheme. With the development of data acquisition methods, it will be feasible to implement dynamic intelligent control over the HOV lanes under connected vehicle environment, which will realize the optimal management of infrastructure resources.

In this section, in order to provide a basis for the dynamic control of HOV lanes with carpool priority, the threshold determination of introducing HOV lanes under connected vehicle environment was analyzed.

2.1. Speed-Volume Model. The BPR (Bureau of Public Roads) model shows the functional relationship between the travel time of road segments and the traffic load:

$$T(q) = T_0\left[1 + \alpha\left(\frac{q}{c}\right)^{\beta}\right], \tag{1}$$

where $T(q)$ refers to the travel time at flow q, T_0 is the travel time when traffic volume $q = 0$, C is the traffic capacity, and α and β are model parameters.

For the same traveler, the travel distance is a constant; therefore, equation (1) can be converted to the following equation:

$$V(q) = \frac{V_0}{\left[1 + \alpha(q/c)^{\beta}\right]}, \tag{2}$$

where $V(q)$ refers to the traffic speed and V_0 refers to the free-flow speed under the condition of mixed traffic of vehicles with different occupancy rates.

The free-flow speed can be determined by the road grade, and its recommended value is shown in Table 1.

In terms of the urban roads, V_0 is mainly related to intersection spacing, stop time of stations, signal period duration, and green signal ratio, which can be calculated by the following equation:

Table 1: Recommended value of free-flow speed for different grades of roads (km/h).

Road grade	Expressway	Arterial road	Collector road
Free-flow speed	60~80	50~60	40~50

$$V_0 = \frac{L}{\left(\left(L/V_f\right) + d\right)}, \tag{3}$$

where d refers to the average delay at intersections, L is the length of road segments, and V_f refers to the free-flow speed.

2.2. Speed-Volume Model Calibration. The least square method was used to calibrate the speed-volume model under the condition of mixed traffic and having HOV lane is as follows:

$$V(q) = \frac{31}{\left[1 + 1.03(q/c)^{3.01}\right]}. \tag{4}$$

2.3. Threshold for Introducing HOV Lane. For traffic travelers, the important indicator for evaluating travel quality is travel time, which heavily depends on the traffic condition. The traffic condition could be divided into two states: the ideal state and the actual state. Then, travel time is divided into ideal travel time and actual travel time as well. Actual travel time usually includes two parts: ideal travel time and ideal travel delay. The ideal travel time is only related to the travel distance and travel mode; that is, when the travel distance and mode are fixed, the ideal travel time is a fixed value, but the ideal travel delay will be determined by the traffic condition and will continue to increase as the traffic condition changes. The improvement and reduction of the traffic condition can effectively reflect the operating efficiency of the road network. This paper takes per capita delay as the evaluation index of road network operation efficiency. The threshold of introducing HOV lanes was investigated by minimizing per capita delay index.

The per capita delay index d' could be calculated by using the following equation:

$$d' = \frac{\left(q_b \cdot n_b \cdot d_b + q_c \cdot n_c \cdot d_C\right)}{\left(q_b \cdot n_b + q_c \cdot n_c\right)}, \tag{5}$$

where q_b refers to the traffic volume of high-occupancy vehicles, n_b represents the number of people in each occupancy vehicle, d_b refers to the delay for each high-occupancy vehicle, q_c refers to the traffic volume of nonhigh-occupancy vehicles, n_c represents the number of people in each nonoccupancy vehicle, and d_c refers to the delay for each nonoccupancy vehicle.

Per vehicle delay d can be calculated as follows:

$$d = \left(\frac{L}{V}\right)(q) - \left(\frac{L}{V_0}\right). \tag{6}$$

According to the previous survey and data analysis, about 2/3 of the people who own private cars are willing to take carpool, and about 1/3 of the people owning private cars show reluctance to carpooling, as shown in Figure 1.

It can be seen from Figure 2 that most (50.3%) high-occupancy vehicles have two passengers, followed by one passenger (24.56%) and three passengers (24.26%). Only 0.89% high-occupancy vehicles have four passengers.

Taking the bidirectional 6-lane road as an example, assume $q_b = (160veh/h)$ and $n_b = 3$, the threshold of setting HOV lanes priority dynamic control was determined as follows: firstly, substitute the traffic volumes into equations (3) and (4) to get the speed of high-occupancy and nonhigh-occupancy vehicles. Then, substitute the speeds into equation (6) to get the per vehicle delay for high-occupancy and nonhigh-occupancy vehicles. Finally, the per capita delay could be obtained by substituting the per vehicle delays into equation (5). Figure 3 shows the relationship between the per capita delay and the traffic volume before and after introducing HOV lane.

If we change the q_b from 160 to 180 vehicle per hour while other conditions remain the same, then the relationship between per capita delay and traffic volume is shown in Figure 4:

When the traffic volume of high-occupancy vehicles equals 160 vehicles per hour, it can be seen from Figure 3 that the normal mixed traffic has less per capita delay than the traffic with HOV lane when traffic volume is less than 600 vehicles per hour. It means that it is unsuitable to set a HOV lane. However, when the traffic volume is greater than 600, a HOV lane should be implemented to reduce the per capita delay. In this case, traffic volume of 600 vehicles per hour is the threshold for setting the HOV lane. Similarly, it can be seen from Figure 4 that when the volume of high-occupancy vehicles equals 180 vehicles per hour, the threshold is 640 vehicles per hour. The thresholds for different traffic volumes of high-occupancy vehicles are presented in Table 2.

2.4. HOV Lane Priority Dynamic Control Process with Carpooling under Connected Vehicle Environment. After determining the threshold of setting HOV lanes, this paper selected carpooling ratio, degree of saturation (v/c), and average traffic speed as the indictors for HOV lane priority dynamic control.

Taking a cycle at the downstream intersection of the road section as the time scale, the dynamic control flow chart is shown in Figure 5.

Step 1: using GPS, RFID, information transmission network, and other information collection technologies under the connected vehicle environment to collect the basic traffic information needed.

Step 2: performing data preprocessing, data cleaning, data repair, and screening on the data collected in step 1.

Step 3: uploading the processed data to the traffic information center.

Step 4: displaying the traffic information and theoretically analyzing the demand for setting HOV lanes based on the carpooling ratio, degree of saturation (v/c), and average traffic speed.

Step 5: setting the time scale as the signal cycle of the downstream intersection.

Step 6: determining the number of passengers on high-occupancy vehicles (carpooling).

Step 7: judging if the normal mixed traffic volume if greater than the threshold value. If yes, then HOV lanes only allow high-occupancy vehicles to access (setting HOV lanes). If no, HOV lanes open to all vehicles with different occupancy rates (removing HOV lanes).

Step 8: repeating step 4 to step 7.

2.5. Evaluation of Implementing HOV Lane Priority Dynamic Control. Real-time traffic information such as number of passengers, travel time, vehicle location, and vehicle type can be obtained through connected vehicle technologies. In this paper, the reduction in per capita travel time and total travel mileage is selected as the evaluation indicator of the implementation of the HOV lane priority dynamic control.

The main ideas are as follows: firstly, the real-time traffic operation condition of the road network in the mixed traffic state (before setting HOV lanes) is obtained: the number of passengers, travel time, and travel mileage. Secondly, based on the information above, the total travel mileage and travel time in the mixed traffic state can be calculated. Thirdly, theoretical analysis will be conducted to estimate the traffic operation condition assuming the HOV lanes were introduced and the total travel mileage and travel time of the new traffic state (after setting the HOV lanes) could be calculated as well. Finally, evaluate the effectiveness of implementing HOV lane priority dynamic control by vehicle mileage saving rate and reduction rate of per capita travel time consumption. The flow chart is shown in Figure 6.

2.5.1. Traffic Information Acquisition in Mixed Traffic. Assume there are m sections in the road network and n cars in each section, then the vehicle mileage of the road network in the most initial operating state (mixed traffic) can be expressed as follows:

$$S_0 = \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij0}, \tag{7}$$

where S_{ij0} is the mileage of the ith vehicle in the jth section of the road network and S_0 is the total mileage of the vehicles.

Then, the total travel time in the initial operating state could be calculated as follows:

$$PI_0 = P_{a0} * T_{a0} + P_{b0} * T_{b0} + P_{c0} * T_{c0}, \tag{8}$$

where PI_0 is the total travel time, P_{a0} is the number of noncarpooling travelers, T_{a0} is the average travel time of noncarpooling travelers, P_{b0} is the number of carpooling travelers, T_{b0} is the average travel time of carpooling travelers, P_{c0} is the number of public transportation travelers,

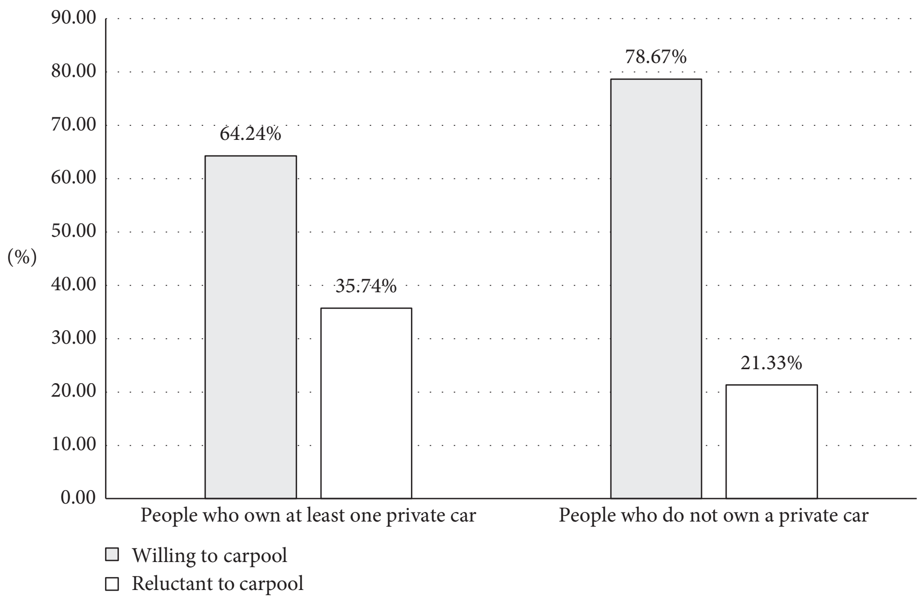

Figure 1: Bar graph of the carpooling willingness.

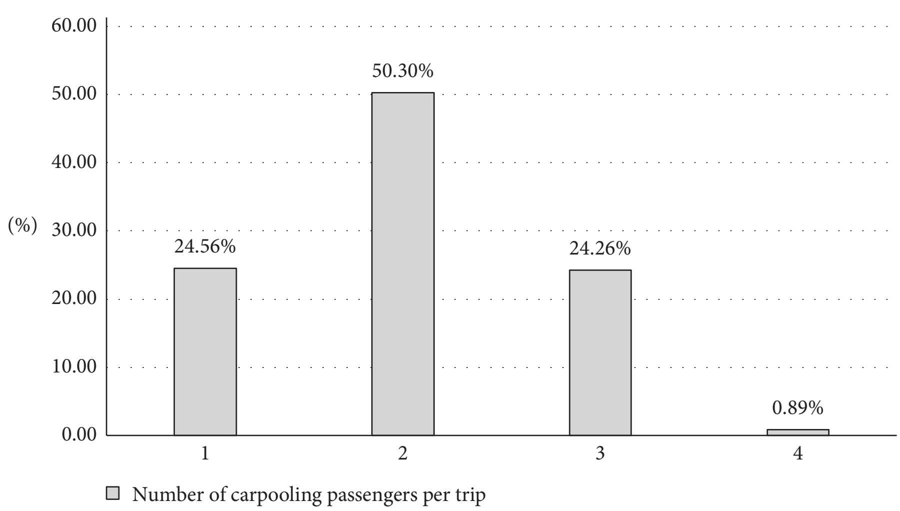

Figure 2: Bar graph of different carpooling passenger numbers.

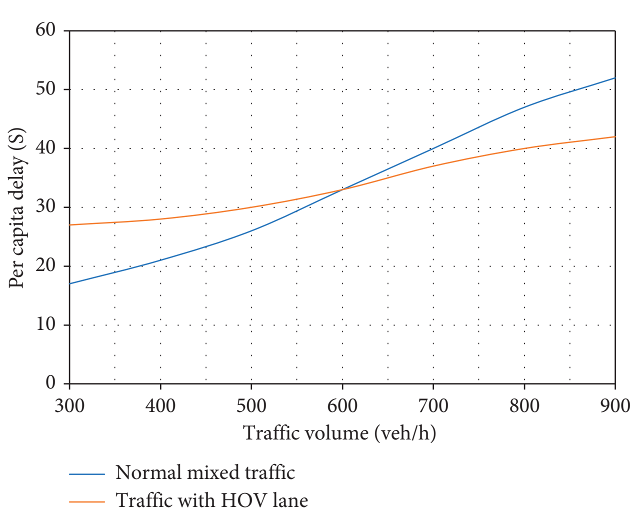

Figure 3: Per capita delay under different traffic conditions at $q_b = 160$ and $n_b = 3$.

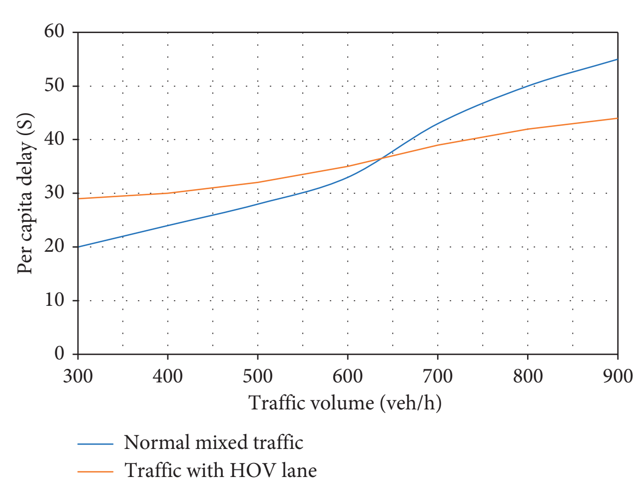

Figure 4: Per capita delay under different driving conditions at $q_b = 180$ and $n_b = 3$.

Table 2: Thresholds for different traffic volumes of high-occupancy vehicles.

Traffic volumes of high-occupancy vehicles (veh/h)	Number of passengers per high-occupancy vehicle (p/veh)	Threshold (veh/h)
150	2	592
	3	580
	4	566
	>4	560
160	2	615
	3	600
	4	582
	>4	575
180	2	650
	3	640
	4	628
	>4	614
200	2	693
	3	675
	4	662
	>4	648

and T_{a0} is the average travel time of public transportation travelers.

2.5.2. Transportation Mode Transfer. After the implementation of the HOV lane priority dynamic control, the trips of low-occupancy vehicles (private cars) in the road network will shift to high-occupancy vehicles (carpool). Through presurvey, the travel mode transfer function under different states is obtained, as shown in Table 3.

2.5.3. Traffic Information Acquisition in Traffic with HOV Lanes. Assume there are m sections in the road network and n cars in each section, and then, the total vehicle mileage of the road network in the posterior operating state (after setting HOV lanes) can be expressed as follows:

$$S_1 = \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij1}, \quad (9)$$

where S_{ij1} is the mileage of the i-th vehicle in the j-th section of the road network and S_1 is the total mileage of the vehicles.

Then, the total travel time in the v could be calculated as follows:

$$PI_1 = P_{a1} * T_{a1} + P_{b1} * T_{b1} + P_{c1} * T_{c1}, \quad (10)$$

where PI_1 is the total travel time, P_{a1} is the number of noncarpooling travelers, T_{a1} is the average travel time of noncarpooling travelers, P_{b1} is the number of carpooling travelers, T_{b1} is the average travel time of carpooling travelers, P_{c1} is the number of public transportation travelers, and T_{a1} is the average travel time of public transportation travelers.

2.5.4. Operating Efficiency Evaluation. The percentage reduction in total travel mileage can be expressed as follows:

$$M = \frac{\sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij0} - \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij1}}{\sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij0}}. \quad (11)$$

Similarly, the percentage reduction in per capita travel time can be expressed as follows:

$$p = \frac{PI_0/(P_{ao} + P_{bo} + P_{co}) - PI/(P_{a1} + P_{b1} + P_{c1})}{PI_0/(P_{ao} + P_{bo} + P_{co})}. \quad (12)$$

2.5.5. Energy Consumption Evaluation. Evaluation and comparison of road network energy consumption before and after HOV lane priority dynamic control is of great significance for the promotion and application of HOV lanes. According to the literature [22, 23], the energy consumption of different transportation modes in cities is summarized in Tables 4 and 5.

According to the actual situation of the investigated city, the energy consumption of noncarpooling private car trips, carpooling private car trips, and public bus trips with single compartment was selected as 10.17 (25%), 3.67 (75%), and 1.24 (50%), respectively.

The total energy-saving rate of road network can be calculated by the following equation:

$$H = \frac{\left(\alpha_m \cdot P_{a0} \cdot J_{a0} \cdot Q_{a0} + \beta_n \cdot P_{b0} \cdot J_{b0} \cdot Q_{b0} + \gamma_g \cdot P_{c0} \cdot J_{c0} \cdot Q_{c0}\right) - \left(\alpha_m \cdot P_{a1} \cdot J_{a1} \cdot Q_{a1} + \beta_n \cdot P_{b1} \cdot J_{b1} \cdot Q_{b1} + \gamma_g \cdot P_{c1} \cdot J_{c1} \cdot Q_{c1}\right)}{\alpha_m \cdot P_{a0} \cdot J_{a0} \cdot Q_{a0} + \beta_n \cdot P_{b0} \cdot J_{b0} \cdot Q_{b0} + \gamma_g \cdot P_{c0} \cdot J_{c0} \cdot Q_{c0}}, \quad (13)$$

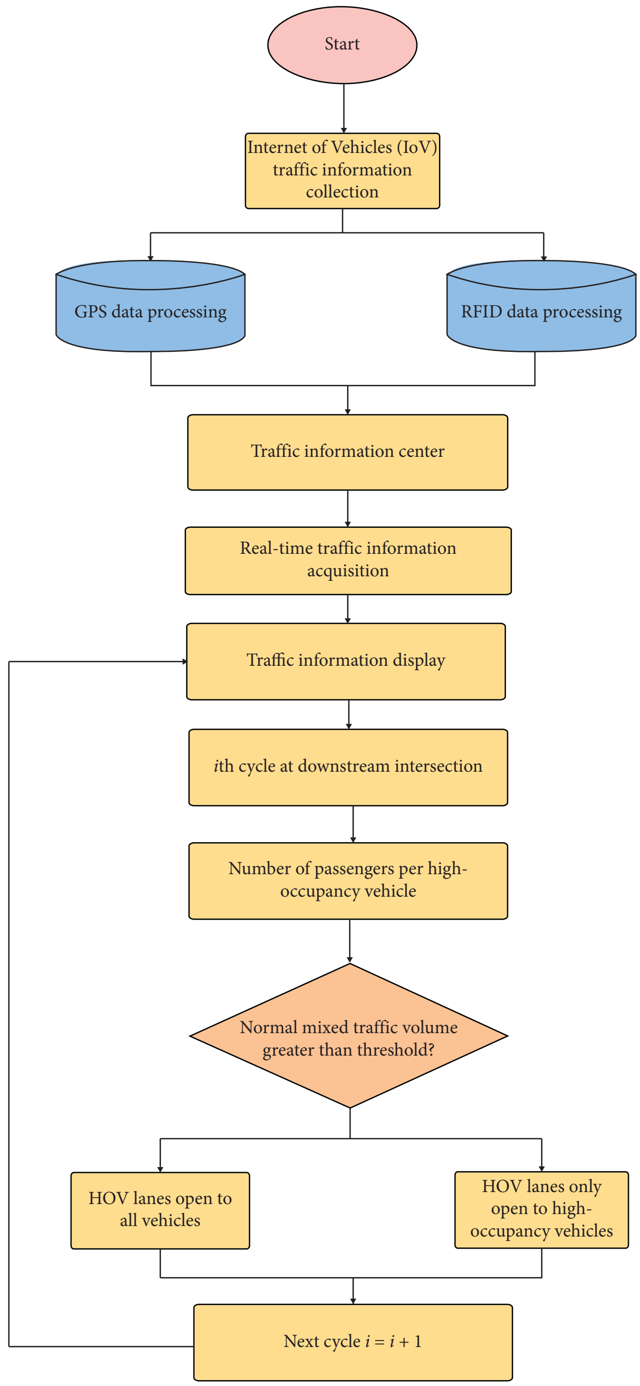

Figure 5: Flow chart of HOV dynamic control process.

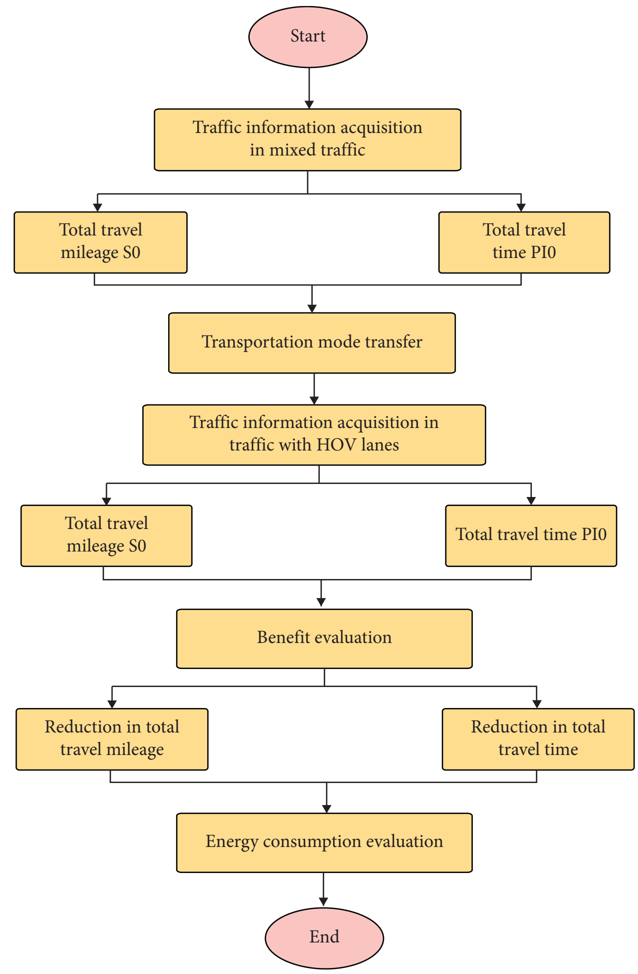

Figure 6: The evaluation process of implementing HOV lane priority dynamic control.

Table 3: The state functions of the transfer from private car to carpool.

State	Percentage increase in travel time (k)	Transfer function $f(k)$
1	<10%	$f(k) = -3.84k + 0.6293$
2	10%–30%	$f(k) = -1.179k + 0.3765$
3	30%–40%	$f(k) = -0.9735k + 0.4224$
4	40%–50%	$f(k) = -0.6045k + 0.0825$
5	>50%	$f(k) = -0.7168k + 0.0029$

where H is the total energy-saving rate of road network; α_m is the energy consumption coefficient of noncarpooling trips, $10.17 \times 10{-}5$ L/p·m; β_n is the energy consumption coefficient of carpooling trips, $3.76 \times 10{-}5$ L/p·m; γ_g is the energy consumption coefficient of public bus trips, $1.24 \times 10{-}5$ L/p·m; J_{a0} is the average travel mileage of noncarpooling trips in the initial operating state (mixed traffic), m; J_{b0} is the average travel mileage of carpooling trips in the initial operating state (mixed traffic), m; J_{c0} is the average travel mileage of public bus trips in the initial operating state (mixed traffic), m; Q_{a0} is the number of vehicles of noncarpooling trips in the initial operating state (mixed traffic), veh; Q_{b0} is the number of vehicles of carpooling trips in the initial operating state (mixed traffic), veh; Q_{c0} is the number of vehicles of public bus trips in the initial operating state (mixed traffic), veh; J_{a1} is the average travel mileage of noncarpooling trips in the posterior operating state (after setting HOV lanes), m; J_{b1} is the average travel mileage of carpooling trips in the posterior operating state (after setting HOV lanes), m; J_{c1} is the average travel mileage of bus trips in the posterior operating state (after

Table 4: Energy consumption comparison of different types of vehicles.

Vehicle categories	Sedan		Public bus	
	Taxi	Private car	Bus with multiple compartments	Bus with single compartment
Fuel consumption (liter/100 km)	10.2	11	25.5	22.5
Energy consumption (liter/(100 people*km))	7.34	6.78	0.41	0.73
Energy consumption (kg standard coal/(100 people*km))	8.52	7.87	0.48	0.85

Note: coefficient for standard coal to fuel conversion = 0.7895 kg/liter × 1.4714 kg standard coal/kg = 1.1617 kg standard coal/liter.

Table 5: Energy consumption comparison of different types of vehicles with different occupancies.

Vehicle categories		Seating capacities	Energy consumption under different occupancies (liter/100 people*km)			
			25%	50%	75%	100%
Sedan	Taxi	4	7.159	3.759	2.68	2.066
	Private car	5	10.17	5.09	3.76	2.95
Public bus	Bus with multiple compartments	80	1.28	0.70	0.51	0.41
	Bus with single compartment	40	2.25	1.24	0.90	0.73

Table 6: Traffic information of the selected roads.

Traffic direction	Road code	Road name	One-way	No. of lanes	Peak hour traffic volume (pcu/h)	Length (m)
Northbound/ Southbound	1	Changjiang North Road	No	6	1548	4120
	2	Xingyuan Middle Road	No	6	1942	4360
	3	Tangnan Road	No	6	1920	3730
	4	Tongyang Road (extended to Jiefang North Road)	No	4	1152	4920
Eastbound/ Westbound	5	Tongjiang Road	No	8	1736	2710
	6	Renmin East Road	No	6	2984	2330
	7	Xueqian East Road	No	6	2275	2340
	8	Yongle East Road	No	6	1697	3690
	9	South Ring Road	No	6	7934	3470

setting HOV lanes), m; Q_{a1} is the number of vehicles of noncarpooling trips in the posterior operating state (after setting HOV lanes), veh; Q_{b1} is the number of vehicles of carpooling trips in the posterior operating state (after setting HOV lanes), veh; and Q_{c1} is the number of vehicles of public bus trips in the posterior operating state (after setting HOV lanes), veh.

3. Case Study-HOV Lane Dynamic Control in Wuxi City, China

3.1. HOV Lane Dynamic Control Scheme in Wuxi City. Wuxi, Jiangsu, is the first city in China to implement HOV lane priority dynamic management and has achieved good results. Both Liangxi District and Xinwu District of Wuxi City are located in the southeast of Jiangsu Province and are located in the city center of Wuxi. The current resident population of Liangxi District is 950,000, and the current resident population of Xinwu District is 364,400. On May 16, 2014, China's first dedicated carpooling lane "HOV lane" was introduced in Wuxi City.

In field survey, the following roads shown in Table 6 were selected to investigate the threshold of setting HOV lanes.

According to the survey, carpooling trips account for 5% of the total private car trips in Wuxi City. Firstly, equation (3) was used to calculate the traffic speed of each road and determine the average delay time considering the signal control of the intersection to obtain the operating efficiency of private car trips in the area, as shown in Table 7.

The operation efficiency of the intersections in the investigated area is summarized in Table 8, and the travel time and travel mileage of different travel modes in the initial operating state are summarized in Table 9.

Travelers in Wuxi City can make reservations online according to their travel time and route in advance. The online system will automatically match according to user needs and supply. This section will scientifically evaluate the efficiency of Wuxi carpooling trips.

Carpooling travel time is mainly composed of waiting time, travel time, and detour time. The travel time is determined by the travel path. The waiting time and detour time are mainly determined by the time and space distribution density of carpooling travelers, as shown in Table 10.

TABLE 7: Operation efficiency of the road network in the investigated area.

Road code	Road name	Traffic volume per hour (pcu/h)	Length (m)	Free-flow speed (km/h)	Traffic speed (km/h)
1	Changjiang North Road	1548	4120	60	54
2	Xingyuan Middle Road	1942	4360	60	56
3	Tangnan Road	1920	3730	50	45
4	Tongyang Road (extended to Jiefang North Road)	1152	4920	40	32
5	Tongjiang Road	1736	2710	80	75
6	Renmin East Road	2984	2330	40	35
7	Xueqian East Road	2275	2340	40	32
8	Yongle East Road	1697	3690	40	36
9	South Ring Road	7934	3470	80	71
10	East Ring Road	10451	6200	80	73
11	Xingchang South Road	3221	4450	80	67

TABLE 8: Operation efficiency of the intersections.

Intersection code	Name of the intersecting roads	Traffic volume (pcu/h)	Signal cycle (s)	Per capita delay (s)
1	Tongyang Road, Tongjiang Road, and Xingyuan Middle Road	561	80	25.36
2	Xingyuan Middle Road and Renmin East Road	1484	125	30.91
3	Tongyang Road and Renmin East Road	464	60	22.15
4	Tangnan Road and Renmin East Road	1434	No signal	—
5	Xingyuan Middle Road and Renmin East Road	473	80	30.15
6	Tongyang Road and Xueqian East Road	397	60	18.36
7	Tangnan Road and Xueqian East Road	1569	80	42.36
8	Xingyuan Middle Road and Xueqian East Road	512	80	35.12
9	Changjiang North Road and Xueqian East Road	833	120	40.48
10	Tongyang Road and Yongle East Road	483	55	18.23
11	Tangnan Road and Yongle East Road	1829	110	37.52
12	Xingyuan Middle Road and Yongle East Road	1669	75	24.58
13	Changjiang North Road and Yongle East Road	948	120	27.93
14	Tongyang Road and South Ring Road	617	No signal	—
15	Tangnan Road and South Ring Road	1973	No signal	—
16	Xingyuan Middle Road and South Ring Road	1967	No signal	—
17	Changjiang North Road and South Ring Road	1132	No signal	—

3.2. Efficiency and Energy Consumption Evaluation of HOV Lane Priority Dynamic Control in Wuxi City

3.2.1. Preliminary Analysis of Operation Efficiency. After setting up HOV lane, the traffic speed of private cars on ordinary lanes (noncarpooling lanes) is shown in Table 11.

After setting up HOV lane, the traffic speed of private cars on the carpooling lanes is shown in Table 12.

The travel time of noncarpooling private car trips and carpooling private car trips is calculated and summarized in Table 13.

3.2.2. Travel Mode Transfer. Based on of the influence of the increment of travel time on carpooling behavior, after setting HOV lanes, the increase in carpooling travel time is 21.7% compared with that of noncarpooling travel time. The transfer ratio of low-occupancy travel mode to high-occupancy travel mode is 12.0%.

3.2.3. Operation Efficiency Analysis after Travel Mode Transferring. The travel time and travel mileage of different travel modes after travel mode transferring are summarized in Table 14. Moreover, the comparison of number of trips, number of travelers, travel time, and travel mileage in initial (mixed traffic) and posterior operating state (after travel mode transferring) is presented in Figures 7–10, respectively.

3.2.4. Final Evaluation of Operation Efficiency and Energy Consumption. The percentage reduction in total travel mileage can be calculated as follows:

$$M = \frac{80704908 - 76729943}{80704908} = 4.93\%. \tag{14}$$

The percentage reduction in per capita travel time can be calculated as follows:

$$p = \frac{1138 - 1089}{1138} = 4.27\%. \tag{15}$$

Table 9: Travel time and travel mileage of different travel modes in the initial operating state (mixed traffic).

Code	Travel mode	Initial operating state (mixed traffic)			
		Number of vehicles (veh)	Number of travelers (p)	Travel time (s)	Travel mileage (m)
1	Noncarpooling private car trips	23188	23188	1054	3243
2	Carpooling private car trips	384	1360	1625	4970
3	Public bus trips	816	6796	1326	4409
Sum	—	24388	31344	—	—

Table 10: Travel time and detour time for different proportions of carpool trips.

Proportion of carpooling trips (%)	Area (km^2)	No. of vehicles (veh)	Time density (veh/s)	Coverage (m)	Waiting time (s)	Detour time (s)	Total (s)
5	14.87	406	8.86	267.78	298	658	955
10.0	14.87	813	4.43	189.35	210	359	569
15.0	14.87	1219	2.95	154.60	172	259	431
20.0	14.87	1626	2.21	133.89	149	209	358
25.0	14.87	2032	1.77	119.75	133	180	313
30.0	14.87	2439	1.48	109.32	121	160	281
35.0	14.87	2845	1.27	101.21	112	145	258
40.0	14.87	3252	1.11	94.67	105	135	240
45.0	14.87	3658	0.98	89.26	99	126	226
50.0	14.87	4065	0.89	84.68	94	120	214

Table 11: The traffic speed of private cars on ordinary lanes.

Code	Road name	Traffic volume per hour (pcu/h)	Length (m)	Free-flow speed (km/h)
1	Changjiang North Road	4120	60	40
2	Xingyuan Middle Road	4360	60	44
3	Tangnan Road	3730	50	34
4	Tongyang Road (extended to Jiefang North Road)	4920	40	28
5	Tongjiang Road	2710	80	48
6	Renmin East Road	2330	40	27
7	Xueqian East Road	2340	40	22
8	Yongle East Road	3690	40	18
9	South Ring Road	3470	80	42
10	East Ring Road	6200	80	36
11	Xingchang South Road	4450	80	45

Table 12: The speed of private cars on HOV lanes.

Code	Road name	Traffic volume per hour (pcu/h)	Length (m)	Free-flow speed (km/h)
1	Changjiang North Road	4120	60	60
2	Xingyuan Middle Road	4360	60	56
3	Tangnan Road	3730	50	50
4	Tongyang Road (extended to Jiefang North Road)	4920	40	38
5	Tongjiang Road	2710	80	78
6	Renmin East Road	2330	40	35
7	Xueqian East Road	2340	40	32
8	Yongle East Road	3690	40	40
9	South Ring Road	3470	80	71
10	East Ring Road	6200	80	75
11	Xingchang South Road	4450	80	74

Table 13: Travel time and travel mileage of different travel modes in posterior operating state (with HOV lanes).

Code	Travel modes	Posterior operating state (with HOV lanes)			
		Number of vehicles (veh)	Number of travelers (p)	Travel time (s)	Travel mileage (m)
1	Noncarpooling private car trips	23188	23188	1060	3243
2	Carpooling private car trips	384	1360	1291	4970
3	Public bus trips	816	6796	1287	4409
Sum	—	24388	31344	—	—

Table 14: Travel time and travel mileage of different travel modes after travel mode transferring in the posterior operating state (with HOV lanes).

Code	Travel mode	Posterior operating state (with HOV lanes)			
		Number of vehicles (veh)	Number of travelers (p)	Travel time (s)	Travel mileage (m)
1	Noncarpooling private car trips	20405	20405	1006	3243
2	Carpooling private car trips	1568	4143	1225	4438
3	Public bus trips	816	6796	1256	4409
Sum	—	22789	31344	—	—

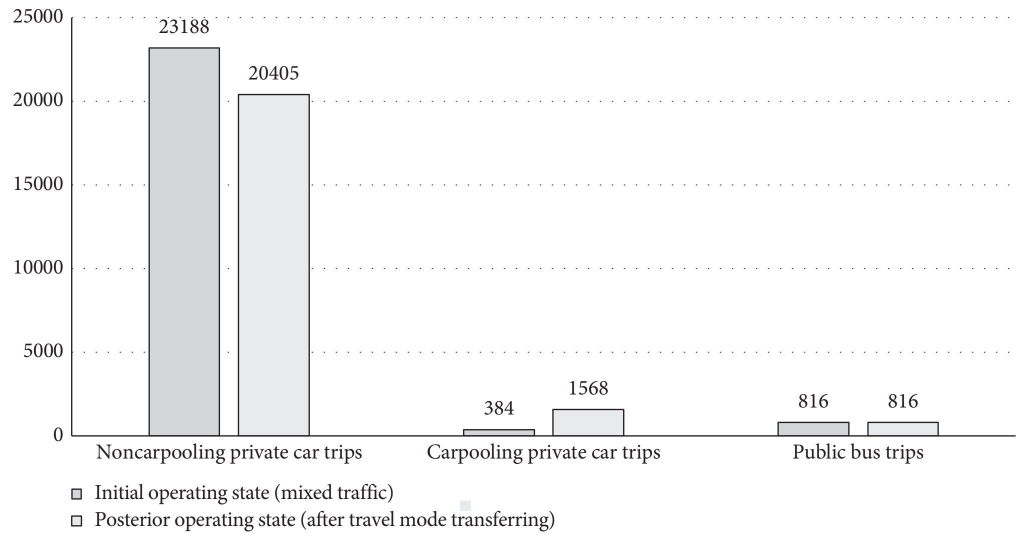

Figure 7: Comparison of number of trips before and after implementing HOV lanes priority dynamic control for different travel modes.

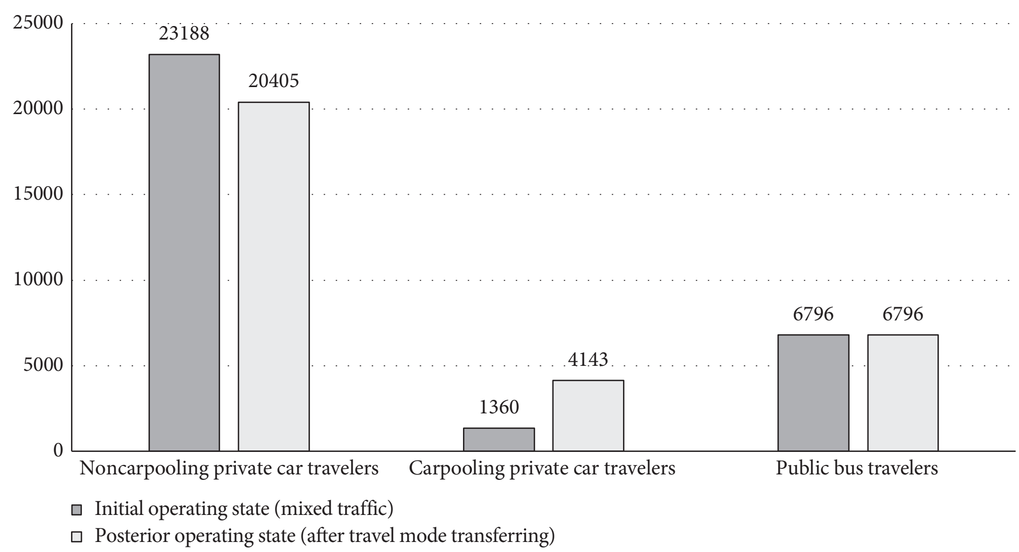

Figure 8: Comparison of number of travelers before and after implementing HOV lanes priority dynamic control for different travel modes.

The total energy-saving rate of the road network can be calculated as follows:

$$H = \frac{177735785.9 - 138709510.2}{177735785.9} = 21.96\%. \quad (16)$$

To sum up, after HOV lane priority dynamic control was implemented and travel mode transferring was completed, the total mileage of vehicles on the road network was saved by 4.93% and the per capita travel time decreased from 1138 s to 1089 s, with a reduction rate of 4.27%; the total

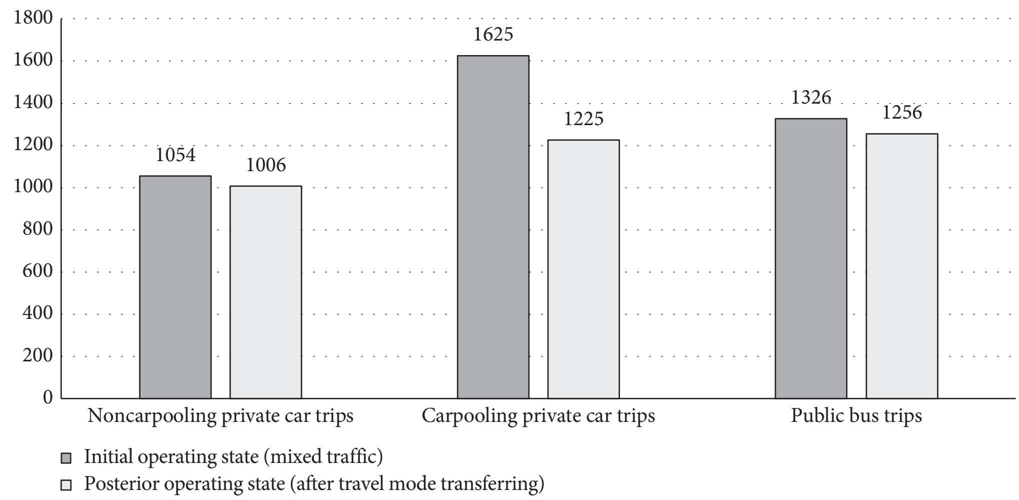

Figure 9: Comparison of travel time before and after implementing HOV lanes priority dynamic control for different travel modes.

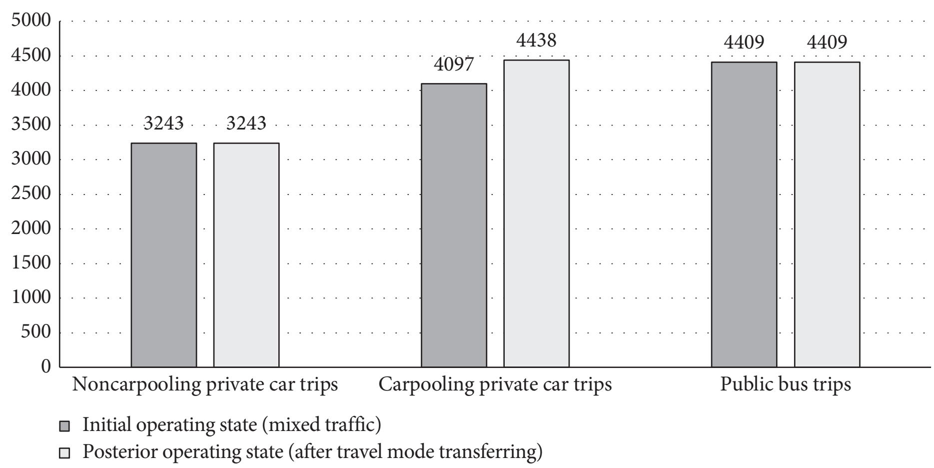

Figure 10: Comparison of travel mileage before and after implementing HOV lanes priority dynamic control for different travel modes.

energy consumption of trips in the network was reduced by 39,26275.62 L, with a saving rate of 21.96%.

4. Conclusions

This paper first summarized the current research on HOV lane implementation and analyzed and identifies the threshold of setting road HOV lane dynamic control under the connected vehicle environment. Moreover, the HOV lane priority dynamic control process was determined, and the operating efficiency and energy consumption evaluation method was proposed. A case study in Wuxi City, China, was carried out. The results showed that, after implementing the HOV lane priority dynamic control, the total mileage of road network vehicles was saved by 4.93%, the average travel time per capita was reduced by 4.27%, and the total energy-saving rate of road network travel was 21.96%. From the results, it can be seen that dynamic control of HOV lanes with priority for carpooling can save the total mileage of vehicles in the road network, the average travel time per capita, and the total energy consumption, thus improving travel efficiency. With the further development of IoV technology, the dynamic management and control of HOV lanes can be combined with real-time dynamic reversible lane technology to achieve real-time dynamic control of HOV reversible lanes to achieve precise control optimization.

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

Guiliang Zhou conceived and designed the paper. Guiliang Zhou and Pengsen Hu wrote the paper. Lina Mao and Pengsen Hu conducted the model. Feng Sun and Xu Bao collected traffic data.

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