Abstract: Bus lanes have gradually become an indispensable infrastructure for the development of urban public transportation networks. A bi-level programming model is used herein to compare the total travel time of social vehicles and buses before and after the bus lane is set up to judge whether the bus lane layout plan is scientific and reasonable considering the road network. The model’s effectiveness is verified using areas of Qingshan Lake in Nanchang City, and the operational efficiency of one bus lane before and after establishing the dedicated bus lane is analyzed. The case results show that the bus lane layout evaluation needs to consider the traffic benefits of a specific road and also judge whether the total travel time of the network traffic volume is improved from the macroscopic road network level. The research results provide theoretical support for the rational layout of bus lanes and are of practical significance for prioritizing the development of public transportation and promoting the sustainable development of urban transportation.

Keywords: bus lane; bi-level programming model; minimum travel time; road resistance function

1. Introduction

Urban transportation issues are commonly addressed by prioritizing the development of public transportation [1,2]. In order to prioritize public transportation, the Ministry of Transport of China launched the “Transit Metropolis” creation demonstration project in 2011. The “Transit Metropolis” [3,4] aims to take full advantage of public transport and achieve a harmonious coexistence between public transport and the city through mutual coordination between public transport services and urban morphology. Establishing bus lanes, as an important measure for creating public transportation in cities and the priority development of public transportation, is vital in ensuring the speed of public transportation and improving its attractiveness [5]. However, many cities’ bus lanes only strive to achieve the assessment indicators for bus lanes in the transit metropolis without considering the factors of traffic and passenger flow and without fully considering the network effect of bus lane layout. Therefore, evaluating the layout effect of bus lanes is an objective requirement for promoting the creation of a transit metropolis.

Numerous scholars have researched the layout methods and effectiveness evaluations of bus lanes. Overall, research results can be divided into two categories: micro-simulation evaluations [6–9] and macro network setting optimizations [10–17]. The former mainly uses simulation tools to evaluate the effectiveness of bus lane setting schemes; the latter often uses a bi-level programming model to determine the optimal layout of bus lanes. The upper level of the model usually takes the minimum total travel time of road network users as the objective function, while the lower level combines vehicle pollution emissions, accidents, and bus travel sharing rates for research.
In terms of micro-simulation evaluations, Zhang et al. [6] proposed a cellular automata traffic model considering bus lane changing behavior with scheduling parameters. Chen et al. [7] used a parametric micro-simulation model to evaluate the performance of bus lanes on urban expressways. Li et al. [8] used simulation-based optimization (SBO) methods to resolve the allocation problem of dedicated bus lanes (DBLs). Several efficient machine learning-based surrogate models and a jackknife uncertainty estimator were introduced to the existing SBO framework in the research. The authors adopted a mesoscopic simulation and used dynamic traffic assignment (DTA) tools to evaluate the DBLs' network performance. Golan et al. [9] assessed the impacts of DBLs on urban traffic congestion and modal split with an agent-based model (ABM). Papageorgiou et al. [10] developed microscopic simulation models to examine several scenarios of dedicated bus lanes and bus priority schemes so that the buses can provide the desired level of service with minimal impact on the rest of the traffic. Micro simulation cannot effectively demonstrate the effect of bus lanes on the entire network.

Regarding the optimization of macro network settings, Yu et al. [11] proposed a bi-level programming model to solve the design problem of bus lane distribution in multi-modal transport networks. The upper-level model aims to minimize the average travel time and passenger comfort variability among bus lines by optimizing bus frequencies. The lower-level model is a multi-modal transport network equilibrium for the joint modal split/traffic assignment problem. Si et al. [12] proposed a bi-level programming model to describe the exclusive bus lanes (EBLs) design problem. The total travel cost of all travelers in the network was regarded as the optimization objective. The equilibrium travel demand was found by solving the lower-level model. Xu et al. [13] introduced a comprehensive framework for the ongoing performance monitoring of urban exclusive bus lane networks. It identified explicit quantitative performance measures from the perspective of both travelers and traffic managers. Danny et al. [14] determined the bus lane path by considering a width greater than 9 m; if the road width was less than 9 m, the assessment was conducted with the volume to capacity (V/C) ratio close to 1:1 and recommended road widening. Kampouri et al. [15] investigated the performance of a bus lane that is (de)activated under specific road traffic and public transport conditions. Various scenarios were modeled to determine the traffic volumes and bus service frequencies for which such a bus lane concept would be effective. Various scholars [16–18] have combined the setting of bus lane networks with dynamic traffic congestion. Bagloee et al. [16] researched transit priority lanes in congested road networks. Petit et al. [17] conducted a careful analysis of the influence of the demand pattern on the dedicated bus lane network design, roadway congestion, and the overall system performance. Tsitsokas et al. [18] studied the problem of optimal dedicated bus lane allocation. They proposed a modeling framework based on a link-level dynamic traffic modeling paradigm, which is compatible with the dynamic characteristics of congestion propagation that can be correlated with the relative positions of bus lanes.

In addition, some scholars [19,20] studied the setting and evaluation of bus lanes in a connected vehicle environment, as well as the sharing of bus lanes with other modes of transportation [21,22]. Wu et al. [19] researched the development and evaluation of bus lanes with intermittent and dynamic priority in a connected vehicle environment. Zhang et al. [20] proposed connected autonomous bus (CAB) lanes in urban transportation networks. Deploying CAB lanes may substantially increase the ridership of CABs and their total social benefit; allowing limited CAV (connected autonomous passenger vehicle) access can further improve the overall system performance. Ceunynck et al. [21] analyzed bicyclists’ safety on bus lanes shared with bicyclists. Yao et al. [22] considered the evaluation of exclusive bus lanes (EBLs) in the road network with three travel modes: bus, solo driving, and carpooling. The numerical results show that demand levels remarkably influence the total system costs under different policies.

There are few studies on the changes in traffic demand after establishing bus lanes at the macro network level in the context of a Transit Metropolis. It is unreasonable to
measure the effectiveness of bus lane settings solely from the perspective of vehicle travel time. It is more scientific and reasonable to measure the effectiveness of bus lanes based on the total travel time changes of all travelers before and after the establishment of bus lanes. For example, to create a transit metropolis in Nanchang, many bus lanes were newly established, but the evaluation at the network level is unknown, and there is no relevant research literature on the evaluation of bus lanes in the Nanchang network. Based on this, in the context of the construction of a transit metropolis and the priority development of public transportation, this article uses some areas of Qingshan Lake in Nanchang City, China, as an example to evaluate the effectiveness of bus lanes at the network level. The minimum travel time of social vehicles and public transportation is used as the evaluation index to determine the pre- and post-establishment of the Fenglin Avenue bus lane in Nanchang City via the Frank Wolf algorithm and road resistance function. The research results support prioritizing the development of public transportation and promoting the sustainable development of urban transportation.

We construct a bi-level programming model for the layout of bus lanes and design a model solution process. Part of the Qingshan Lake District of Nanchang City, China, is used as a case analysis, and the final section presents the research conclusions.

2. A Bi-Level Programming Model for the Layout of Bus Lanes

2.1. Model Assumptions

Considering the travel time of the total vehicles in the road network, two objective functions are established under relevant constraints. The total vehicle travel time is an upper-level objective function, and the user equilibrium in the transportation network is considered a lower-level objective function. The model construction is based on the following model assumptions:

(i) The bus-dedicated road network in the study area is a closed road network.
(ii) Bus stops are set on the nodes of the road network.
(iii) Priority is given to bus signals at intersections without considering the delay of buses at intersections.
(iv) Due to the separation of motor vehicles and non-motor vehicles, the travel mode in the transportation network only considers two types of motor vehicles: social vehicles and buses.
(v) The traffic sharing rate is determined by the departure frequency and average passenger capacity. After removing the share of public transportation from the total travel demand, the value of car traffic volume in the road network is assigned.

2.2. Model Construction

2.2.1. Upper-Level Model

From the perspective of decision makers in the road network, the layout of bus lanes was determined by minimizing the total travel time of the system’s vehicles. The objective functions of the model were to determine whether to set bus lanes as the decision variable or the minimum total travel time of social vehicles and buses during the use of bus lanes. The objective function of the upper-level model is as follows:

$$\min \phi_1 = \sum_i \sum_a \left[ x_{\text{car}}^i(a) t_{\text{car}}(x_i, a) + x_{\text{bus}}^i(a) t_{\text{bus}}(x_i, a) \right]$$

(1)

where

$$\mu_a \in \{0, 1\}$$

(2)

$\phi_1$: the generalized total cost.

$a$: road section.

$i$: the $i$-th hour during the exclusive bus lane period.
$x^\text{car}_a(i)$: the traffic flow of social vehicles on road $a$ in the $i$-th hour during the exclusive period of bus lanes.

$t^\text{car}_a(i)$: the travel time of social vehicles on road $a$ in the $i$-th hour during the exclusive period of bus lanes.

$x^\text{bus}_a(i)$: the traffic volume of the $i$-th hour on road $a$ during the exclusive period of the bus lane, including social and bus vehicles.

$\mu_a$: indicates whether a bus lane is set on section $a$, with a value of 1 when setting a bus lane, otherwise 0.

$t^\text{bus}_a(i)$: the travel time of road $a$ in the $i$-th hour during the exclusive period of bus lanes.

The Davidson model [23] was used as a road resistance function to calculate the travel time of road sections $t_a$. The function is listed as follows:

$$t_a = t_0 \left[1 + \lambda c_a / (C^{d}_a - c_a)\right]$$

where

$t_a$: travel time of vehicles on road section $a$.

$t_0$: the free travel time of vehicles on road section $a$ under unobstructed conditions.

$\lambda$: service level parameter, with a value of 0.855.

$c_a$: motor vehicle flow on road section $a$, vehicle/hour.

$C^{d}_a$: design capacity on road section $a$, vehicle/hour.

By modifying the theoretical capacity $C$ of the road section, the design capacity of the road section was obtained. The theoretical traffic capacity needs to be corrected for the effects of bicycles, intersections, lane width, and number of lanes, while also considering the impact of road section length on travel time. Furthermore, the road section length needs to be corrected because the construction of the Transit Metropolis requires that public transportation enjoy signal priority at intersections and that motor and non-motor vehicles drive separately. Therefore, the impact of intersections and bicycles is ignored in this research. The revised formula is as follows:

$$C^{d}_a = \alpha_a \beta_a C$$

where

$\alpha_a$: lane width correction factor for road section $a$.

$\beta_a$: correction coefficient for the number of lanes on road section $a$.

$C$: the theoretical capacity of a single lane on an urban road, expressed as the maximum number of standard vehicles passing through it per hour (vehicle/hour).

In addition, considering that bus stops can also affect the road’s traffic capacity when calculating the road’s design capacity, a correction factor $\gamma$ for bus stops is added [7]. The calculation formula is as follows:

$$\gamma = 1 - \frac{K(fT - 3600/Q_{x})r_b}{3600\beta_a} - \frac{(t_+ + t_-) \sum_{x=1}^{k} \rho_x f / x}{3600}$$

where

$K$: the arrival rate of buses, representing the number of buses arriving at the stop per unit time.

$f$: the number of stopping times of buses at the platform.

$T$: bus stop time at the platform.

$Q_{x}$: traffic volume on adjacent motor vehicle lanes.

$r_b$: utilization coefficient of the lane where the bus stop is located.
lost time for buses accelerating to leave the bus stop.

$t_{-}$: lost time for buses to slow down and reach the bus stop.

$\rho$: probability of bus arrival per unit time.

$x$: total number of vehicles arriving within the same time period.

Based on the above analysis, the expression of the road resistance function model can be obtained, as shown in Formulas (6) and (7), where $\beta$ is the Davidson model parameter.

$$
t_{\text{car}}^{\text{car(i)}} = (1 - \mu_{\text{a}})t_{0,\text{a}}^{\text{car}} \left\{ 1 + \lambda \left[ \frac{x^{\text{car(i)}}_{\text{a}} + x^{\text{bus(i)}}_{\text{a}}}{C_{\text{a}} - x^{\text{car(i)}}_{\text{a}} - x^{\text{bus(i)}}_{\text{a}}} \right]^\beta \right\} + \mu_{\text{a}} t_{0,\text{a}}^{\text{car}}, \forall a \tag{6}
$$

$$
t_{\text{bus}}^{\text{bus(i)}} = (1 - \mu_{\text{a}})t_{0,\text{a}}^{\text{bus}} \left\{ 1 + \lambda \left[ \frac{x^{\text{car(i)}}_{\text{a}} + x^{\text{bus(i)}}_{\text{a}}}{C_{\text{a}} - x^{\text{car(i)}}_{\text{a}} - x^{\text{bus(i)}}_{\text{a}}} \right]^\beta \right\} + \mu_{\text{a}} t_{0,\text{a}}^{\text{bus}}, \forall a \tag{7}
$$

2.2.2. Lower-Level Model

Multi-period bus lanes were set to meet the demand for public transportation during peak hours in the morning and evening. Considering that the usage time of bus lanes in Nanchang City is from 7:00 a.m. to 9:00 a.m. and from 5:00 p.m. to 7:00 p.m., the origin-destination (OD) travel demand varies within different hours, so the optimal layout of bus lanes planned is different. To set up bus lanes for optimal road operation, this study modeled the bus lane operation period of the road network into $m$ hours. Using a comparative study of individual travel time OD demand, peak hour OD demand, and average OD demand, the overall operational efficiency of the road before and after the establishment of bus lanes was compared.

After determining the layout of bus lanes, the lower-level model used the user equilibrium model [24] according to Wardrop’s first principle to allocate travelers to the road network. The travel time of the road section is influenced by traffic flow, which is more in line with the reality. The expression of the lower-level model is as follows:

$$
\min \phi_2 = \sum_a x_a^{\text{car}}(x_a, \mu_{\text{a}}) dx \tag{8}
$$

$$
\sum_a p_k^{rs} = q_{rs}, \forall r \in R, s \in S \tag{9}
$$

$$
p_k^{rs} \geq 0, \forall k \in p_{rs}, \forall r \in R, s \in S \tag{10}
$$

$$
x_a = \sum_{r \in R} \sum_{s \in S} \sum_{k \in p_{rs}} p_k^{rs} \delta_{ak}^{rs}, \forall a \tag{11}
$$

where

$r$: traffic production node.

$R$: the set of traffic production nodes.

$s$: traffic attraction node.

$S$: the set of traffic attraction nodes.

$k$: route sequence number.

$q_{rs}$: for an OD (origin–destination) pair, the traffic flow between the production and the attraction point.

$p_{rs}$: the set of routes.

$p_k^{rs}$: traffic flow on the $k$-th route.

$\delta_{ak}^{rs}$: 0–1 variable.
3. Model Solution

For the road network in the selected study area, we considered both the bus-exclusive road network in the surrounding area and the minimum total travel time of vehicles in the road network from the entire road network system. The evaluation process is shown in Figure 1. Firstly, we solve the lower-level objective function to obtain the traffic flow of each section in the researched road network. Then, based on the upper-level planning model, we calculate the comprehensive travel time of the entire road network and evaluate the effectiveness of bus lane settings.

![Figure 1. Multi-time public transport special road layout evaluation process for double-layer planning model.](image)

For the lower-level programming model solution, we calculated the travel time of social vehicles and buses on road sections under free flow and current traffic flow. Then, based on Wardrop’s first principle, travelers were allocated to the road network using the user equilibrium model. The allocation of road traffic and the calculation of road travel time is an iterative process; if the change rate of a road section under free flow or current traffic flow is less than 1% and all sections have been calculated, the traffic flow and travel time of road sections are obtained in the user equilibrium state. If the change rate of a road section under free flow or current traffic flow is more than 1% or the traffic flows of some road sections are not calculated, then we continue to calculate the travel time of the road sections and update the traffic flows in the next iteration until the judgement condition is satisfied.
For the upper-level programming model solution, the minimum vehicle travel time before and after setting up the bus lanes was compared and analyzed. If the effect of setting up bus lanes on a road section was better than not setting up bus lanes, the location of bus lanes could be determined. Otherwise, redefining the road sections where bus lanes are set up is necessary.

3.1. Solution of the Traveler Path Selection in the Lower-Level Model

The Frank Wolf algorithm was used to solve the lower-level traveler path selection [24]. The calculation is as follows:

We calculated the free flow time $t_{car}^{(0)}$ and $t_{bus}^{(0)}$ of social vehicles and public transportation between an OD pair. Then we allocated OD demand based on the shortest path to obtain the traffic flow value on each road section. We calculated the travel time of each road section based on the traffic flow of the same road section. The calculation formula is as follows:

$$t_{bus}^{(m)} = t_{bus}^{(x_m)}, t_{car}^{(m)} = t_{car}^{(x_m)} \forall a$$

The OD shortest path was obtained based on the travel time of the road section. The auxiliary flow was calculated by loading the OD matrix, and the optimal step size was calculated under an auxiliary flow rate using the following formula:

$$x_{m+1} = x_m + \delta(u_{m} - x_{m}), 0 < \delta < 1$$

The section flow is reloaded based on the shortest path of the objective model function $\min \phi_3 = \sum x_m^{m+1} t_m^{m+1}$. Next, we determine whether the changing rate of road traffic is less than 0.01. If so, we calculate the objective function. Otherwise, the algorithm will return $m = m + 1$ to the calculation of road travel time and iterate the calculation in sequence.

3.2. Solution of the Upper-Level Model

After calculating the allocation OD demand matrix based on the lower-level model, the total travel time of buses and social vehicles was obtained by iteratively solving the road resistance function. The vehicle operation time before and after setting up bus lanes was compared to determine whether the layout of bus lanes was beneficial for the total vehicle travel time in the road network.

4. Case Analysis

4.1. Case Introduction

Using the road network in some areas of Qingshan Lake as an example, the researched road network is shown in Figure 2a,b. The model follows the Sioux Falls network [9] and extracts the bus route network from the actual road network, as shown in Figure 2c.

The road network parameters are set as follows:

1. The roads in the road network are all bidirectional and have six lanes, each lane is 3.5 m wide and has a traffic capacity of 1000 pcu/h.
2. There are 17 bus routes in the road network, assuming a departure frequency of 5 min per vehicle. The stops that the bus routes pass through are shown in Table 1.
3. The sum of bus acceleration and deceleration loss time at a bus stop is 4 s.
4. The lengths of road network sections and the number of bus routes passing through are shown in Table 2.
5. The one-way traffic flow on each section of the road network is shown in Table 3. (Assuming the current two-way traffic flow is the same, with a social vehicle speed of 50 km/h and a bus speed of 40 km/h.)
Figure 2. Road network in some areas of the Qingshanhu District, Nanchang City, China. (a) Research area (b) Public transportation network (marked with magenta) (c) Extracted public transportation network (note: the values inside the red circles are the node numbers, the arrows present running directions, and sideline values are road section numbers). The source link of the base map (a): https://www.google.com.tw/maps/@28.7291664,115.8244665,13.5z?hl=en&entry=ttu (accessed on 29 May 2023).

Table 1. Bus routes in the research area.

<table>
<thead>
<tr>
<th>Bus Route Serial Number</th>
<th>Bus Route</th>
<th>The Bus Stop Number (Node Number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>214</td>
<td>1-8-9-11-12-13-23</td>
</tr>
<tr>
<td>2</td>
<td>232</td>
<td>13-12-7-6-5-4-16</td>
</tr>
<tr>
<td>3</td>
<td>853</td>
<td>10-11-9-8-7-6-5-4-16</td>
</tr>
<tr>
<td>4</td>
<td>K232</td>
<td>16-4-5-6-7-12-13</td>
</tr>
<tr>
<td>5</td>
<td>211</td>
<td>3-4-5-6-14-13-23</td>
</tr>
<tr>
<td>6</td>
<td>520</td>
<td>3-4-5-6-7-8</td>
</tr>
<tr>
<td>7</td>
<td>257</td>
<td>1-2-5-6-7-12-17-22</td>
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### Table 1. Cont.

<table>
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<th>Bus Route</th>
<th>The Bus Stop Number (Node Number)</th>
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<td>266</td>
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<td>9</td>
<td>835</td>
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<td>10</td>
<td>240</td>
<td>3-4-16</td>
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<td>131</td>
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<td>541</td>
<td>3-4-16-15-14</td>
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<td>13</td>
<td>210</td>
<td>3-4-16</td>
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<tr>
<td>14</td>
<td>247</td>
<td>18-21-22-23</td>
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<td>15</td>
<td>213</td>
<td>20-21-22</td>
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<td>16</td>
<td>35</td>
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</tr>
<tr>
<td>17</td>
<td>708</td>
<td>5-4-16</td>
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### Table 2. Road section information of the bus route network.

<table>
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<tr>
<th>Road Section Number</th>
<th>Length of Road Section/km</th>
<th>The Amount of Bus Routes</th>
<th>Road Section Number</th>
<th>Length of Road Section/km</th>
<th>The Amount of Bus Routes</th>
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</thead>
<tbody>
<tr>
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<td>2.1</td>
<td>2</td>
<td>33 &amp; 34</td>
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<tr>
<td>2 &amp; 3</td>
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<td>0</td>
<td>35 &amp; 36</td>
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### Table 3. Traffic flow in a single direction on road sections.

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<th>Traffic Flow, pcu/h</th>
<th>Road Section Number</th>
<th>Traffic Flow, pcu/h</th>
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<td>23 &amp; 24</td>
<td>920</td>
<td>55 &amp; 56</td>
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<td>25 &amp; 26</td>
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<td>57 &amp; 58</td>
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</tr>
<tr>
<td>27 &amp; 28</td>
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<td>59 &amp; 60</td>
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<td>61 &amp; 62</td>
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</tr>
<tr>
<td>31 &amp; 32</td>
<td>709</td>
<td>63 &amp; 64</td>
<td>806</td>
</tr>
</tbody>
</table>

Note: pcu means standard vehicle. For uniformity, different models of motor vehicles can be converted into standard vehicles.
4.2. Calculation Results

This article analyzes the OD operating time of vehicles in the current road network, and the vehicle operating time is calculated using the Davidson model as the road resistance function. The road network research section of Fenglin Avenue, which is the node section labelled 4–9, shows the vehicle operation time before and after setting up bus lanes, as shown in Table 4. See Figure 3 for the line chart of the comparative analysis of vehicles’ running time before and after the bus lane is set up under five different scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Buses Travel Time</th>
<th>Social Vehicles Travel Time</th>
<th>Total Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>74</td>
<td>627</td>
<td>701</td>
</tr>
<tr>
<td>Scenario 1 *</td>
<td>69</td>
<td>647</td>
<td>716</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>82</td>
<td>747</td>
<td>829</td>
</tr>
<tr>
<td>Scenario 2 *</td>
<td>72</td>
<td>788</td>
<td>860</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>84</td>
<td>855</td>
<td>939</td>
</tr>
<tr>
<td>Scenario 3 *</td>
<td>73</td>
<td>896</td>
<td>969</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>85</td>
<td>698</td>
<td>784</td>
</tr>
<tr>
<td>Scenario 4 *</td>
<td>75</td>
<td>735</td>
<td>810</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>90</td>
<td>749</td>
<td>839</td>
</tr>
<tr>
<td>Scenario 5 *</td>
<td>79</td>
<td>780</td>
<td>859</td>
</tr>
</tbody>
</table>

Note: Scenario 1 means present situation, scenario 1 * means setting up bus lanes under present traffic flow; Scenario 2 represents a 5% increase in social traffic flow, scenario 2 * means setting up bus lanes under scenario 2; Scenario 3 means a 10% increase in social traffic flow, scenario 3 * means setting up bus lanes under scenario 3; Scenario 4 represents a 5% increase in bus vehicle flow, scenario 4 * represents setting up bus lanes under scenario 4; Scenario 5 represents a 10% increase in bus vehicle flow, scenario 5 * represents setting up bus lanes under scenario 5.

Due to the fact that the number of passengers carried by bus is higher than that of cars, it is obviously unreasonable to measure the effectiveness of bus lane settings solely from the perspective of vehicle travel time. It is more scientific and reasonable to measure the effectiveness of bus lanes based on the total travel time changes of all travelers before and after the establishment of bus lanes. As can be seen from Table 5 and Figure 4, although the setting of bus lanes is negative for social vehicle passengers, the total passengers’ travel time decreases under five scenarios. Therefore, setting up bus lanes is effective in reducing the total travel time of all travelers.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bus Passengers’ Travel Time</th>
<th>Social Vehicle Passengers’ Travel Time</th>
<th>Total Passengers’ Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>1471</td>
<td>1255</td>
<td>2726</td>
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<tr>
<td>Scenario 1 *</td>
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<td>1295</td>
<td>2678</td>
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<td>1644</td>
<td>1494</td>
<td>3138</td>
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<td>Scenario 2 *</td>
<td>1446</td>
<td>1576</td>
<td>3022</td>
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<tr>
<td>Scenario 3</td>
<td>1672</td>
<td>1711</td>
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<td>3106</td>
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<td>Scenario 5</td>
<td>1793</td>
<td>1498</td>
<td>3291</td>
</tr>
<tr>
<td>Scenario 5 *</td>
<td>1576</td>
<td>1560</td>
<td>3136</td>
</tr>
</tbody>
</table>

Note: Assuming that a bus carries an average of 20 passengers and a social vehicle carries an average of 2 passengers. The symbol “*” presents setting a bus lane.
This study also has some shortcomings and limitations. To optimize bus lane layout in the bi-
ness of motor vehicles and non
s of bus lanes set at Fenglin Avenue in the road network is unreasonable for the current traffi-
the total operation time of road vehicles increases greatly. This is because the area does not belong to the central business
district, with fewer bus routes and departure frequencies and less demand for bus passengers. The
establishment of bus lanes has not played a significant role. Nevertheless, in creating a transit
metropolis in Nanchang city, to meet the task of setting up bus lanes, Fenglin Avenue was set up with
bus lanes. Perhaps in the future, with the development of land along bus lanes and the increase in
demand for public transportation, the effectiveness of bus lane settings will become apparent. This
must be combined with urban land research and comprehensive transportation planning to predict
future traffic demand.

Figure 3. Comparison of running time before and after setting up bus lanes under different scenarios.
From the comparative analysis chart and table, it can be seen that with Fenglin Avenue as the center
of the road network, a bus lane is set up in some sections of Fenglin Avenue. The total travel time
of buses did not decrease significantly, while the total travel time of social vehicles increased even
more, indicating that the bus lane reduced the right-of-way of social vehicles in the road network
and promoted an increase in the total travel time of social vehicles. Therefore, the layout of bus
lanes set at Fenglin Avenue in the road network is unreasonable for the current traffic flow from the
perspective of vehicle travel time, the impact of bus operation time is small, and the total operation
time of road vehicles increases greatly. This is because the area does not belong to the central business
district, with fewer bus routes and departure frequencies and less demand for bus passengers. The
establishment of bus lanes has not played a significant role. Nevertheless, in creating a transit
metropolis in Nanchang city, to meet the task of setting up bus lanes, Fenglin Avenue was set up with
bus lanes. Perhaps in the future, with the development of land along bus lanes and the increase in
demand for public transportation, the effectiveness of bus lane settings will become apparent. This
must be combined with urban land research and comprehensive transportation planning to predict
future traffic demand.

Figure 4. Comparison of passengers’ travel time before and after setting up bus lanes under different
scenarios.
5. Conclusions

This article evaluated the layout effect of bus lanes, solved the total travel time of road network users, and studied the layout of the Fenglin Avenue section of bus lanes in multiple time periods. The results show the following:

(1) Some areas of Qingshan Lake in Nanchang City have an unreasonable layout of planned bus lanes from the perspective of vehicle travel time, but from the perspective of total passengers’ travel time, setting up bus lanes is effective in reducing the total travel time of all travelers. The Fenglin Avenue bus lane has a relatively small impact on the total operating time of buses. However, it has a greater impact on the total operating time of social vehicles in the road network. Perhaps, with the construction of Transit Metropolis, public transportation services will improve, and the demand for public transportation will also increase. Thus, the effect of setting up bus lanes will be more apparent.

(2) By using a bi-level programming model to redistribute the traffic flow of OD demand in different sections of the road network after the establishment of bus lanes, the model is more practical and can effectively improve the scientific, accuracy, and reliability evaluations of the model.

(3) The vehicle operation time and total passengers’ travel time of the road network solved through a two-level programming model can intuitively display the operation effects before and after setting up bus lanes.

(4) To optimize bus lane layout in the bi-level programming model, further in-depth research should be conducted on the input of OD demand.

This study also has some shortcomings and limitations. First, the research hypothesis is somewhat idealized. In reality, intersections do not use bus signal priority very well. The reason for this is the opposition of car users to bus signal priority. Unfortunately, the decision makers are mostly car users. In addition, some old roads have not achieved the separation of motor vehicles and non-motor vehicles, and the impact of mixed traffic on vehicle operation time and traffic flow allocation in the road network needs further research. Finally, regarding the effectiveness of setting up bus lanes, future traffic demand predictions need to be considered, not just current traffic conditions. The above shortcomings and limitations require further in-depth research and exploration in the future.

Author Contributions: The individual contribution and responsibilities of the authors are listed as follows: Y.X. designed the research, developed the model and conducted model validation, and wrote the paper; L.C. guided the research process; M.Z. collected the data and constructed the bi-level programming model; X.S. provided some comments on the case study and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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References


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