Research Article

Research on HOV Lane Priority Dynamic Control under Connected Vehicle Environment

Guiliang Zhou,1,2 Lina Mao,1,3 Pengsen Hu,4 Feng Sun,5 and Xu Bao1

1Jiangsu Key Laboratory of Traffic and Transportation Security, Huaiyin Institute of Technology, Huaian 223003, China
2School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China
3School of Transportation, Southeast University, Nanjing 210096, China
4Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, USA
5School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, Shandong 255049, China

Correspondence should be addressed to Guiliang Zhou; zglpaper@qq.com and Lina Mao; 30721409@qq.com

Received 5 May 2020; Revised 16 July 2020; Accepted 23 July 2020; Published 8 August 2020

Academic Editor: Zhuping Zhou

Copyright © 2020 Guiliang Zhou et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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
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:

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

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 \( \alpha \) and \( \beta \) are model parameters.

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

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

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:

\[ V_0 = \frac{L}{\left( \frac{L}{V_f} + d \right)}, \quad (3) \]

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:

\[ V(q) = \frac{31}{\left( 1 + 1.03 \left( \frac{q}{c} \right)^{0.01} \right)}, \quad (4) \]

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:

\[ d^* = \frac{\left( q_b \cdot n_b \cdot d_b + q_c \cdot n_c \cdot d_c \right)}{\left( q_b \cdot n_b + q_c \cdot n_c \right)}, \quad (5) \]

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 non-high-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:

\[ d = \left( \frac{V}{V_0} \right) - \left( \frac{L}{V_0} \right). \quad (6) \]
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 \( q_b = (160 \text{veh/h}) \) 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 non-high-occupancy vehicles. Then, substitute the speeds into equation (6) to get the per vehicle delay for high-occupancy and non-high-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 indicators 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:

\[
S_0 = \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij0},
\]  

(7)

where \( S_{ij0} \) is the mileage of the \( i \)th vehicle in the \( j \)th 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:

\[
PI_0 = P_{a0} \cdot T_{a0} + P_{b0} \cdot T_{b0} + P_{c0} \cdot T_{c0},
\]  

(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 $n_b = 3$. 

Willing to carpool
Reluctant to carpool

Number of carpooling passengers per trip

Per capita delay (S)

Normal mixed traffic
Traffic with HOV lane
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:

$$S_i = \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij},$$  \hspace{1cm} (9)$$

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

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

$$PL_v = P_{a1} \cdot T_{a1} + P_{b1} \cdot T_{b1} + P_{c1} \cdot T_{c1},$$  \hspace{1cm} (10)$$

where $PL_v$ 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 $T_{c1}$ 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:

$$M = \frac{\sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij} - \sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij}}{\sum_{j=0}^{m} \sum_{i=0}^{n} S_{ij}},$$  \hspace{1cm} (11)$$

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

$$P = \frac{PL_v/(P_{a0} + P_{b0} + P_{c0}) - PL_v/(P_{a1} + P_{b1} + P_{c1})}{PL_v/(P_{a0} + P_{b0} + P_{c0})},$$  \hspace{1cm} (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:

$$H = \frac{\left(\sigma_m \cdot P_{a0} \cdot J_{a0} \cdot Q_{a0} + \beta_n \cdot P_{b0} \cdot J_{b0} \cdot Q_{b0} + \gamma_g \cdot P_{c0} \cdot J_{c0} \cdot Q_{c0}\right) - \left(\sigma_m \cdot P_{a1} \cdot J_{a1} \cdot Q_{a1} + \beta_n \cdot P_{b1} \cdot J_{b1} \cdot Q_{b1} + \gamma_g \cdot P_{c1} \cdot J_{c1} \cdot Q_{c1}\right)}{\sigma_m \cdot P_{a0} \cdot J_{a0} \cdot Q_{a0} + \beta_n \cdot P_{b0} \cdot J_{b0} \cdot Q_{b0} + \gamma_g \cdot P_{c0} \cdot J_{c0} \cdot Q_{c0}}$$  \hspace{1cm} (13)$$
where $H$ is the total energy-saving rate of road network; $\alpha_m$ is the energy consumption coefficient of non-carpooling trips, $10.17 \times 10^{-5} \text{L}/\text{p.m}$; $\beta_n$ is the energy consumption coefficient of carpooling trips, $3.76 \times 10^{-5} \text{L}/\text{p.m}$; $\gamma_g$ is the energy consumption coefficient of public bus trips, $1.24 \times 10^{-5} \text{L}/\text{p.m}$; $J_{a0}$ 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

- The energy consumption coefficient of non-carpooling trips is $\alpha_m = 10.17 \times 10^{-5} \text{L}/\text{p.m}$. 
- The energy consumption coefficient of carpooling trips is $\beta_n = 3.76 \times 10^{-5} \text{L}/\text{p.m}$. 
- The energy consumption coefficient of public bus trips is $\gamma_g = 1.24 \times 10^{-5} \text{L}/\text{p.m}$. 
- The average travel mileage of noncarpooling trips in the initial state is $J_{a0}$. 
- The average travel mileage of carpooling trips in the initial state is $J_{b0}$. 
- The average travel mileage of public bus trips in the initial state is $J_{c0}$. 
- The number of noncarpooling trips in the initial state is $Q_{a0}$. 
- The number of carpooling trips in the initial state is $Q_{b0}$. 
- The number of public bus trips in the initial state is $Q_{c0}$.

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

<table>
<thead>
<tr>
<th>State</th>
<th>Percentage increase in travel time ($k$)</th>
<th>Transfer function $f(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$&lt;10%$</td>
<td>$f(k) = -3.84k + 0.6293$</td>
</tr>
<tr>
<td>2</td>
<td>$10%$–$30%$</td>
<td>$f(k) = -1.179k + 0.3765$</td>
</tr>
<tr>
<td>3</td>
<td>$30%$–$40%$</td>
<td>$f(k) = -0.9735k + 0.4224$</td>
</tr>
<tr>
<td>4</td>
<td>$40%$–$50%$</td>
<td>$f(k) = -0.6045k + 0.0825$</td>
</tr>
<tr>
<td>5</td>
<td>$&gt;50%$</td>
<td>$f(k) = -0.7168k + 0.0029$</td>
</tr>
</tbody>
</table>

### Figure 5: Flow chart of HOV dynamic control process.

- **Start**
  - Internet of Vehicles (IoV) traffic information collection
  - GPS data processing
  - RFID data processing
  - Traffic information center
  - Real-time traffic information acquisition
  - Traffic information display
  - $i$th cycle at downstream intersection
  - Number of passengers per high-occupancy vehicle
  - Normal mixed traffic volume greater than threshold
  - HOV lanes open to all vehicles
  - HOV lanes only open to high-occupancy vehicles
  - Next cycle $i = i + 1$

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

- **Start**
  - Traffic information acquisition in mixed traffic
  - Total travel mileage $S_{00}$
  - Total travel time $P_{I0}$
  - Transportation mode transfer
  - Traffic information acquisition in traffic with HOV lanes
  - Total travel mileage $S_{10}$
  - Total travel time $P_{I1}$
  - Benefit evaluation
  - Reduction in total travel mileage
  - Energy consumption evaluation
  - End
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 4: Energy consumption comparison of different types of vehicles.

<table>
<thead>
<tr>
<th>Vehicle categories</th>
<th>Sedan</th>
<th>Privat car</th>
<th>Bus with multiple compartments</th>
<th>Bus with single compartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption (liter/100 km)</td>
<td>10.2</td>
<td>11</td>
<td>25.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Energy consumption (liter/(100 people·km))</td>
<td>7.34</td>
<td>6.78</td>
<td>0.41</td>
<td>0.73</td>
</tr>
<tr>
<td>Energy consumption (kg standard coal/(100 people·km))</td>
<td>8.52</td>
<td>7.87</td>
<td>0.48</td>
<td>0.85</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Vehicle categories</th>
<th>Seating capacities</th>
<th>Energy consumption under different occupancies (liter/(100 people·km))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedan</td>
<td>Taxi 4</td>
<td>Private car 5</td>
</tr>
<tr>
<td>Public bus</td>
<td>Bus with multiple compartments 80</td>
<td>Bus with single compartment 40</td>
</tr>
</tbody>
</table>

### Table 6: Traffic information of the selected roads.

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

\[
M = \frac{80704908 - 76729943}{80704908} = 4.93\%.
\]

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

\[
P = \frac{1138 - 1089}{1138} = 4.27\%.
\]

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

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

### Table 8: Operation efficiency of the intersections.

<table>
<thead>
<tr>
<th>Intersection code</th>
<th>Name of the intersecting roads</th>
<th>Traffic volume (pcu/h)</th>
<th>Signal cycle (s)</th>
<th>Per capita delay (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tongyang Road, Tongjiang Road, and Xingyuan Middle Road</td>
<td>561</td>
<td>80</td>
<td>25.36</td>
</tr>
<tr>
<td>2</td>
<td>Xingyuan Middle Road and Renmin East Road</td>
<td>1484</td>
<td>125</td>
<td>30.91</td>
</tr>
<tr>
<td>3</td>
<td>Tongyang Road and Renmin East Road</td>
<td>464</td>
<td>60</td>
<td>22.15</td>
</tr>
<tr>
<td>4</td>
<td>Xingyuan Middle Road and Renmin East Road</td>
<td>1434</td>
<td>No signal</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>Tongyang Road and Xueqian East Road</td>
<td>473</td>
<td>80</td>
<td>30.15</td>
</tr>
<tr>
<td>6</td>
<td>Xingyuan Middle Road and Xueqian East Road</td>
<td>397</td>
<td>60</td>
<td>18.36</td>
</tr>
<tr>
<td>7</td>
<td>Xingyuan Middle Road and Xueqian East Road</td>
<td>1569</td>
<td>80</td>
<td>42.36</td>
</tr>
<tr>
<td>8</td>
<td>Xingyuan Middle Road and Xueqian East Road</td>
<td>512</td>
<td>80</td>
<td>35.12</td>
</tr>
<tr>
<td>9</td>
<td>Changjiang North Road and Xueqian East Road</td>
<td>833</td>
<td>120</td>
<td>40.48</td>
</tr>
<tr>
<td>10</td>
<td>Tongyang Road and Yongle East Road</td>
<td>483</td>
<td>55</td>
<td>18.23</td>
</tr>
<tr>
<td>11</td>
<td>Tangnan Road and Yongle East Road</td>
<td>1829</td>
<td>110</td>
<td>37.52</td>
</tr>
<tr>
<td>12</td>
<td>Xingyuan Middle Road and Yongle East Road</td>
<td>1669</td>
<td>75</td>
<td>24.58</td>
</tr>
<tr>
<td>13</td>
<td>Changjiang North Road and Yongle East Road</td>
<td>948</td>
<td>120</td>
<td>27.93</td>
</tr>
<tr>
<td>14</td>
<td>Tangnan Road and South Ring Road</td>
<td>617</td>
<td>No signal</td>
<td>—</td>
</tr>
<tr>
<td>15</td>
<td>Tangnan Road and South Ring Road</td>
<td>1973</td>
<td>No signal</td>
<td>—</td>
</tr>
<tr>
<td>16</td>
<td>Xingyuan Middle Road and South Ring Road</td>
<td>1967</td>
<td>No signal</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>Changjiang North Road and South Ring Road</td>
<td>1132</td>
<td>No signal</td>
<td>—</td>
</tr>
</tbody>
</table>
### Table 9: Travel time and travel mileage of different travel modes in the initial operating state (mixed traffic).

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

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

<table>
<thead>
<tr>
<th>Proportion of carpooling trips (%)</th>
<th>Area (km²)</th>
<th>No. of vehicles (veh)</th>
<th>Time density (veh/s)</th>
<th>Coverage (m)</th>
<th>Waiting time (s)</th>
<th>Detour time (s)</th>
<th>Total (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>14.87</td>
<td>406</td>
<td>8.86</td>
<td>267.78</td>
<td>298</td>
<td>658</td>
<td>955</td>
</tr>
<tr>
<td>10.0</td>
<td>14.87</td>
<td>813</td>
<td>4.43</td>
<td>189.35</td>
<td>210</td>
<td>359</td>
<td>569</td>
</tr>
<tr>
<td>15.0</td>
<td>14.87</td>
<td>1219</td>
<td>2.95</td>
<td>154.60</td>
<td>172</td>
<td>259</td>
<td>431</td>
</tr>
<tr>
<td>20.0</td>
<td>14.87</td>
<td>1626</td>
<td>2.21</td>
<td>133.89</td>
<td>149</td>
<td>209</td>
<td>358</td>
</tr>
<tr>
<td>25.0</td>
<td>14.87</td>
<td>2032</td>
<td>1.77</td>
<td>119.75</td>
<td>133</td>
<td>180</td>
<td>313</td>
</tr>
<tr>
<td>30.0</td>
<td>14.87</td>
<td>2439</td>
<td>1.48</td>
<td>109.32</td>
<td>121</td>
<td>160</td>
<td>281</td>
</tr>
<tr>
<td>35.0</td>
<td>14.87</td>
<td>2845</td>
<td>1.27</td>
<td>101.21</td>
<td>112</td>
<td>145</td>
<td>258</td>
</tr>
<tr>
<td>40.0</td>
<td>14.87</td>
<td>3252</td>
<td>1.11</td>
<td>94.67</td>
<td>105</td>
<td>135</td>
<td>240</td>
</tr>
<tr>
<td>45.0</td>
<td>14.87</td>
<td>3658</td>
<td>0.98</td>
<td>89.26</td>
<td>99</td>
<td>126</td>
<td>226</td>
</tr>
<tr>
<td>50.0</td>
<td>14.87</td>
<td>4065</td>
<td>0.89</td>
<td>84.68</td>
<td>94</td>
<td>120</td>
<td>214</td>
</tr>
</tbody>
</table>

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

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

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

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

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

<table>
<thead>
<tr>
<th>Code</th>
<th>Travel modes</th>
<th>Posterior operating state (with HOV lanes)</th>
<th>Number of vehicles (veh)</th>
<th>Number of travelers (p)</th>
<th>Travel time (s)</th>
<th>Travel mileage (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Noncarpooling private car trips</td>
<td>23188</td>
<td>23188</td>
<td>1060</td>
<td>3243</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Carpooling private car trips</td>
<td>384</td>
<td>1360</td>
<td>1291</td>
<td>4970</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Public bus trips</td>
<td>816</td>
<td>6796</td>
<td>1287</td>
<td>4409</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>—</td>
<td>24388</td>
<td>31344</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
The total energy-saving rate of the road network can be calculated as follows:

\[ H = \frac{177735785.9 - 138709510.2}{177735785.9} = 21.96\%. \]  

(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...
The energy consumption of trips in the network was reduced by 39,262.75 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.
Acknowledgments

This research was supported by the Open Fund for Jiangsu Key Laboratory of Traffic and Transportation Security (Huaiyin Institute of Technology) (TTS2020-05 and TTS2020-09), Enterprise-University-Research Institute Collaboration Project of Jiangsu Province (DH20190231), Graduate Innovative Projects of Jiangsu Province (KYLX15_0148), National Natural Science Foundation of China (61573098 and 51308246), University Natural Science Major Basic Project of Jiangsu Province (15KJA580001), Youth Foundation of Huaiyin Institute of Technology (HGC1408), and Natural Science Foundation of Jiangsu Province, China (BK20171426).

References

[22] T. Zhang, Study on Different Urban Transport Modes’ energy consumption, Beijing Jiaotong University, Beijing, China, 2010.