applied sciences

Article

Coordinated Control Method for Passive Bus Priority Arterials Considering Multi-Conversion Standard and Bus Stopping Time

Liang Zou [1], Zhifan Li [1], Lingxiang Zhu [2] and Zhitian Yu [1,*]

[1] College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China
[2] College of Mathematics and Informatics, South China Agricultural University, Guangzhou 510642, China
* Correspondence: y2209706217@163.com

Abstract: Public transport priority is the development trend in public transport, and signal priority is its main means. In order to further improve the accuracy of delay calculation and realize the priority of bus signals, this paper proposes the idea of multiple conversion criteria and consideration of stop time for the coordination and control of bus and car mixed traffic flow trunk roads. First of all, on the basis of in-depth analysis of the differences in the characteristics of bus and car models, a multi-conversion standard delay calculation method is proposed, and its effectiveness is verified by simulation. The results show that compared with the single conversion standard delay calculation method, the average delay error of cars and buses calculated by this method is reduced by 22.54% and 82.21%, respectively. Then, the influence of bus stops on bus speed and delay is further analyzed, and the coordinated control model of bus priority trunk roads considering bus stops is constructed with the passenger capacity of each bus line and the per capita delay as the goal, and the solution is given. Finally, 178 randomly generated examples are used to verify and analyze the effectiveness and sensitivity of this model.

Keywords: bus speed; bus stop time; model conversion factor; vissim simulation

Citation: Zou, L.; Li, Z.; Zhu, L.; Yu, Z. Coordinated Control Method for Passive Bus Priority Arterials Considering Multi-Conversion Standard and Bus Stopping Time. *Appl. Sci.* **2023**, *13*, 3634. https://doi.org/10.3390/app13063634

Academic Editor: Luís Picado Santos

Received: 14 February 2023
Revised: 8 March 2023
Accepted: 10 March 2023
Published: 12 March 2023

1. Introduction

In recent years, to improve the problem of urban traffic congestion, China has been vigorously developing public transportation. Since the public transport priority became the trend in public transport development, the Ministry of Transport released the "Thirteenth Five-Year Plan" for the development of urban public transport in 2017, which clearly put forward the in-depth implementation of public transport priority development strategy. At present, the main bus priority strategy includes right-of-way priority and signal priority, of which right-of-way priority is developing rapidly [1], bringing a total of 16,551.6 km of bus lanes set up nationwide in 2020, an increase of 51.65% since 2017. In contrast, China's bus signal priority control technology is relatively lagging behind and needs to be studied in depth.

The existing bus signal priority research mainly includes passive priority and active priority, among which active priority has been studied more and applied in some cities, with Nanjing first conducting a pilot project in the Jianye District in 2014 and gradually promoting active bus signal priority in the city. In 2021, Changsha opened three bus priority routes based on vehicle–road cooperation technology in areas with high traffic flow within the city center. However, active bus priority requires a comprehensive intelligent transformation of buses, signal control equipment, roadside equipment, etc., which is costly and prone to cause traffic congestion in nonpriority phase time, leading to detrimental problems to traffic safety and management. Therefore, the study of passive bus signal priority is still of great significance.

China's arterial road coordination control technology is becoming increasingly mature and has been widely used in many cities, achieving good application effects. By 2021, coordinated control of two-way green waves has been implemented on 50 road sections in Beijing, including 289 signalized intersections, and the overall road traffic efficiency has been improved by over 40% after optimization [2]; 574 green wave road sections have been set up in Shenzhen, involving 1742 signalized intersections. The cumulative green wave road length spans 520 km, and the vehicle traffic condition of arterial roads has been greatly improved after optimization. Take Heping Road as an example, its two-way travel time reduced by 31% and 46%, respectively [3].

Arterial coordination control methods mainly include the maximum green wave band method and the minimum delay method [4]. The minimum delay method takes the operating conditions of vehicles into account, which is more consistent with the actual situation so that it can improve the traffic efficiency to a greater extent. For the mixed traffic flow of buses and cars in arterial coordination control, the existing delay calculation method with a single conversion standard converts buses into cars and calculates the delays of all vehicles first, and then receives the delays of buses and cars, without considering the differences in the operating characteristics of different vehicle types. Because the speed and stop of buses and cars are quite different [5], and the stopping time and passenger capacity of different bus routes are different, the average vehicle delay and per capita delay obtained are subject to large errors.

On the basis of the research on vehicle delay, some scholars have proposed a method of minimizing the total delay of the trunk lines [6,7]; some scholars have optimized the intersection characteristics of bus vehicles through the combination of speed guidance [8], active priority, and signal adjustment based on the coordination of social vehicle trunk lines [9,10]; some scholars have also proposed an analysis method of the impact of bus signal priority on vehicle delay [11] and an evaluation method of the effect of bus priority [12]. Additionally, some scholars proposed a signal control method for bus priority considering the delay of non-priority vehicles in a connected-vehicle environment [13]. These studies are all related to the delay calculation results. In addition, some scholars have considered the delay calculation of intersections in the research of path planning using heuristic algorithms [14–17]. The calculation error will affect the matching degree of the intersection signal timing plan and the traffic demand. When the coordinated control of the bus priority arterial road is carried out, the expected bus priority effect will not be achieved.

Therefore, this paper takes arterial coordination control as the research object to realize the passive bus priority. Firstly, based on the existing research on vehicle delays of arterial coordination control, a multi-conversion standard delay calculation method is proposed for the mixed traffic flow of buses and cars of arterial coordination control. This method calculates the delay of cars and buses on each line separately. Then, arterial coordination control arithmetic cases are generated to calculate vehicle delays, and the accuracy of the method is verified by simulation software. Finally, on the basis of in-depth analysis of the impact of the stop time on the average speed of the bus, we comprehensively considered the bus stop and passenger capacity to establish an optimization model of bus priority arterial coordination control with per capita delay as the optimization objective and verify the validity and parameter sensitivity of the model through the calculation cases.

The research in this paper can calculate the delay of two kinds of vehicles more accurately. On this basis, considering the bus stop and the passenger capacity of the line, from the point of view of people, this paper proposes an optimization method for the coordinated control of the bus priority trunk road, and, at the same time, it can give more priority to the bus line with more passenger capacity, which is more in line with the actual bus operation needs.

2. Single Conversion Standard Delay Calculation Method

In this paper, we refer to the vehicle delay calculation method in the "Phase Difference Model of Arterial coordinating Control and Its Optimization Method" [18], which considers the discrete phenomenon of fleet from upstream intersections to downstream intersections for the adjacent intersections under arterial coordination control, to analyze the arrival and departure at downstream intersections of fleets in the same traveling direction. It classifies the cases of fleet generating delays into six categories and calculates the total fleet delay separately.

In mixed bus and car traffic, the two types of vehicles affect each other, thus the delays of the two types cannot be calculated directly. The existing single conversion standard delay calculation method converts buses into cars, first calculates the total delay of all vehicles, and then finds the delay of the two types of vehicles. The following will introduce the input parameters of delay calculation and the specific steps of the single commutation standard delay calculation method, respectively. Considering that the acceleration, speed, and stopping characteristics of the vehicle all influence the delay, we will also analyze the difference in the characteristics of the two vehicles.

2.1. Parameter Definition

The input parameters and definitions for calculating the delay of mixed buses and cars in the coordinated control of the arterial road are shown in Table 1, where m is used to indicate the two driving directions of the arterial road, m is down to indicate the down direction, and m is up to indicate the upward direction.

Table 1. Parameter definition.

Parameters	Definition
l	Adjacent intersection spacing (m)
C	Intersection common signal period (s)
λ^m	Downstream intersection arterial direction (coordinated control phase) green-signal ratio
O^m	Relative phase difference of the downstream intersection to the upstream intersection (s)
${N_c}^m$	Number of cars in the direction of the downstream intersection arterials (vehicles)
${N_b}^m$	Number of buses in the direction of downstream intersection arterials (vehicles)
${N_{bi}}^m$	Number of vehicles of each bus line in the direction of the downstream intersection artery (vehicles)
${v_c}^m$	Speed of the car (m/s)
${v_{bi}}^m$	Speed of each bus line vehicle (m/s)
${v_b}^m$	Speed of all buses (m/s)
s	Saturated flow rate in the direction of the intersection arterial (pcu/hour)
q^m	Vehicle arrival rate at downstream intersections (pcu/hour)
E_b	Conversion factor for public transport vehicles

2.2. Single Conversion Standard

For the mixed traffic flow of buses and cars, when calculating the delays of two vehicles, it is the car that is usually used as the conversion standard, and the buses are converted into cars. According to this method, the total delays of all vehicles are calculated first, and then the delays of two vehicles are calculated simultaneously according to the ratio of the number of cars to the number of buses after conversion. The specific calculation process is as follows.

(1) Taking the car as the conversion standard, convert the bus into a car to determine the input parameters of the total delay calculation, and calculate the total delay of all vehicles. The input parameters for the total delay calculation take the following values.

The number of vehicles is:

$$N^m = (N_c{}^m + E_b \times N_b{}^m) \tag{1}$$

The speed is:

$$v^m = \frac{(v_c{}^m \times N_c{}^m + E_b \times v_b{}^m \times N_b{}^m)}{(N_c{}^m + E_b \times N_b{}^m)} \tag{2}$$

Vehicle arrival rate is derived based on the relationship between the three parameters of traffic flow, as the arterial coordination control is not applicable to intersections with high traffic flow, and there is generally not few vehicles on arterial roads. A single-segment linear relationship model between vehicle density and speed can be used to derive the expression of the relationship between vehicle arrival rate and speed [19], the specific formula is as follows:

$$q^m = k^m \times v^m \tag{3}$$

$$k^m = k_{jc} \times (1 - \frac{v^m}{v_f}) \tag{4}$$

$$q^m = k_{jc} \times v^m \times (1 - \frac{v^m}{v_f}) \tag{5}$$

where
k^m is the vehicle density (vehicle/km);
k_{jc} is the blocking density of cars (vehicle/km);
v_f is the free flow velocity (m/s);

After determining the values of the input parameters, the total delay D^m of all vehicles is calculated by referring to the total delay calculation method in Ref. [1].

(2) Based on the ratio of the number of cars to the converted number of buses, the delays of both vehicles are calculated simultaneously, and thus the average vehicle delay is determined.

The average car delay is:

$$d_c{}^m = \frac{D^m}{(N_c{}^m + E_b \times N_b{}^m)} \tag{6}$$

The average bus delay is:

$$d_b{}^m = \frac{E_b \times D^m}{(N_c{}^m + E_b \times N_b{}^m)} \tag{7}$$

2.3. Analysis of Vehicle Characteristics Differences

There are differences in acceleration, speed, and stopping characteristics between buses and cars that impact on vehicle delay. The following is a specific analysis of the acceleration of the two types of vehicles, peak hour speeds in Shenzhen from 2011 to 2019, and bus stops on selected arterial roads in Shenzhen.

2.3.1. Acceleration

According to the existing studies, the deceleration interval of the bus entering the bus stop is usually (0.15, 2.5), and the acceleration interval of the exiting is (0, 2.5) [20]; the braking deceleration interval of the car is usually (1.2, 3.2) and the maximum acceleration interval is (2, 4) [21]. It can be seen that the acceleration of the two vehicles is quite different.

2.3.2. Speed

Summarized by all of the Shenzhen Urban Transportation White Paper during 2011~2019, the average speed of cars and buses during peak hours in Shenzhen can be seen from Figure 1, the speed of the car is significantly higher than that of the bus, the average speed of the car is 27.53 km/h, and the average speed of the bus is 19.77 km/h. The speed of the two vehicles is quite different.

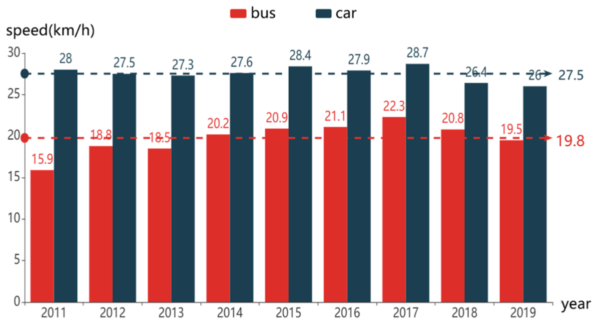

Figure 1. Average speed of cars and buses during peak hours in Shenzhen from 2011 to 2019.

2.3.3. Bus Stops

Based on the online platform of Baidu Map, we obtained the number of bus stops per kilometer included in several arterial roads in the city of Shenzhen. It can be seen from Figure 2 that there are 1.43 bus stops on average per kilometer of arterial roads. The stations distribute more densely, meaning the buses stop more often, which has a greater impact on the speed of buses.

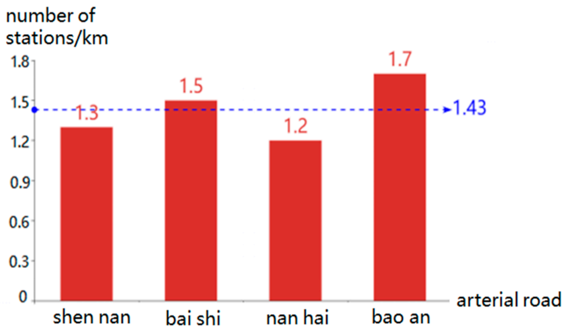

Figure 2. Number of bus stops per kilometer included in arterial roads.

3. Multi-Conversion Standard Delay Calculation Method

Due to the large differences in acceleration, speed, and stopping characteristics between buses and cars, there would be large errors in calculating the delay of the two types of vehicles if we took the car as a single conversion standard. To receive more accurate vehicle delay results, this paper proposes a multi-conversion standard delay calculation method to calculate the delays of the two types of vehicles separately, and the cars are converted when calculating the bus delay. In addition, there are differences in the stopping time of different bus lines, thus the bus delay is calculated by line. The detailed calculation steps of the multi-conversion standard delay calculation method are introduced below.

In order to calculate the delay of various types of vehicles in the mixed traffic flow more accurately, each type of vehicle is considered as a fleet and its delay is calculated separately. When calculating the delay of any type of vehicle, take it as the standard, and convert other types of vehicle according to the vehicle conversion coefficient to obtain the input parameters in the unit of standard vehicle type. Then, calculate the total delay of the converted traffic flow by substituting the parameters, and calculate the delay of the model according to the proportion of the actual number of standard models in the mixed traffic flow and the converted traffic flow.

3.1. By-Vehicle Type

The characteristics of buses and cars differ greatly, resulting in different arrival and departure situations of the two types of vehicles at downstream intersections, and the generations of delays are different. Therefore, this paper regards buses and cars as two fleets and proposes a delay calculation method with multiple conversion standards. On the basis of considering the impact of mixed vehicles, the delays of the two types of vehicles are calculated separately.

When calculating the delay of cars, buses are converted into cars, considering their influence, and the arrival rate of vehicles at downstream intersections is calculated first. As the distribution of buses and cars in mixed traffic is relatively uniform, then the arrival rate and maximum departure rate of cars at downstream intersections are calculated based on the ratio of the number of input cars to the total number of converted cars. Finally, car delays are calculated.

When calculating bus delays, cars are converted into buses, considering their influence, and the vehicle arrival rate of downstream intersections is first calculated. Then, the bus arrival rate and maximum departure rate of downstream intersections are calculated based on the ratio of the number of input buses to the total number of converted buses. Finally, bus delays are calculated.

The detailed processes for calculating the delays of the two vehicles are as follows.

(1) Calculate the average car delay

① Taking the car as the conversion standard, buses are converted into cars to calculate the vehicle arrival rate q^m.

$$v^m = \frac{({v_c}^m \times {N_c}^m + E_b \times {v_b}^m \times {N_b}^m)}{({N_c}^m + E_b \times {N_b}^m)} \tag{8}$$

$$q^m = k_{jc} \times v^m \times (1 - \frac{v^m}{v_f}) \tag{9}$$

② Calculate the arrival rate and maximum departure rate of cars based on the ratio of the input number of cars entered to the total number of cars converted.

The car arrival rate is:

$${q_c}^m = q^m \times \frac{{N_c}^m}{{N_c}^m + E_b \times {N_b}^m} \tag{10}$$

The maximum car departure rate is:

$${s_c}^m = s \times \frac{{N_c}^m}{{N_c}^m + E_b \times {N_b}^m} \tag{11}$$

③ Taking the number of cars ${N_c}^m$, speed ${v_c}^m$, arrival rate ${q_c}^m$, and maximum departure rate ${s_c}^m$ as input parameters, the total delay of cars ${D_c}^m$ is calculated, and then the average delay of cars ${d_c}^m$ is obtained.

$${d_c}^m = \frac{{D_c}^m}{{N_c}^m} \tag{12}$$

(2) Calculate the average bus delay

① Taking the bus as the conversion standard, cars are converted into buses to calculate the vehicle arrival rate q^m.

$$v^m = \frac{({v_c}^m \times \frac{{N_c}^m}{E_b} + {v_b}^m \times {N_b}^m)}{(\frac{{N_c}^m}{E_b} + {N_b}^m)} \tag{13}$$

$$q^m = k_{jb} \times v^m \times (1 - \frac{v^m}{v_f}) \tag{14}$$

② Calculate the arrival and maximum departure rates of buses based on the ratio of the number of buses entered to the total number of buses converted.

The bus arrival rate is:

$$q_b{}^m = q^m \times \frac{N_b{}^m}{\frac{N_c{}^m}{E_b} + N_b{}^m} \tag{15}$$

The maximum bus departure rate is:

$$s_b{}^m = s \times \frac{N_b{}^m}{\frac{N_c{}^m}{E_b} + N_b{}^m} \tag{16}$$

③ Taking the number of bus vehicles $N_b{}^m$, speed $v_b{}^m$, arrival rate $q_b{}^m$, and maximum departure rate $s_b{}^m$ as input parameters, the total delay of buses delay $D_b{}^m$ is calculated, and then the average delay of buses $d_b{}^m$ is obtained.

$$d_b{}^m = \frac{D_b{}^m}{N_b{}^m} \tag{17}$$

3.2. By-Bus-Line Type

In addition to the differences in bus and car characteristics, the stopping time and passenger capacity of bus vehicles on each line are also different, which has a significant impact on the average bus delay and per capita delay calculation results. Therefore, each line of buses can be considered as a fleet of buses, and the average delay of each line of buses can be calculated. The specific calculation process is as follows.

(1) Taking the bus as the conversion standard, cars are converted into buses to calculate the vehicle arrival rate q^m.

$$v^m = \frac{v_c{}^m \times \frac{N_c{}^m}{E_b} + \sum_{i=1}^{n} v_{bi}{}^m \times N_{bi}{}^m}{\frac{N_c{}^m}{E_b} + \sum_{i=1}^{n} N_{bi}{}^m} \tag{18}$$

$$q^m = k_{jb} \times v^m \times (1 - \frac{v^m}{v_f}) \tag{19}$$

(2) Calculate the arrival and maximum departure rates of vehicles on each bus line based on the ratio of the number of vehicles entered on each bus line to the total number of converted buses.

The bus arrival rate of each line is:

$$q_{bi}{}^m = q^m \times \frac{N_{bi}{}^m}{\frac{N_c{}^m}{E_b} + \sum_{i=1}^{n} N_{bi}{}^m} \tag{20}$$

The maximum departure rate of buses on each route is:

$$s_{bi}{}^m = s \times \frac{N_{bi}{}^m}{\frac{N_c{}^m}{E_b} + \sum_{i=1}^{n} N_{bi}{}^m} \tag{21}$$

(3) Taking the number of vehicles $N_{bi}{}^m$, the speed $v_{bi}{}^m$, the arrival rate $q_{bi}{}^m$, and the maximum departure rate $s_{bi}{}^m$ as input parameters, the total delay $D_{bi}{}^m$ of each bus line is calculated, and then the average delay of each bus line $d_{bi}{}^m$ is obtained.

$$d_{bi}{}^m = \frac{D_{bi}{}^m}{N_{bi}{}^m} \tag{22}$$

4. Coordinated Control Example and Simulation

In the following, 178 sets of arterial road coordination control examples were generated through Python. According to the above single conversion standard and multi-conversion standard delay calculation methods, the two-way bus and car delays on the arterial road were calculated, respectively.

4.1. Coordinated Control Example

4.1.1. Example Data Generation

The data generation of the example was divided into three parts: firstly, the intersection attribute parameters were determined, then the parameters related to the traffic flow were generated, and, finally, the signal timing parameters were determined. The parameter generation basis and values of each part are described below.

(1) Intersection Attribute Parameters

The study showed that the intersection spacing for arterial coordination control should be between 300 m and 800 m [4], and this paper determined the intersection spacing l as 495 m based on the actual adjacent intersections, which was within the appropriate range. Then, we referred to the study "Analysis of the effect of saturation flow rate and start-up delay of signal intersections" [22] and determined the saturation flow rate of the intersection in the straight direction s as 1800 pcu/h.

(2) Traffic flow related parameters

First, set the value range of the car input in each direction of the intersection and the proportion of vehicles in each flow direction, randomly generate the input quantity of cars, and calculate the flow quantity of cars in the arterial direction of the downstream intersection based on the input quantity and flow ratio of cars at the upstream intersection ${N_c}^m$. Then, set the ratio of the number of buses to cars at 10–20%, randomly generate the total number of buses in each direction ${N_b}^m$. Set the value range of bus lines to 2–6, randomly generate the number of bus routes in both directions of the arterial and determine the number of vehicles on each bus line ${N_{bi}}^m$. Finally, with reference to evaluation criteria of the service level of signal intersection, keeping the saturation rate of the intersection below 0.75 [23], to adjust the input flow of cars and buses.

In this paper, we set the travel speeds of car and bus as 45–55 km/h and 40–50 km/h, respectively. When calculating the vehicle delay, the speed of car and bus was taken as 50 km/h and 45 km/h, respectively. At the same time, we analyzed the bus operation data of Guangzhou city, took the stopping time of some bus lines as the example data, and determined the travel speed of each bus line ${v_{bi}}^m$. The calculation formula of v_{bi} is as follows.

$$ {v_{bi}}^m = \frac{l}{l/v + t_{bi} + t_{ad}} = \frac{l \times v}{l + t_{bi} \times v + t_{ad} \times v} \tag{23} $$

where

t_{bi}—stop time of bus line i;
v—the speed of the bus;
t_{ad}—acceleration and deceleration loss time;

$$ t_{ad} = \frac{v \times (\alpha_a + \alpha_b)}{2 \times \alpha_a \times \alpha_b} \tag{24} $$

α_a—the starting acceleration;
α_b—the braking deceleration.

Referred to "Analysis of Road Traffic Capacity", the general value is α_a = 1 m/s^2, α_b = 1.5 m/s^2.

With reference to existing studies, it was determined that the coefficient of converting buses into cars was 2 [24]. Then, the car blocking density k_{jc} and bus blocking density k_{jb} were calculated, and the vehicle arrival rate q^m at downstream intersections was derived from the relationship between the three parameters of traffic flow. The values of k_{jc} and k_{jb} were as follows [25].

If the length of the car was about 5 m, the minimum head distance was about 2 m, determined $k_{jc} = \frac{1000}{7} \approx 143$ vehicle/km;

If the length of the bus was about 12 m, the minimum head distance was about 2 m, determine $k_{jb} = \frac{1000}{14} \approx 71$ vehicle/km.

(3) Signal timing parameters

First, determine the signal phase of the two intersections; then, calculate the signal timing parameters according to Webster's timing method, including the common signal cycle length C and the green signal ratio of the coordinated control phase λ^m. For the two-way coordinated control of arterial roads, the two relative phase differences of adjacent intersections have a certain constraint relationship, the expression is: $O^{down} + O^{up} = C$. This paper sets the relative phase difference in the downward direction of the arterial road o^{down} as 30 s, and the relative phase difference in the upward direction o^{up} is signal cycle length minus 30 s.

Based on the above data generation principles, 178 sets of arterial road coordination control examples were generated.

4.1.2. Data Distribution of the Examples

The number of vehicles in the downstream intersection arterial direction was calculated based on the number of vehicles and the flow direction ratio generated by each entrance of the upstream intersection, with a certain degree of randomness. Therefore, it was necessary to further analyze the distribution of the number of car vehicles, the number of bus vehicles, and the ratio of the two types of vehicles in the 178 sets of examples.

(1) Number of cars

For the distribution of the number of cars arriving at the downstream intersection arterial direction in the two travel directions, the number of vehicles was between 550 and 950, and the analysis was carried out at an interval of 50 vehicles. The overall distribution of the number of cars was relatively uniform. Among them, the number of vehicles was 550–600, and 900–950 were relatively low, accounting for 6.75% and 8.58%, respectively; the proportions of other quantity ranges were between 13% and 15%.

(2) Number of buses

For the distribution of the number of buses arriving at the downstream intersection arterial direction in both directions of travel, the number of vehicles was between 90 and 120, and the analysis was carried out at an interval of 5 vehicles. The overall distribution of the number of buses was relatively uniform, with the proportion of each number interval ranging from 15% to 19%.

(3) The ratio of the number of buses to the number of cars

The proportional distribution of the number of buses and cars in the downstream intersection arterial direction. The proportion was between 10% and 20%, which was analyzed at an interval of 2%. The overall distribution was uneven, with more cases of 12–14%.

4.1.3. Delay Calculation

After generating 178 sets of examples, the delays of vehicles in both directions of the arterial road were calculated by the above-mentioned single conversion standard and multi-conversion standard delay calculation methods. The average delays of buses and cars were calculated by the single conversion standard. The standard included two types: by-vehicle and by-bus-line, in which the average delay of cars and buses were calculated by vehicles, and the average delay of cars and buses on each line were calculated by bus lines.

4.2. Simulation

Based on two adjacent intersections on the actual arterial road, the arterial road coordination control simulation model was firstly established by using VISSIM software and then the simulation parameters were calibrated; finally, the generated 178 sets of examples were simulated through the secondary development of VISSIM, and the simulation results of vehicle average delay were obtained.

4.2.1. Construction of the Simulation Model

Taking two adjacent intersections with a spacing of 495 m on an arterial road in Shenzhen as an example, a simulation model of arterial road coordination control was established by VISSIM software. There were bus lines and bus stops on both directions of the arterial road, and a travel time detector was set up to collect vehicle delay data. The simulation model is shown in Figure 3. The Chinese characters on the image are the names of the several surrounding places, like libraries and parks, which come with the map originally.

Figure 3. Simulation model of coordinated control of arterial road.

4.2.2. Calibration of Simulation Parameters

The car-following model and the lane-changing model in the VISSIM simulation software have a great influence on the driving state of the vehicle. To obtain a more realistic simulation effect, six parameters in the two models were calibrated, which were average stopping distance, additional part of safety distance, multiplier part of safety distance, minimum head gap, maximum deceleration of overtaking vehicle, and maximum deceleration of overtaken vehicle [26].

The process of parameter calibration was as follows:

(1) The average delay and stopping time of vehicles were used as evaluation indicators, and the actual intersection data were counted.
(2) A reasonable range of values and step sizes for the six parameters were determined, and the actual data from the statistics were input into the simulation model. The parameter values were changed for multiple simulations, and the average delay and stopping time for each inlet lane were extracted.
(3) The simulated average vehicle delays and stopping times were compared with the statistical actual values to calculate the error for each simulation and determine the most suitable parameter combination. The errors before and after the parameter calibration were 25.5% and 20%, respectively, which were reduced by 5.5% and were more consistent with the actual operating conditions of the vehicle. The calibration results are shown in Table 2.

Table 2. Calibration results of driving behavior parameters.

	Average Parking Spacing	Additional Parts of the Safety Distance	Multiplier Part of the Safety Distance	Minimum Headroom	Overtake the Maximum Deceleration of the Car	Maximum Deceleration of Overtaken Vehicles
Default Value	2	2	3	0.5	−4	−3
Calibration results	2.2	2	3	0.5	−4	−3.5

4.2.3. Simulation Results

After calibrating the simulation parameters, the 178 sets of examples were simulated separately by a secondarily-developed VISSIM, and the average vehicle delays of cars, buses, and buses of each route in both directions of the arterial road are obtained.

5. Delay Calculation Error Analysis

In the following, on the basis of the simulation results of 178 sets of examples, firstly we analyzed the delay calculation results of the single conversion standard and the multi-conversion standard by-vehicle type. The error values of the average delay of cars and buses calculated by the two methods were compared to verify that the multi-conversion standard delay calculation method was more accurate. Secondly, we compared the delay calculation errors of by-vehicle type and by-bus-line type of the multi-conversion standard, and then determined the delay calculation method of bus priority coordination control.

5.1. Calculation Errors of Single Conversion Standard and By-Vehicle Type

Based on the average delay simulation results of 178 sets of examples, the delay calculation errors of the single conversion standard and by-vehicle type in the multi-conversion standard were calculated. The average errors of the average delay of cars are shown in Figure 4, which are 7.32 s and 5.69 s, respectively. The average errors of the average delay of buses are shown in Figure 5, which are 21.75 s and 3.52 s, respectively. It can be seen that the multi-conversion standard delay calculation method was more accurate, and the errors of the average delay of cars and the average delay of buses were reduced by 1.63 s and 18.23 s, respectively, with a reduction rate of 22.54% and 83.82%.

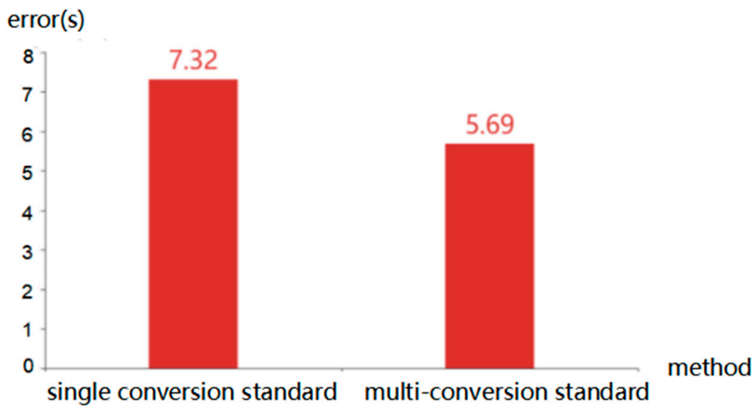

Figure 4. Average error in average delay of cars.

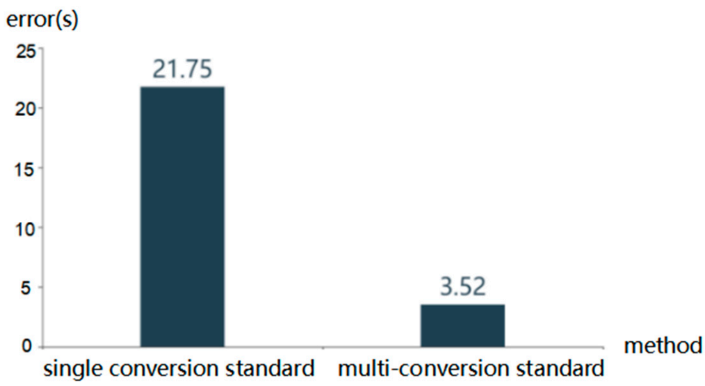

Figure 5. Average error in average delay of buses.

The following are the average delay of cars and buses for the 178 sets of examples, including the simulation results, the calculation results of delays of by-vehicle type in single, and multi-conversion standard.

(1) Average delay of cars

As can be seen from Figure 6, the number ratio of buses to cars varies between 10% and 20%, compared with the single conversion standard, most of the calculation results of the multi-conversion standard are closer to the simulation results, with 99% of the average delay for cars being calculated with less error.

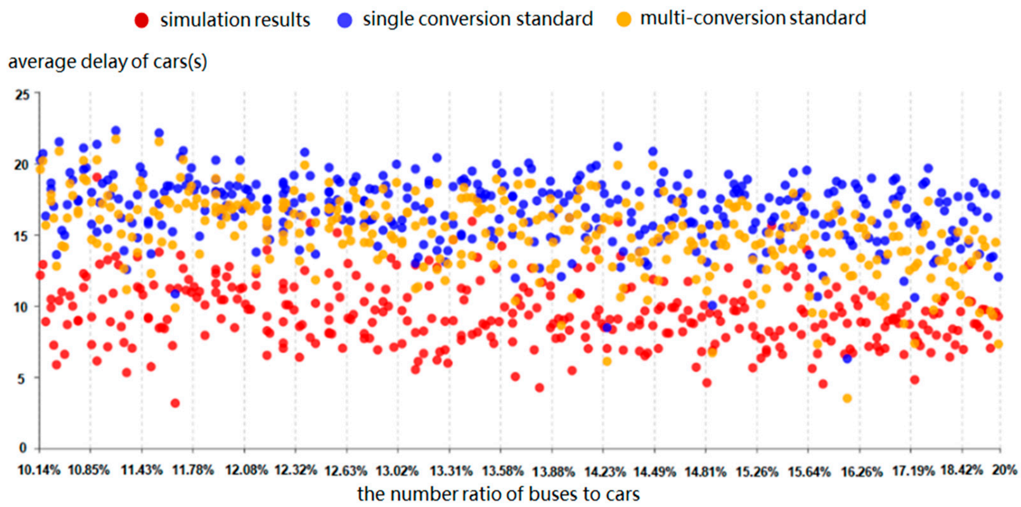

Figure 6. Average delay of cars.

(2) Average delay of buses

As can be seen from Figure 7, the number ratio of buses to cars varies between 10% and 20%, compared with the single conversion standard, most of the calculation results of the multi-conversion standard are closer to the simulation results, with 98% of the average delay for buses being calculated with less error and a greater reduction in error.

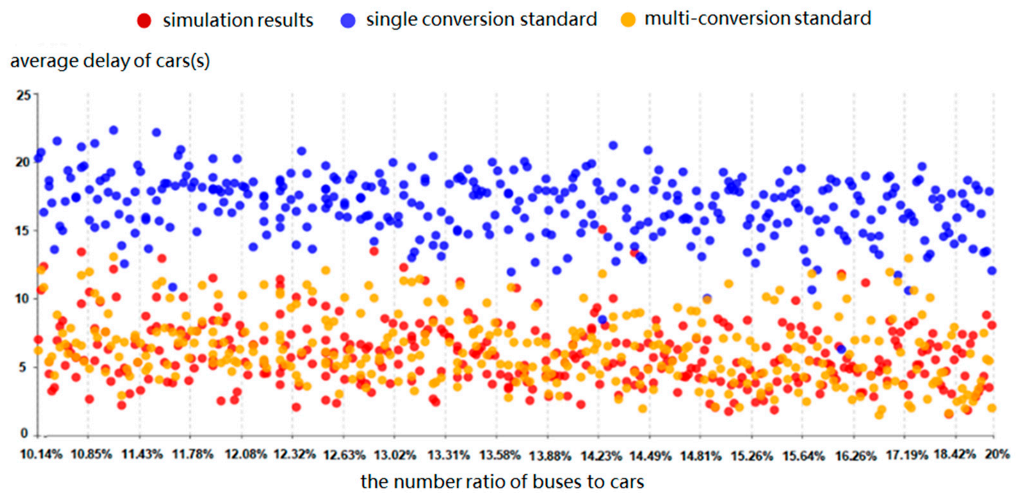

Figure 7. Average delay of buses.

The calculation result of bus delay was improved because the single conversion standard method calculated the bus delay with the small car as the standard, and the speed was calculated as the average value of the small car and the bus, while the multi-conversion standard method proposed in this paper was calculated with the bus as the standard, and the speed was calculated as the bus speed, which was more consistent with the actual situation.

5.2. Calculation Errors of By-Vehicle Type and By-Bus-Line Type

Based on the simulation results of the average vehicle delay of 178 sets of examples, we compared and analyzed the delay calculation results by-vehicle type and by-bus-line in the multi-discounting standard. The average errors of the average delay of cars were both 5.69 s. The average errors of the average delay of bus, where the average error of by-vehicle type, was 3.52 s and the average error of by-bus-line type was 3.9 s. There was little difference between the two results, and the error of by-bus-line type was slightly higher by 0.38 s. The main reason for this was that there is a certain error in calculating the total fleet delay, and the number of vehicles on each bus line was relatively small, thus the error of the average delay of buses on each line would be larger.

The calculation of bus lines took the average delay of each bus line, and the result was more refined, which took into account the difference in passenger capacity of each bus line when carrying out the coordinated control of bus priority, and received a more accurate per capita delay result, thus reducing the per capita delay at intersections. In addition, compared with the single conversion standard delay calculation method, the average error of the average delay of cars and the average delay of buses in bus line reduced by 1.63 s and 17.85 s, respectively, with a reduction rate of 22.27% and 82.07%, which was more accurate. Therefore, for the coordinated control of bus priority, it is appropriate to adopt the calculation method of by-bus line in multi-conversion standard.

6. Optimization Model for Coordinated Control of Bus Priority Arterial Road

The factor that had a direct impact on the delay was the travel speed. Therefore, the impact of stop time on bus delay was analyzed first. The main purpose of urban passenger transportation is to realize the movement of people. Considering that the passenger capacity of buses is usually much larger than that of cars, the goal of minimum delay per capita can achieve a certain degree of bus priority, which also reflects the concept of "people-oriented" concepts of transportation. In the following, an optimization model for coordinated control of bus priority arterial roads will be developed with the target of per capita delays on arterial roads in both directions.

6.1. Stopping Time

In this section, we used the bus operation data of Guangzhou city in one week to analyze the stopping time of all buses. The frequency distribution and cumulative frequency distribution of the stopping time are shown in Figure 8, with 10 s as the interval. The frequency of 30–40 s was the highest, and 97.71% of the bus stopping time was within 150 s. Therefore, the latter analysis only considers the case where the bus stop time was within 150 s.

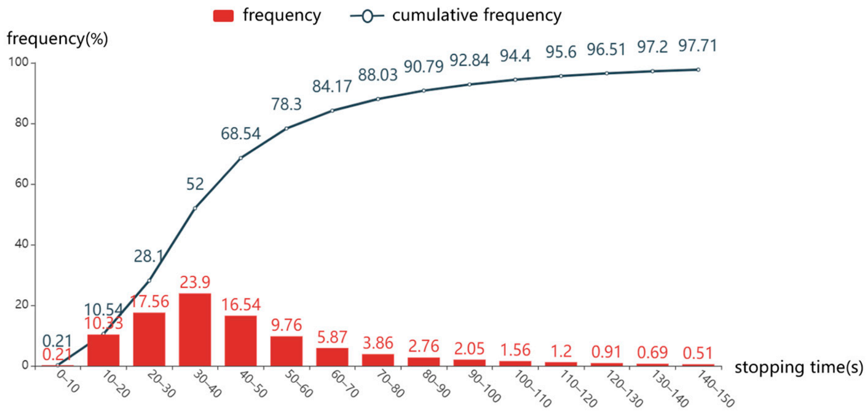

Figure 8. Frequency distribution and cumulative frequency of bus stopping time.

6.2. Impact of Stopping Time on Bus Delay

Based on the examples generated in this paper, the distance between the two intersections was 495 m, and the speed of the running bus was 12.5 m/s. In the range of 0–150 s, the speed corresponding to different stopping times was calculated with 10 s as the interval, as shown in Figure 9. When the stopping time was 150 s, the speed dropped to 2.48 m/s, indicating that the stopping time had a great influence on the speed.

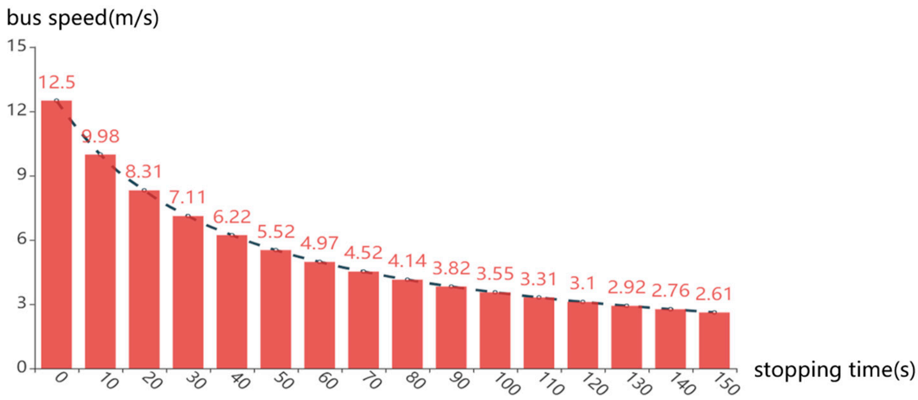

Figure 9. Speeds corresponding to different stopping time.

The bus speeds corresponding to different stopping times were substituted into 178 sets of examples, respectively, and the average delays of buses in all examples were calculated. Compared with the average delay of buses when not stopping, the average change value in the average bus delay for each stopping time in the downward direction is shown in Figure 10. The maximum difference was 8.35 s, with a difference ratio of 48.03%. The average change in the average bus delay for each stopping time in the upward direction is shown in Figure 11. The maximum difference was 6.79 s, with a difference ratio of 47.27%. These indicate that the stopping time has a greater impact on bus delays, and the average change in delay value for each stopping time shows a certain periodicity.

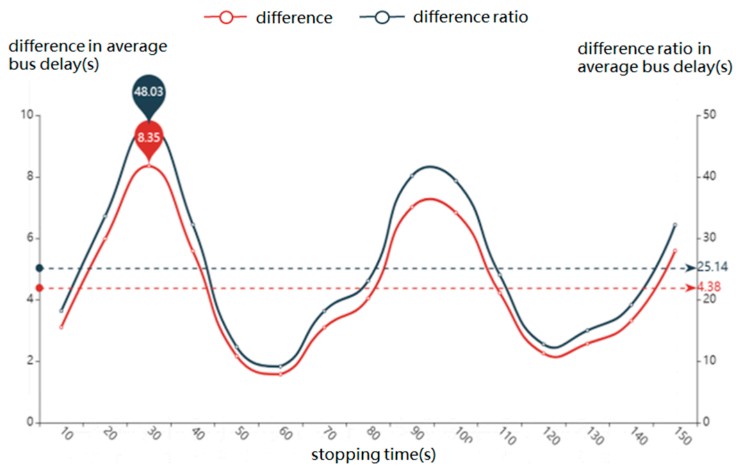

Figure 10. Change in average delay for each stopping time in the downstream direction.

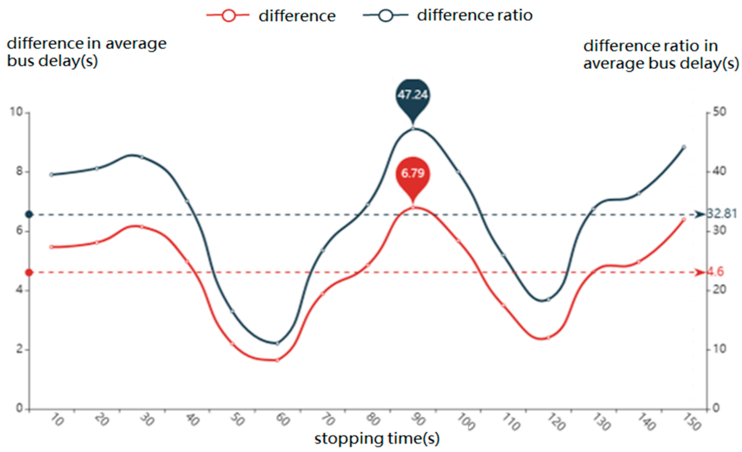

Figure 11. Change in average delay for each stopping time in the upstream direction.

6.3. Objective Function

To achieve bus priority and not cause a large negative impact on car traffic, this paper takes the two-way per capita delay of arterial roads as the optimization goal, which not only realizes the priority of public transportation to a certain extent but also reflects the "people-oriented" concept of transportation.

Due to the great impact of stopping time on bus delays, this paper, based on the consideration of bus stopping, according to the delay calculation method of by-bus line in standard $d()$, calculates the average delay of cars in the downward direction ${d_c}^{down} = d\left(l, C, \lambda^{down}, {N_c}^{down}, {N_b}^{down}, {N_i}^{down}, {v_c}^{down}, {v_{bi}}^{down}, {v_b}^{down}, O^{down}, s\right)$, the average delay of buses on each line in the downward direction ${d_{bi}}^{down} = d\left(l, C, \lambda^{down}, {N_c}^{down}, {N_b}^{down}, {N_i}^{down}, {v_c}^{down}, {v_{bi}}^{down}, {v_b}^{down}, O^{down}, s\right)$, the average delay of cars in the upward direction ${d_c}^{up} = d(l, C, \lambda^{up}, {N_c}^{up}, {N_b}^{up}, {N_i}^{up}, {v_c}^{up}, {v_{bi}}^{up}, {v_b}^{up}, O^{up}, s)$, and the average delay of buses on each line in the upward direction ${d_{bi}}^{up} = d(l, C, \lambda^{up}, {N_c}^{up}, {N_b}^{up}, {N_i}^{up}, {v_c}^{up}, {v_{bi}}^{up}, {v_b}^{up}, O^{up}, s)$. On this basis, the arterial road delay per capita in both directions was calculated by the following formula:

$$d_p = \frac{\left({N_c}^{down} \times {d_c}^{down} + {N_c}^{up} \times {d_c}^{up}\right) \times p_c + \sum_{i=1}^{n1} {N_{bi}}^{down} \times {d_{bi}}^{down} \times {p_{bi}}^{down} + \sum_{i=1}^{n2} {N_{bi}}^{up} \times {d_{bi}}^{up} \times {p_{bi}}^{up}}{\left({N_c}^{down} + {N_c}^{up}\right) \times p_c + \sum_{i=1}^{n1} {N_{bi}}^{down} \times {p_{bi}}^{down} + \sum_{i=1}^{n2} {N_{bi}}^{up} \times {p_{bi}}^{up}} \quad (25)$$

where

p_c is the passenger capacity of the car;
${p_{bi}}^{down}$ is the passenger capacity of bus line i in the downward direction;
${p_{bi}}^{up}$ is the passenger capacity of bus route i in the upward direction.

6.4. Model Construction

With the two-way per capita delay as the optimization objective and the relative phase difference as the decision variable, the constructed optimization model for coordinated control of bus priority arterial road can be described as:

Objective function:

$$min\ d_p$$

Constraints:

$$\begin{cases} 0 \leq O^{down} < C \\ O^{down} + O^{up} = C \end{cases}$$

In the above constraints, the first constraint indicates the range of the value of phase difference; the second constraint indicates the relationship of relative phase differences between adjacent intersections.

6.5. Model Solving

The objective function of the model in this paper is a nonlinear quadratic function, and the constraints include equivalent constraints and non-equivalent constraints, which is a nonlinear programming problem with multiple constraints. Since the decision variable of this model is only the relative phase difference, and the value range of the relative phase difference is less than the nonnegative number of the common signal period, while the actual signal timing period is usually less than 180 s, the timing step is 1 s, all values of the relative phase difference are few; thus, this model can be solved by traversal. The specific implementation process is as follows: firstly, the calculation of the average delay of cars, the average delay of buses, and per capita delay in both directions of the arterial road is realized by programming; then, with the goal of minimizing two-way per capita delay, the optimal solution is obtained by traversing the relative phase difference.

7. Results and Analysis

In this section, the 178 sets of arterial coordination control examples generated above are used to find the optimal phase difference for each set of examples based on this paper's model and the model without considering bus priority, as well as the examples bus average delay, per capita delay, car average delay, and vehicle average delay, respectively. The effectiveness of this model is analyzed by comparing the example results of the model without considering bus priority, and the sensitivity analysis of the model in this paper is carried out from three aspects: the proportion of buses, bus passenger capacity, and bus stopping time.

7.1. Validity Analysis

With 178 sets of examples as input, the optimal phase difference and the corresponding per capita delay, average delay, average delay of bus, and average delay of cars were calculated for all examples according to this model and the model without considering the bus priority. Compared with the optimization result of the model without considering the bus priority, the average change in each delay after the optimization of this model was calculated as an evaluation index to analyze the effectiveness of this model. The optimization target of the model without considering bus priority was the average vehicle delay d_v, and the calculation formula of d_v, as follows:

$$d_v = \frac{{N_c}^{down} \times {d_c}^{down} + {N_c}^{up} \times {d_c}^{up} + \sum_{i=1}^{n1} {N_{bi}}^{down} \times {d_{bi}}^{down} + \sum_{i=1}^{n2} {N_{bi}}^{up} \times {d_{bi}}^{up}}{{N_c}^{down} + {N_c}^{up} + \sum_{i=1}^{n1} {N_{bi}}^{down} + \sum_{i=1}^{n2} {N_{bi}}^{up}} \quad (26)$$

As shown in Figure 12, compared with the model without considering bus priority, the per capita delay and bus average delay after optimization of the model in this paper decreased by 1.88 s and 3.85 s, respectively, with a reduction ratio of 13% and 24.85%; the average vehicle delay and car average delay increased by 0.9 s and 1.59 s, respectively, with an increase ratio of 6.63% and 11.9%. Comparing the changes of each type of delay, it can be seen that the increase in average vehicle delay and average car delay is small compared with the decrease in per capita delay and average bus delay. This indicates that the model in this paper can effectively reduce bus delay and per capita delay and has a small negative impact on car traffic and the overall vehicle traffic at the intersection.

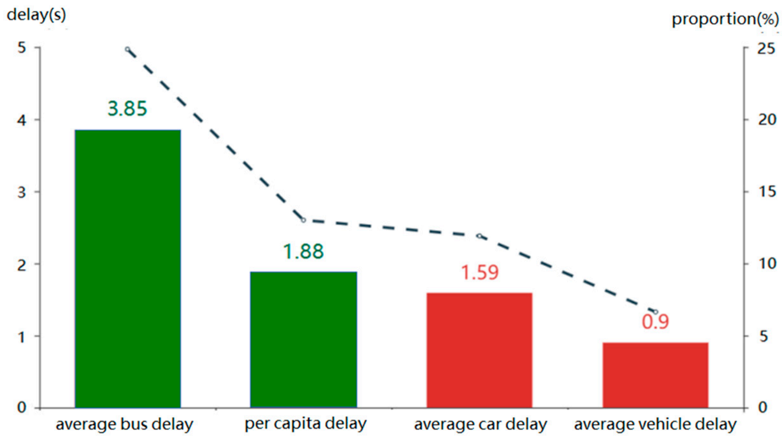

Figure 12. Comparison of the variations in each delay.

The following are the results of average bus delay, per capita delay, average car delay, and average vehicle delay after optimizing 178 sets of examples for both models.

(1) Average bus delay

As can be seen from Figure 13, compared with the average bus delay after optimization of the model without considering the bus priority, 3% of the optimized results of the model in this paper were larger, 10% were equal, and 87% were smaller, indicating that the average bus delay was lower in most of the examples optimized by this model. Moreover, the average bus delay was reduced by 3.85 s on average and 12.49 s maximum. A total of 45% of the reduction value was higher than the average, indicating that the optimization effect of bus delay in nearly half of the examples was higher than the average level.

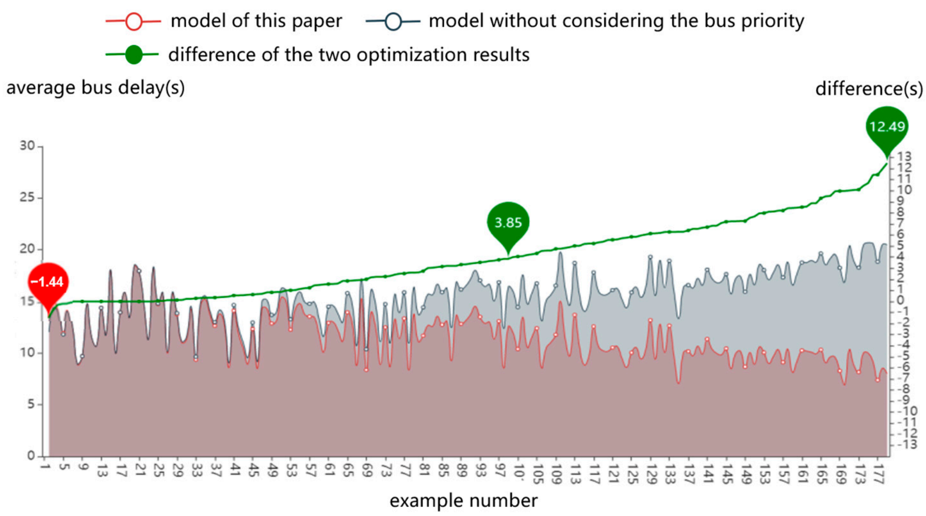

Figure 13. Comparison of the average bus delay after the optimization of the two models.

(2) Per capita delay

As can be seen from Figure 14, compared with the per capita delay after optimization of the model without considering the bus priority, 10% of the optimized results of the model in this paper were equal to it, and 90% were smaller, which meant that the per capita delay of most of the examples optimized by this model was lower. Moreover, the per capita delay was reduced by 1.88 s on average and 6.84 s maximum. A total of 44% of the reduction value was higher than the average, indicating that the optimization effect of per capita delay in nearly half of the examples was higher than the average level.

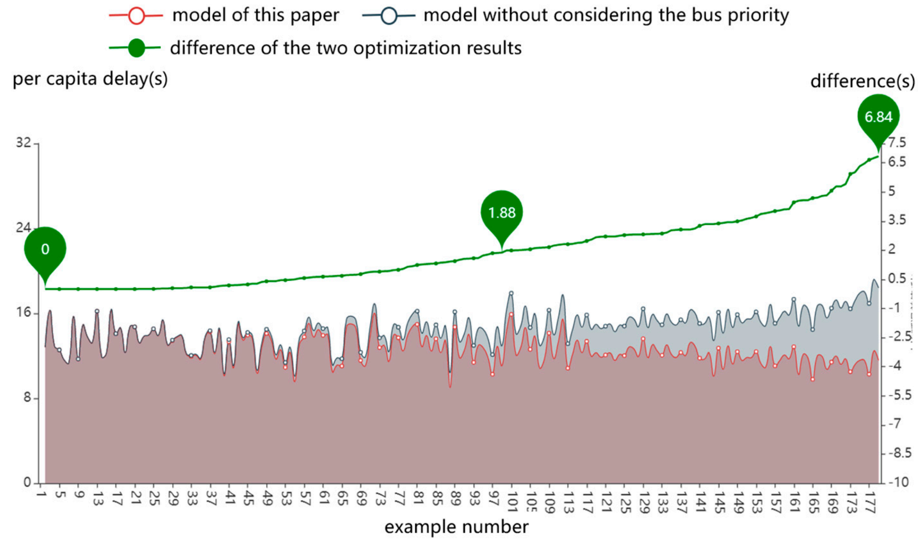

Figure 14. Comparison of per capita delay after the optimization of the two models.

(3) Average car delay

As can be seen from Figure 15, compared with the average delay of cars after optimization of the model without considering the bus priority, 1% of the optimization results of the model in this paper are smaller, 10% are equal to it, and 89% are larger, which means that the average delay of cars is higher in most of the examples optimized by this model. Moreover, the average delay of cars increased by 1.59 s on average and 5.14 s maximum. A total of 56% of the increase value was lower than the average, indicating that the optimization effect of the average delay of cars in more than half of the examples was higher than the average level.

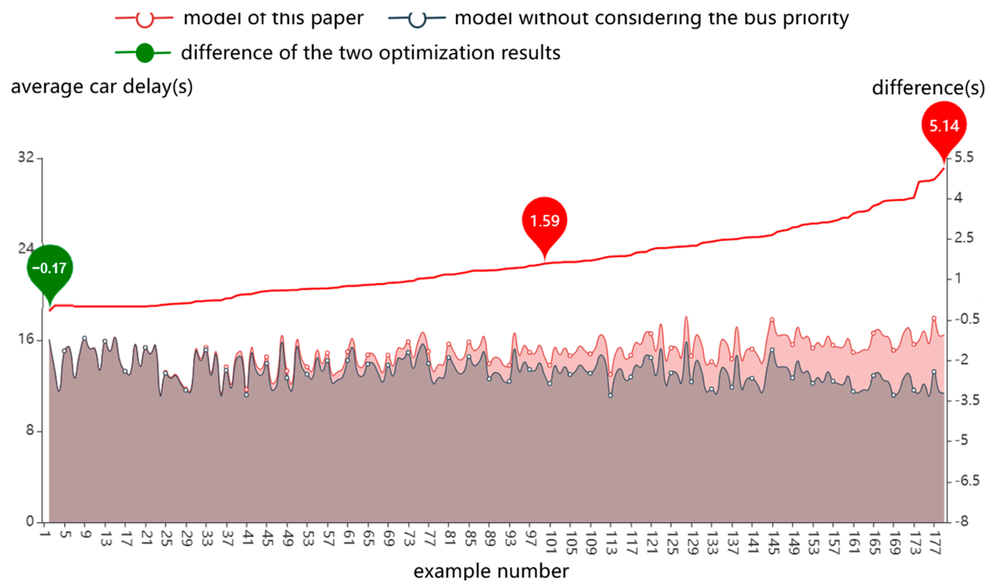

Figure 15. Comparison of the average car delay after the optimization of the two models.

(4) Average vehicle delay

As can be seen from Figure 16, compared with the average vehicle delay after optimization of the model without considering the bus priority, 10% of the optimization results of this model are equal to it, and 90% are larger, indicating that the average vehicle delay is higher in most of the examples optimized by this model. Moreover, the average vehicle delay increased by 0.9 s on average and 3.55 s maximum. A total of 63% of the increase value was lower than the average, indicating that the optimization effect of average vehicle delay in more than half of the examples was higher than the average level.

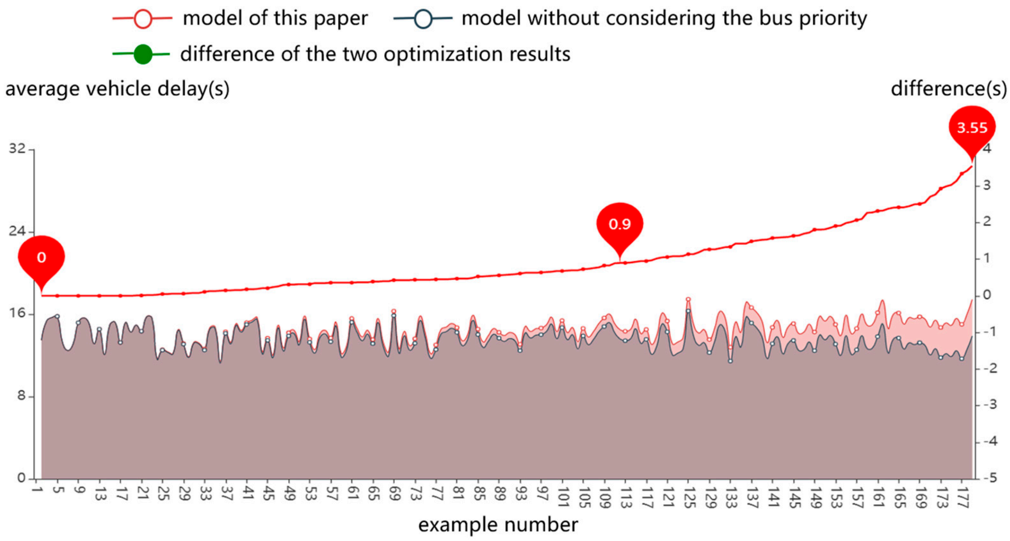

Figure 16. Comparison of the average vehicle delay after the optimization of the two models.

7.2. Sensitivity Analysis

According to the results of per capita delay, the bus average delay and car average delay after 178 sets of examples were optimized by the model in this paper, and the sensitivity analysis of the model was carried out from three aspects: the proportion of buses, bus passenger capacity, and bus stopping time.

7.2.1. The Proportion of Buses

A total of 178 sets of examples were classified according to the proportion of buses and cars on the arterial road, and the average values of per capita delay, per bus delay, and per car delay of each type of examples were calculated, respectively. Based on the average value of the first type of examples, the reduced value of per bus delay, the increased value of per car delay, and the difference between the two were calculated. The results are shown in Figure 17.

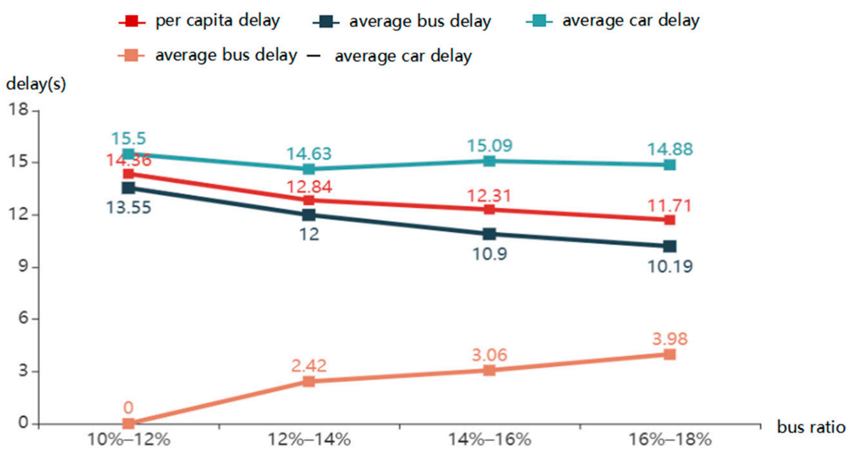

Figure 17. Optimization results with different bus ratios.

Within the range of 10% to 18%, as the proportion of buses increases, the per capita delay and bus average delay decreased significantly, with a decrease of 18.5% and 24.8%, respectively. The average delay of cars changed little and had no evident pattern. The difference between the decrease in the average delay of buses and the increase in the average delay of cars was greater than 0 and showed an increasing trend, indicating that the decrease in the average delay of buses was greater than the increase in the average delay of small cars, and, as the proportion of buses increases, the model in this paper was more effective in reducing the average delay of buses.

7.2.2. Bus Passenger Capacity

A total of 178 sets of examples were classified according to the passenger capacity of the buses on the arterial road, and the average values of per capita delay, per bus delay, and per car delay of each type of example were calculated, respectively. Based on the average value of the first type of examples, the reduced value of per bus delay, the increased value of per car delay, and the difference between the two were calculated. The results are shown in Figure 18.

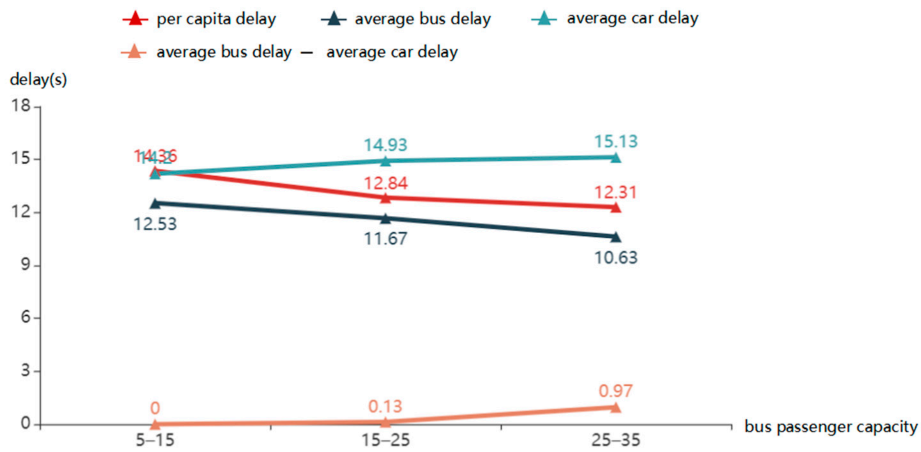

Figure 18. Optimization results for buses with different passenger capacity.

Within the range of 5 to 35, with the increase in bus passenger capacity, the per capita delay and bus average delay decreased significantly, with a decrease of 14.3% and 15.2%, respectively, and the average delay of cars increased, with an increase of 7.7%. The difference between the decrease in the average delay of buses and the increase in the average delay of cars was greater than 0 and showed an increasing trend, indicating that the decrease in the average delay of buses was greater than the increase in the average delay of small cars, and, as the bus passenger capacity increases, the model in this paper was more effective in reducing the average delay of buses.

7.2.3. Bus Stopping Time

The stopping time of the bus affected the speed of the bus. When the speed of the car was constant, the speed difference of the two vehicles could represent the stop time of the bus; however, the difference in speed led to differences in the vehicle delay results after the optimization of the model in this paper. Therefore, the influence of the speed difference of the two vehicles on the optimization results can be directly analyzed.

A total of 178 sets of examples were classified according to the speed difference between the buses and cars on the arterial road, and the average values of per capita delay, per bus delay, and per car delay of each type of examples were calculated, respectively. Based on the average value of the first type of examples, the reduced value of per bus delay, the increased value of per car delay, and the difference between the two were calculated. The results are shown in Figure 19.

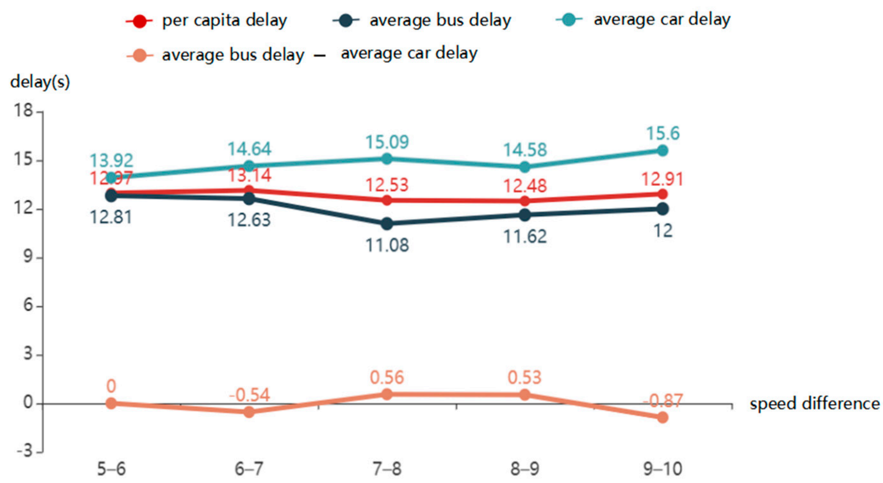

Figure 19. Optimization results for two vehicles with different speed differences.

In the range of 5 m/s to 10 m/s, with the increase in speed difference, there was no evident change rule in the per capita delay and the average car delay. The average delay of buses first decreased and then increased. When the speed difference was 7–8 m/s, the delay per bus was the smallest, and the difference between the reduction value of the delay per bus and the added value of the delay per car and the delay per bus was the largest, which meant that the model of this paper had the best effect of reducing the average delay of the bus at that time.

8. Conclusions

In this paper, we proposed the idea of multi-conversion standard and considering the bus stopping time to further improve the delay calculation accuracy and realize the priority of bus signal for the problem of coordinated control of mixed traffic arterials of buses and cars. First, based on the comparison and analysis of the differences in the characteristics of different vehicles, the multi-conversion standard delay calculation method was proposed, and its effectiveness was verified by simulation, which showed that the average delay error calculation of cars and buses calculated by the method reduced by 22.54% and 82.21%, respectively, compared with the single-discount standard delay calculation method. Then, the impact of bus stopping on bus speed and delay was analyzed in depth, and a coordinated control model of bus priority arterial considering bus stopping time was constructed by combining the passenger capacity of each bus line with the target of per capita delay. Finally, the validity and sensitivity of this paper's model were verified and analyzed by 178 sets of randomly generated arithmetic examples. After the optimization of the model, the average bus delay and per capita delay were reduced by 24.85% and 13%, respectively, which was about twice of the corresponding delay increase in small cars. The sensitivity analysis showed that the average bus delay decreased with the increase in bus share and bus passenger capacity, while the average bus delay showed a trend decreasing and then increasing when the bus stopping time increased, which indicated that the model was suitable for the coordinated control problem of mixed traffic arterials with large bus share and passenger capacity.

Author Contributions: Conceptualization, L.Z. (Liang Zou) and Z.L.; methodology, L.Z. (Liang Zou); software, L.Z. (Lingxiang Zhu); validation, Z.L., Z.Y. and L.Z. (Liang Zou); formal analysis, L.Z. (Liang Zou); writing—original draft preparation, Z.Y.; writing—review and editing, L.Z. (Liang Zou). All authors have read and agreed to the published version of the manuscript.

Funding: This paper is supported by Shenzhen Municipal Science and Technology Innovation Committee (Grant No. JCYJ20170818142947240).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shang, C.L.; Liu, X.M.; Tian, Y.L.; Dong, L.X. A deep reinforcement learning based method for integrated arterial coordination control. *J. Transp. Syst. Eng. Inf. Technol.* **2021**, *21*, 64–70.
2. Beijing's "Green Belt" Road Has Reached 50. Available online: https://baijiahao.baidu.com/s?id=1651833783687311747&wfr=spider&for=pc (accessed on 12 January 2023).
3. Shenzhen Traffic Police to Explore the Implementation of "Green Wave Belt" Measures. Available online: https://baijiahao.baidu.com/s?id=1696977679298053291&wfr=spider&for=pc (accessed on 12 January 2023).
4. Guo, H.F.; Huang, X.H.; Xu, J.; Qiao, H.S. A coordinated control method for trunk lines based on dynamic adaptive chaotic particle swarm optimization algorithm. *High Technol. Lett.* **2021**, *31*, 1189–1201.
5. Qiang, T.C.; Liu, T.; Pei, Y.L.; Yang, S.J. Optimal control model of green wave for arterial buses considering green light extension. *J. Transp. Inf. Safe* **2021**, *39*, 87–94.
6. Liu, Y.; Chang, G.L. An arterial signal optimization model for intersections experiencing queue spillback and lane blockage. *Transport. Res. C-Emer.* **2010**, *19*, 130–144. [CrossRef]
7. Li, Z.C. Modeling Arterial Signal Optimization with Enhanced Cell Transmission Formulations. *J. Transp. Eng.* **2011**, *137*, 445–454. [CrossRef]
8. Truong, L.T.; Currie, G.; Wallace, M.; De Gruyter, C.; An, K. Coordinated transit signal priority model considering stochastic bus arrival time. *IEEE T. Intel. Transp.* **2019**, *20*, 1269–1277. [CrossRef]
9. Colombaroni, C.; Fusco, G.; Isaenko, N. A simulation—Optimization method for signal synchronization with bus priority and driver speed advisory on connected vehicles. *Transport. Res. Procedia* **2020**, *45*, 890–897. [CrossRef]
10. Zhang, W.H.; Li, J.; Ding, H. Arterial traffic signal coordination model considering buses and social vehicles. *J. Southeast Univ. Engl. Ed.* **2020**, *36*, 206–212.
11. Abdy, Z.R.; Hellinga, B.R. Analytical Method for Estimating the Impact of Transit Signal Priority on Vehicle Delay. *J. Transport. Eng.* **2011**, *137*, 67–73. [CrossRef]
12. Mehdi, B.; Mahmoud, M.; Luis, F. Using Delay Functions to Evaluate Transit Priority of Signals. *J. Public Transport.* **2015**, *7*, 101–105.
13. Tan, B.H.; Zhang, Z.J.; Zhang, Y. A signal control method for bus priority considering the delay of non-priority vehicles in a connected-vehicle environment. *J. Transp. Info. Safe.* **2022**, *40*, 86–95.
14. Caban, J.; Nieoczym, A.; Dudziak, A.; Krajka, T.; Stopková, M. The Planning Process of Transport Tasks for Autonomous Vans—Case Study. *Appl. Sci.* **2022**, *12*, 2993. [CrossRef]
15. Nieoczym, A.; Caban, J.; Stopka, O.; Krajka, T.; Stopková, M. The planning process of transport tasks for autonomous vans. *Open Eng.* **2021**, *11*, 871–879. [CrossRef]
16. Misztal, W. The Impact of Perturbation Mechanisms on the Operation of the Swap Heuristic. *Archi. Auto. Eng.* **2019**, *86*, 27–39. [CrossRef]
17. Stopka, O.; Stopkova, M.; Kampf, R. Application of the Operational Research Method to Determine the Optimum Transport Collection Cycle of Municipal Waste in a Predesignated Urban Area. *Sustainability* **2019**, *11*, 2275. [CrossRef]
18. Lu, K.; Xu, J.M. Coordinated control phase difference model for dry roads and its optimization method. *Chin. J. Highw.* **2008**, *2008*, 83–88.
19. Wang, W.; Guo, X.C. *Transportation Engineering*, 1st ed.; Nanjing Southeast University Press: Nanjing, China, 2000; pp. 81–86.
20. Zhang, Y.L.; Yuan, W.; Fu, R.; Wang, H.X.; Ge, Z.Z. Design and simulation of energy-saving driving strategy for pure electric buses in and out of stations. *Transport. Syst. Eng. Inf.* **2021**, *21*, 106–117.
21. Lu, T.; Liu, Z.; Liu, T.T.; Liu, C.J.; Chai, Y.J.; Fang, H. A virtual simulation method for vehicles based on heel-chase model. *Comput. Eng.* **2016**, *42*, 305–309.
22. Bie, Y.M.; Tang, R.R.; Wang, Y.H.; Wen, B.; Feng, T.J.; Wang, L.H. A method for estimating the saturation flow rate of inlet lanes at signal intersections. *J. Jilin Univ. Eng. Ed.* **2019**, *49*, 1459–1464.
23. *CJJ/T 141-2010*; China Academy of Urban Planning and Design. Technical Standards for Traffic Impact Assessment of Construction Projects. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2010.
24. Xu, J.M.; Yan, X.W.; Ma, Y.Y.; Wang, Y.J. Sensitivity analysis of MFD on model composition and calculation method of vehicle conversion factor. *Chin. J. Highw.* **2018**, *31*, 145–154.

25. Liu, P. A Mesoscopic Traffic Flow Model Based on Wiedemann's Following Behavior. Master's Thesis, Changsha University of Technology, Hunan, China, 14 June 2016.
26. Zhang, K.P.; Liu, D.; Xie, B.L. Research on the calibration of micro traffic simulation model parameters based on VISSIM. *Value Eng.* **2020**, *39*, 189–193.