

Research Article

Analysis of the Low-Carbon, Environmental-Friendly, Energy-Saving, and Emission-Reduction Evaluation Model of Urban Rail Transit Based on the Spatiotemporal Distribution of Passenger Flow

Hong Zhang ^{1,2}

¹*School of Transportation and Logistics, Southwest Jiaotong University, Chengdu 611756, China*

²*The Second Research Institute of Civil Aviation Administration of China, Chengdu 610041, China*

Correspondence should be addressed to Hong Zhang; caaczh@my.swjtu.edu.cn

Received 19 July 2022; Revised 13 August 2022; Accepted 20 August 2022; Published 13 September 2022

Academic Editor: Lianhui Li

Copyright © 2022 Hong Zhang. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The development of the urban economy and the effect of linkage radiation are inseparable from the urban transportation system's efficient operation. In the context of the new era, environmental pollution caused by economic development has gradually become an invisible killer that endangers human health and the atmospheric environment. It is a pillar industry of economic development, a key part of urban infrastructure construction, and a necessary guarantee for urban residents to travel and live, and it is important to develop a low-carbon, environmental-friendly, energy-saving, and emission-reduction potential for urban transportation systems. On the basis of a large number of literature research, this paper attempts to establish the role of an urban rail transit system in energy conservation and emission reduction in three aspects: residents' travel behavior, ground transportation operation, and low carbon, energy conservation, and reduced emission under the influence of the urban rail transit system. Based on the temporal and spatial distribution characteristics of urban rail transit passenger flow, a relatively complete energy-saving and emission-reduction evaluation model is established. Through case analysis, it is verified that the model can effectively evaluate the effect of energy saving and emission reduction under different rail transit settings and its spatial and temporal distribution characteristics, and provides ideas and technical guidance for multidimensional quantitative analysis of urban rail transit carbon environmental protection, energy conservation, and emission reduction.

1. Introduction

The rapid development of urban economy and scale has brought earth-shaking changes to people's lives. However, at the same time, this leap-forward development process that exceeds the speed of perfecting urban supporting facilities also makes people pay a corresponding price. Environmental pollution and energy consumption are increasingly threatening the living environment of human beings and the realization of sustainable urban development goals. "Energy saving and emission reduction" has become a huge challenge faced by all fields worldwide. As the pillar industry of urban economic development, the urban transportation system is a key part of urban infrastructure construction, and a

necessary guarantee for urban residents to travel and live, energy conservation and emission reduction for the urban transportation system is imperative.

As one of the most important public travel tools in the modern urban transportation system, urban rail transit is a breakthrough to achieve energy conservation, reduced emission, and sustainable development. Compared with the traditional ground transportation mode, urban rail transit, as a large-capacity passenger vehicle driven by electric energy, has developed rapidly in major cities around the world in recent years due to its advantages of low pollution and low energy consumption. Considering the problems faced by the sustainable development of the urban transportation system, it is the key to carry out the energy-saving and emission-

reduction strategy of the urban transportation system. Since the passenger flow of urban rail transit is complex and has significant spatial and temporal distribution characteristics, its energy-saving and emission-reduction effects will have corresponding spatial and temporal differences due to the size of the passenger flow. The mechanism of action has not been fully considered and explored, and there are certain limitations in the application of the model.

Therefore, this paper will make up for the insufficiency of the traditional evaluation model in the analysis of the action mechanism, analyze its energy-saving and emission-reduction action mechanism through the multidimensional influence of the urban rail transit system, build a more reasonable quantitative evaluation method for the energy-saving and emission-reduction effect, and provide technical support and theoretical basis for the implementation of emission-reduction strategies.

2. Related Work

With the continuous deterioration of urban rail transit pollution around the world, researchers in the field of environmental engineering aim to establish regional emission inventories, which are represented by MOBILE [1], COPERT [2], and HBEFA [3]. The research shows [4] that this will lead to the emission measurement results being about 30% higher than the actual emission level, but the construction idea of the MOBILE model has reference significance for the development of the emission model. At this stage, similar modeling ideas are adopted in the widely used urban rail transit energy conservation and emission-reduction evaluation models, that is, by establishing urban transit system scenarios with or without rail, comparing rail transit and rail transit alternative modes of transportation and the emission difference between the two, and then drawing the conclusion of rail transit energy saving and emission reduction. Sostenibile et al. [5] believe that the essential reason for urban rail energy saving and emission reduction is to effectively reduce the per capita emission intensity to achieve the purpose of energy saving and emission reduction. Hodges et al. [6] compared the per capita CO₂ emission factors of different transportation vehicles and found that there is a certain multiple relationship between different transportation vehicles and unit emission factors. Obviously, only the per capita emission intensity of different transportation modes cannot reflect the impact of the complexity of transportation on its emission results. Therefore, Wang et al. [7] established a city-level comprehensive transportation emission model, combined with urban rail transit passenger flow data and average haul distance data to compare the differences in emissions of different modes of transport with macro emissions. The problem with the above model is that its focus is on the emission of urban rail transit, and it cannot truly quantitatively evaluate the emission reduction of urban rail transit.

Therefore, analyzing the quantitative substitution relationship between urban rail transit and other modes of transportation is a solution to break through this bottleneck. The model estimation method of the emission impact after

returning the passenger flow to the original travel mode is simple and easy to implement [8, 9], but it is unreasonable to summarize the emission factors under all conditions only with a single comprehensive emission factor value. Based on Chen et al. [10], the above model is optimized, and the model solves the shortcomings of the original model to a certain extent. In recent years, with the increase in the proportion of environmental indicators in urban transportation planning schemes, the research on the evaluation model of urban rail transit energy conservation and emission reduction has also introduced a traffic demand forecast model, which provides a basis for the construction of urban rail transit energy conservation and emission-reduction models and new ideas [11, 12].

The study found that most scholars have discussed and analyzed the evaluation model of urban rail transit energy conservation and emission reduction, and established effective research models from different perspectives; however, there is a lack of full consideration and exploration of the mechanism of urban rail transit energy conservation and emission reduction; there are certain limitations in considering the model application scenarios. The passenger flow of urban rail transit is complex and has significant spatial and temporal distribution characteristics. Therefore, it should be noted that there are corresponding spatial and temporal differences in its energy-saving and emission-reduction effects. Regarding this point, no scholars have yet found a multidimensional analysis of the energy-saving and emission-reduction mechanism of urban rail transit systems to form a more comprehensive and reasonable quantitative evaluation method for energy-saving and emission-reduction effects.

3. Related Theories

3.1. Multidimensional Influence Relationship between Urban Rail Transit and Urban Transportation System. The research goal of this paper was to quantitatively evaluate and explore the energy-saving and emission-reduction effects of urban rail transit on the urban transportation system to which it belongs. Therefore, the impact of the construction and operation of urban rail transit on the urban transportation system is the entry point for the analysis of its energy-saving and emission-reduction mechanism. Based on the research of the previous part, the urban transportation system is a complex system composed of people, vehicles, and roads, and the impact of urban rail transit on the system is shown in Figure 1, including the travel behavior of travelers, the transfer of transportation modes, and ground transportation running changes.

3.2. Characteristics of Urban Rail Transit Passenger Flow Transfer. In the process of the subway network gradually, the attraction degree of urban rail transit to passenger flow is mainly related to the nature of land use along the line and the service level of replacing buses. With the increase in development intensity, residential area density, and population density along the line, the passenger flow will increase, which

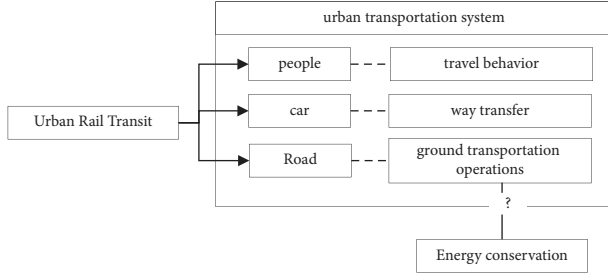


FIGURE 1: Multidimensional influence of urban rail transit on the urban transportation system.

will also promote the growth of the passenger flow in the original section.

The passenger flow of urban rail transit generally includes three parts: trend passenger flow, transfer passenger flow, and induced passenger flow [13].

3.2.1. Trend Passenger Flow. Trend passenger flow refers to the normal growth of the passenger flow at rail stations and along the line.

3.2.2. Transfer Passenger Flow. Diverted passenger flow refers to the passenger flow that is attracted and transferred to urban rail transit by other modes of transportation, and this part of the passenger flow is usually caused by competition between modes of transportation. A small part of the diverted passenger flow comes from private cars and taxis, while most of them come from regular bus and bicycle trips.

3.2.3. Induced Passenger Flow. Induced passenger flow means that with the rapid construction and operation of urban rail transit lines, land development and population agglomeration along the lines are promoted, the accessibility between different areas of the city is improved, the city's subway service level is improved, and residents' travel intensity is increased, thereby increasing traffic.

3.3. Influencing Factors of Emission Measurement in the Urban Rail Transit Emission Model. This paper will refer to Xie et al. [14] to establish the link between ground transportation operation data and emission measurement results to analyze the mechanism of energy conservation and emission reduction. The established urban road traffic emission model shows that the calculation of ground traffic emissions is shown in formulas (1) and (2):

$$E_{\text{mission}_{i,j}} = EF_{i,v} \times VKT_{i,j}, \quad (1)$$

$$E_{\text{mission}_{\text{net}}} = \sum_i \sum_j E_{\text{mission}_{i,j}}, \quad (2)$$

$E_{\text{mission}_{i,j}}$ represents emissions of vehicle i on road segment j (g); $E_{\text{mission}_{\text{net}}}$ represents total emissions from the road network (g); $EF_{i,v}$ represents the emission factor for model i

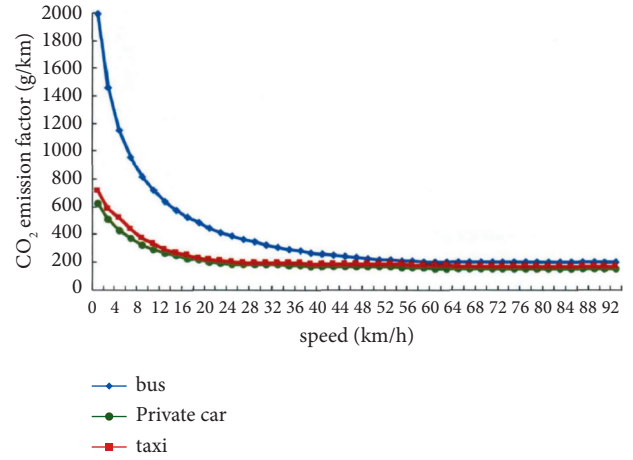


FIGURE 2: CO₂ emission factor variation curve of different vehicle models with speed.

at speed v (g/km); $VKT_{i,j}$ represents the vehicle mileage of vehicle type i on road j (pcu-km); i, j, v represent the model, road segment, and speed, respectively.

According to the calculation formula of the transportation emission model shown above, it can be found that the emission factor and VKT are two important components of the road network emission measurement, and they are also the factors that directly affect the emission measurement results.

3.3.1. Relationship between Emission Factor and Speed Change. The emission factor is defined as the amount of emissions produced by a motor vehicle per unit mileage, which is composed of the distribution of vehicle driving conditions and the emission rate as shown in the following formula:

$$EF_{i,v} = \frac{\sum VSP \text{Distribution} \times ER_i}{\bar{v}}, \quad (3)$$

where $VSP \text{Distribution}$ represents the vehicle driving condition distribution based on VSP characterization; ER_i represents the emission rate of model i (g/s); \bar{v} is the average speed (km/m).

From the calculation formula of the emission factor, it can be found that different vehicle types have different emission factor values at different average driving speeds. Therefore, the emission factor is characterized by a distribution curve that changes with speed as shown in Figure 2. The emission factor gradually decreases with the increase in speed, and the emission factor value in the low-speed range is much larger than that in the high-speed range; from the perspective of the relationship between the emission factor and the vehicle model, the emission factor curves of different models have obvious differences with the speed. The low-speed interval is more significant. At the same speed, the emission factor of buses is the largest, followed by social vehicles, and the emission factor of taxis is the smallest.

3.3.2. The Relationship between VKT and Road Flow Calculation. VKT (vehicle kilometer traveled) is the number of kilometers traveled by motor vehicles, which reflects the

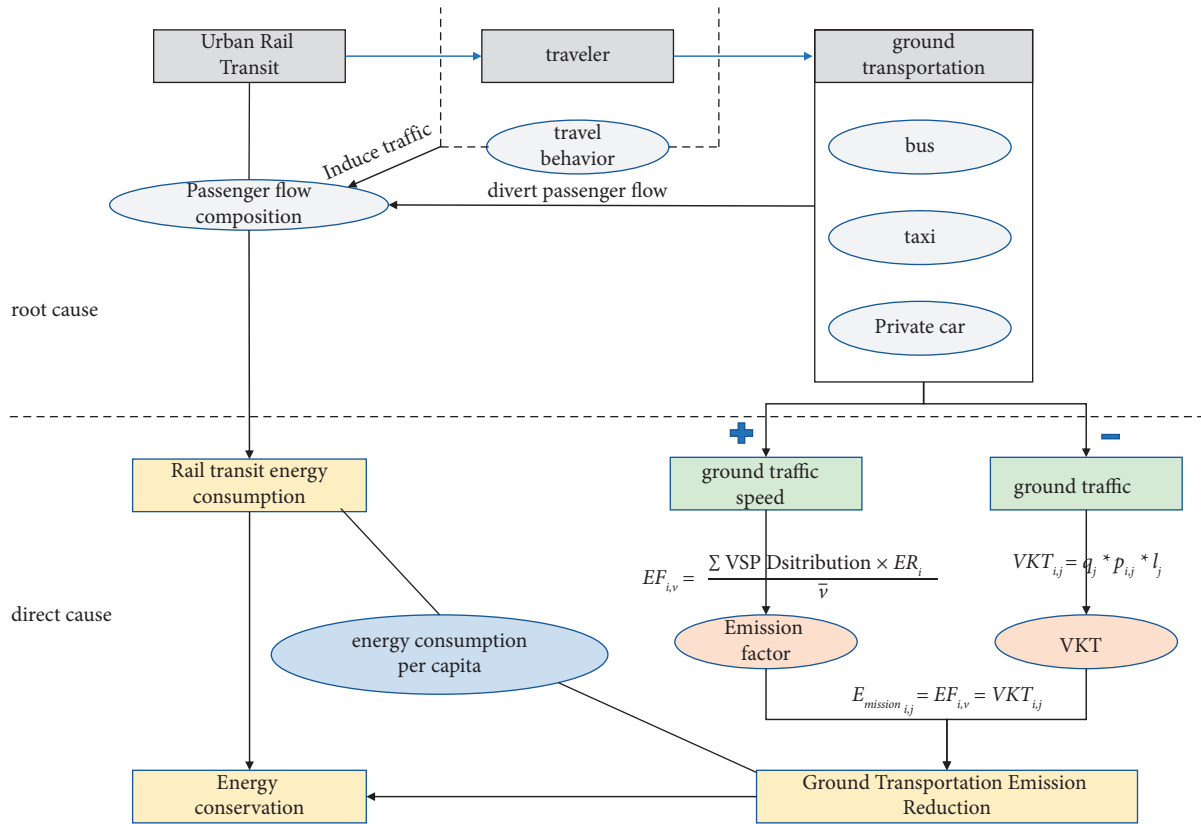


FIGURE 3: Analysis of the mechanism of low-carbon, environmental-friendly, energy-saving, and emission-reduction action of urban rail transit.

traffic activity level of motor vehicles. It is multiplied by the emission factor to obtain the total emission and emission inventory. It is a key parameter for the coupling of the traffic model and the emission model. The calculation method is shown in the following formula:

$$VKT_{i,j} = q_j * p_{i,j} * l_j, \quad (4)$$

where $VKT_{i,j}$ represents the vehicle mileage of vehicle type i on road j (pcu-km) q_j represents the traffic flow on road segment j (pcu); $p_{i,j}$ represents the proportion of traffic of vehicle i on road j to the total traffic; l_j is the length of road segment j (km).

It can be found that VKT is composed of three parts: road traffic volume, road length, and vehicle model ratio. Therefore, there is a linear positive correlation calculation relationship between VKT and road flow; that is, when the ratio of road and vehicle models is determined, the greater the flow of the road is, the greater the calculation result of VKT is, and the greater the final discharge result of the road is.

3.4. Mechanism and Distribution Characteristics of Low Carbon, Environmental Protection, Energy Saving, and Emission Reduction in Urban Rail Transit

3.4.1. Mechanism of Action. This study summarizes the mechanism of energy saving and emission reduction of urban rail transit based on the corresponding literature

[14–22], as shown in Figure 3. It can be found that the mechanism of energy saving and emission reduction of urban rail transit is relatively complex, which is the result of comprehensively considering the multidimensional impact of urban rail transit on the urban transportation system.

The direct reason for energy saving and emission reduction of urban rail transit lies in its impact on the “road” dimension of the urban transportation system. The opening and operation of urban rail transit lines share the traffic pressure in the area where the line radiates, and part of the ground transportation travel demand is transferred to urban rail transit. The traffic flow on the ground is reduced, and the traffic operation in the surrounding area of the line is improved.

The fundamental reason for urban rail transit energy conservation and emission reduction lies in its impact on the two dimensions of “people” and “vehicles” in the urban transportation system. Urban rail transit lines affect the travel behavior of travelers on the line, and on the one hand, some people originally travel on different grounds. Passengers who have completed their trips by means of transportation are transferred to the subway, and on the other hand, it has induced some travelers to generate new travel needs. It can be found that the impact of urban rail transit on the two dimensions of “people” and “vehicles” is also the reason for the formation of urban rail transit passenger flow.

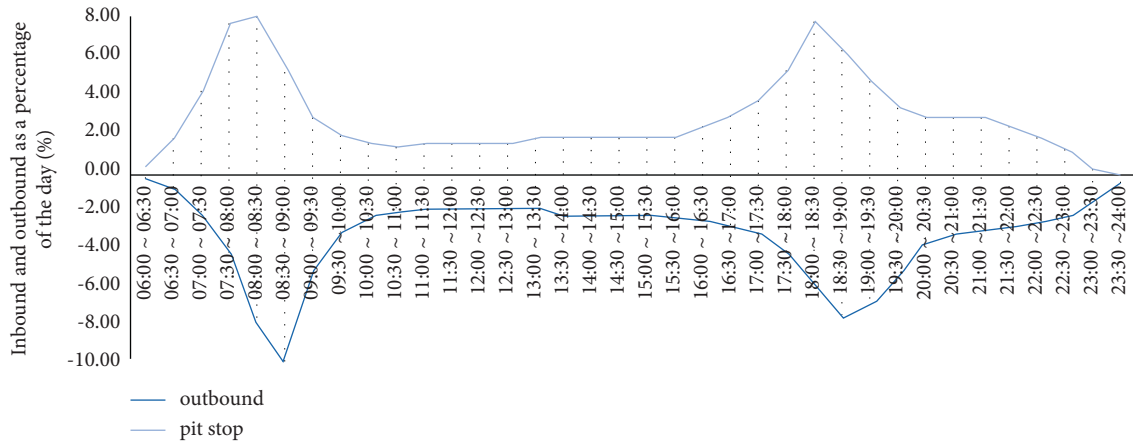


FIGURE 4: Time distribution of passenger flow in and out of rail transit stations.

3.4.2. *Spatial and Temporal Distribution Characteristics of Passenger Flow.* Using the urban rail transit AFC (automatic fare collection system), that is, the automatic fare collection system swiping data to analyze the spatiotemporal distribution characteristics of urban rail transit passenger flow, it has the following characteristics.

(1) *Imbalance.* In the lines or stations of the urban rail transit system, there is a specific phenomenon of the mismatch between the supply of transport capacity and the demand for passenger flow in time, space, and direction. With the formation of the rail transit network, the share of rail transit in urban public transport has gradually increased. The main purpose of travel for passengers is commuting. People who work and go to school take the subway at a fixed time every day. Therefore, in terms of the rail transit network, within one day, the fluctuating state of the passenger flow of the railway shows the unbalanced characteristics of two peaks in the morning and evening, and the time distribution of rail transit passenger flow in and out of the station is shown in Figure 4.

(2) *Travel periodicity.* In the urban rail transit system, the passenger flow presents a periodic change in a fixed period of time. Since the commuter passenger flow accounts for a large proportion of the daily passenger flow, and its work cycle is carried out in a weekly cycle, the rail transit passenger flow generally presents a cyclical change in the weekly time unit throughout the year. The daily passenger flow curve of rail transit is shown in Figure 5.

(3) *Travel tidal nature.* In the lines or stations of the urban rail transit system, there are a large passenger flow in one direction and a less passenger flow in the opposite direction at a certain period of time, but the phenomenon of the opposite passenger flow characteristics occurs in another period of time. With the continuous expansion of the city scale, the rail transit system has become an important mode of transportation connecting the central city and surrounding suburbs. Passengers will have different travel modes due to different travel purposes such as work, school,

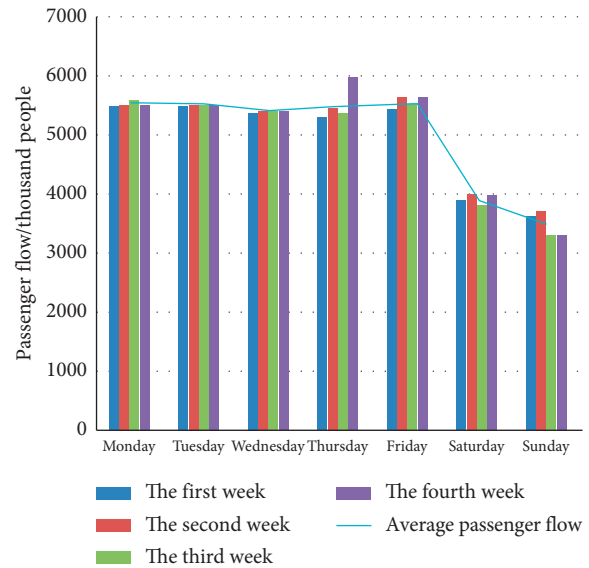


FIGURE 5: Curve of daily passenger flow of rail transit.

shopping, and business, and rail transit travel presents significant tidal characteristics. During the morning peak period on weekdays, the passenger flow is reflected in the commuting passenger flow generated by passengers going to work and school, and passengers flow from the place of residence to the place of work. In the evening rush hour on weekdays, the passenger flow is reflected in the commuter passenger flow generated by the passengers getting off work and school. The basic flow direction of the passenger flow is opposite to that of the morning rush hour. Passengers flow from the office to the residence. During weekends, there is no obvious morning and evening peak period, and a large number of passengers travel between residential areas, shopping areas, and tourist areas due to travel purposes such as shopping and tourism. In lines with obvious tidal phenomena, the passenger flow of rail transit is unevenly distributed in time and space, which is very likely to cause tension in the capacity of some lines.

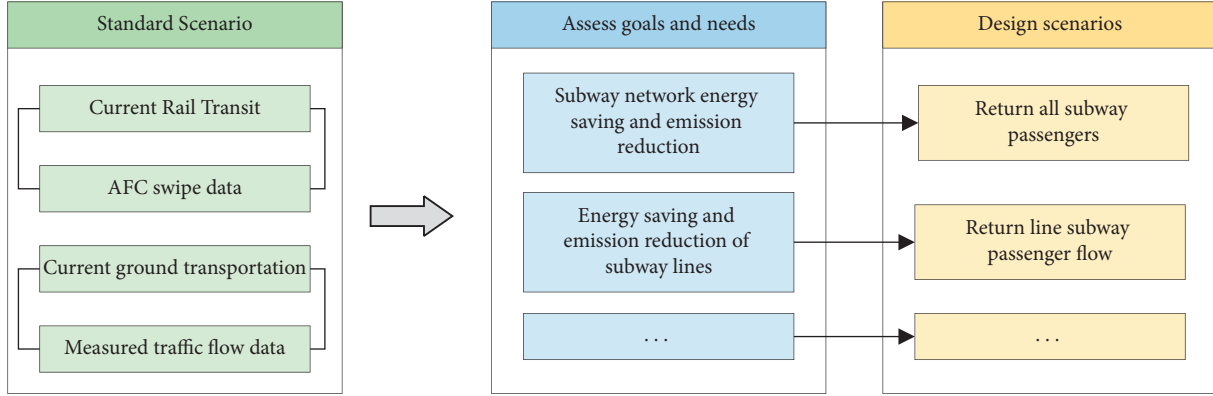


FIGURE 6: Scenario design flow idea based on low-carbon, environmental protection, energy conservation, and emission-reduction assessment targets.

4. Construction of the Low-Carbon, Environmental-Friendly, Energy-Saving, and Emission-Reduction Evaluation Model for Urban Rail Transit

4.1. Model Building Ideas

4.1.1. Model Assumptions and Scenario Design. From the previous research and analysis, it can be seen that the direct reason for energy conservation and emission reduction of urban rail transit is that the construction and operation of the urban rail transit network shares the passenger flow of ground transportation, improves the operation of ground transportation, and then achieves the effect of energy conservation and emission reduction of urban transportation system. Based on this, this paper makes a reasonable inversion and assumes that when there is no rail transit in the urban transportation system, passengers who originally traveled by subway will return to ground transportation to complete their travel needs. At the same time, considering the complexity and diversity of urban rail energy conservation and emission-reduction assessment targets and needs, this paper takes the current urban rail transit setup as the standard scenario, and forms corresponding design scenarios according to different assessment targets and needs, as shown in Figure 6. Then, this paper analyzes the ground transportation operation under the influence of the standard scenario and the design scenario, respectively, and measures the ground transportation emission difference under the different scenarios, that is, the ground transportation emission reduction under the design scenario and the urban rail transit energy saving and emission reduction of the design scenario. The evaluation of the scenario design helps in comparative analysis and improves the applicability of the model.

Figure 6 shows the scenario design idea of urban rail transit. It can be found that the energy-saving and emission-reduction evaluation model constructed in this paper is suitable for various evaluation objectives, including the evaluation of the energy-saving and emission-reduction effect of the existing subway operation network in the city and energy conservation and emission-reduction assessment. It should be noted that in order to ensure the use of the traffic

demand forecast model to analyze the ground traffic operation under its influence in the design scenario, the current urban traffic situation is considered, so the standard scenario in this paper is based on the current urban rail transit and ground traffic as a reference. Therefore, the ground traffic operation situation under the standard scenario is calculated through the measured traffic flow data, and only the design scenario is predicted using the traffic demand forecasting model established in the literature [23] that considers the impact of urban rail transit.

4.1.2. Low-Carbon, Environmental-Friendly, Energy-Saving, and Emission-Reduction Model Framework for Urban Rail Transit. As shown in Figure 7, the urban rail transit energy conservation and emission-reduction evaluation model consists of two parts, namely, ground transportation emission reduction and urban rail transit operation energy consumption. The calculation method is shown in the following formula:

$$E_{\text{save}} = \Delta E_{\text{road}} - \Delta E_{\text{rail}} = (E_{B,\text{road}} - E_{A,\text{road}}) - (E_{A,\text{rail}} - E_{B,\text{rail}}), \quad (5)$$

where E_{save} represents the energy saving and emission reduction of urban rail transit in urban transportation system (g); ΔE_{road} represents the urban rail transit affecting the energy saving and emission reduction of the ground transportation system (g); ΔE_{rail} represents the emission reductions added by urban rail transit to urban transportation systems (g); $E_{A,\text{road}}$ and $E_{B,\text{road}}$ represent surface transportation emissions for standard and design scenarios (g), respectively; $E_{A,\text{rail}}$ and $E_{B,\text{rail}}$ represent rail transit emissions for standard and design scenarios (g), respectively.

Since the emissions generated by the operation of urban rail transit are mainly due to the carbon emissions generated by the consumption of electric energy, the existing research on energy conservation and emission reduction of urban rail transit often only uses carbon emission reduction as the only energy conservation and emission-reduction evaluation index. However, this study believes that the traffic pollution situation including NO_x, PM, and other pollutants has become more and more serious in recent years [24]. Based on this, the pollutants and emission indicators evaluated in

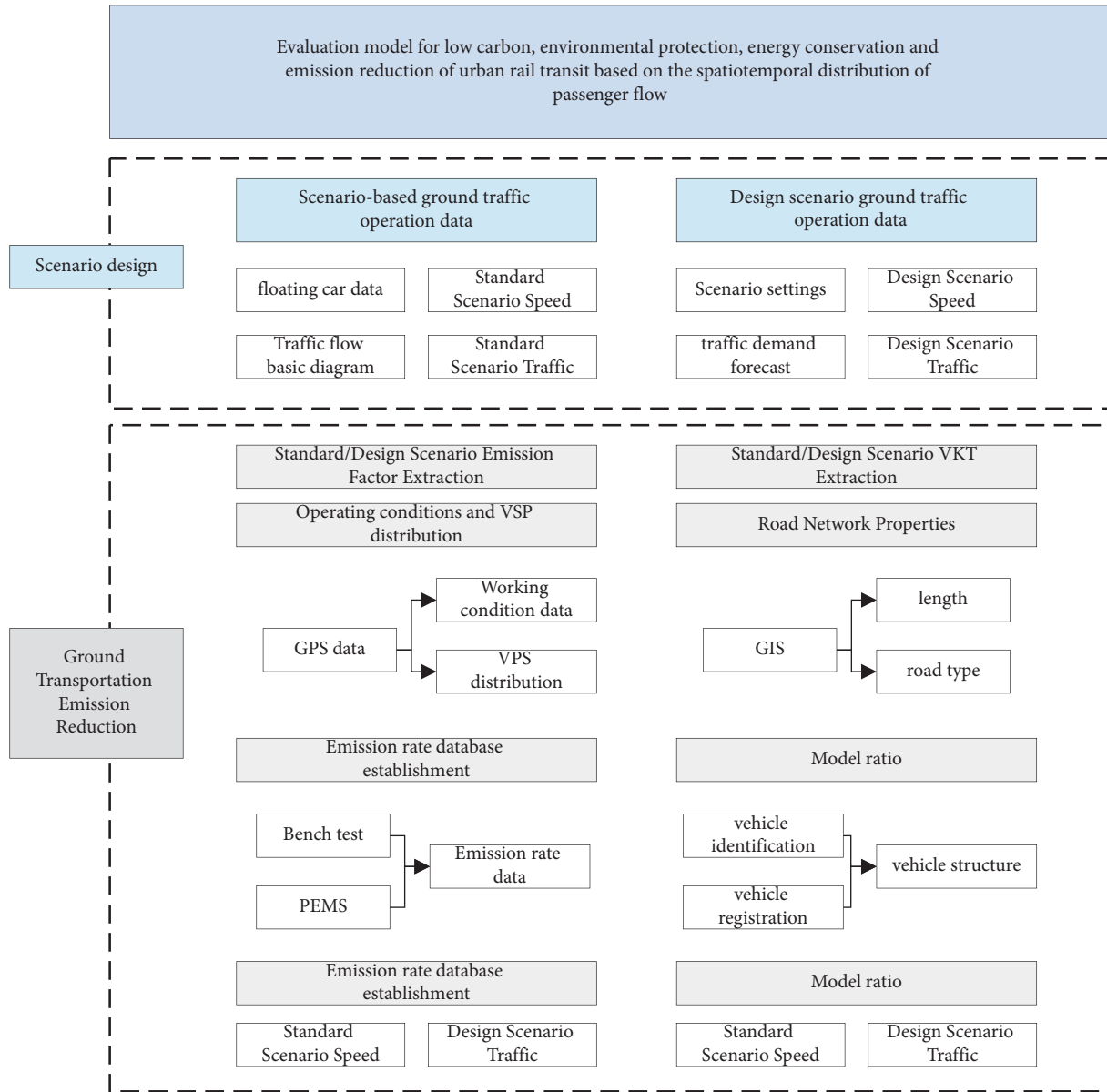


FIGURE 7: Architecture of the low-carbon, environmental-friendly, energy-saving, and emission-reduction model of urban rail transit.

TABLE 1: Evaluation indicators for energy conservation and emission reduction.

	Transportation	Emissions	Energy-saving emission indicators
Urban transport system	Rail	CO ₂	Indicator 1
		CO ₂	Indicator 2
		NOx	Indicator 3
	The traffic	CO	Indicator 4
		HC	Indicator 5
		PM	

this paper for energy conservation and emission reduction are shown in Table 1.

4.2. Calculation of Ground Transportation Emission Reduction under the Influence of Urban Rail Transit. The measurement of ground transportation emission reduction under the

influence of urban rail transit is one of the important components of the urban rail transit energy conservation and emission-reduction evaluation model constructed in this paper, and it is also an indicator that reflects the mechanism of urban rail transit energy conservation and emission reduction. Combining the model technical route in Subsection 4.1 and the calculation formula of the

transportation emission model in 3.3, the calculation method of ground transportation emission reduction is shown in formulas (6) and (7):

$$\Delta E_{road} = \sum_{i,v}^j EF_{i,v} * VKT_{i,j} = \sum_{i,v}^j EF_{i,v} * (l_j * q_j * p_{i,j}), \quad (6)$$

$$\Delta E_{road} = \sum_{i,v}^j EF_{i,v^A} * (l_j * q_j^A * p_{i,j}^A) = \sum_{i,v}^j EF_{i,v^B} * (l_j * q_j^B * p_{i,j}^B), \quad (7)$$

where $EF_{i,v}$ represents the emission factor for model i at speed v (g/km); $VKT_{i,j}$ is the number of kilometers traveled by vehicle i on road j (km); v^A and v^B represent the ground traffic operating speeds for standard and design scenarios, respectively (km/h); q_j^A and q_j^B are the traffic routes of section j in the standard scenario and the design scenario, respectively (pcu); $p_{i,j}^A$ and $p_{i,j}^B$ —are the proportion of vehicle i on road j in the standard scenario and the design scenario, respectively.

According to the above formula, it can be found that the measurement of ground transportation emission reduction under the influence of urban rail transit is mainly composed of emission factor and VKT. The emission factor is mainly affected by the change in ground transportation operating speed under different scenarios, while VKT is mainly affected by the impact of changes in ground traffic flow and vehicle model proportions under different scenarios.

4.2.1. Calculation of Emission Factors under Different Scenarios. According to the introduction of the establishment process of emission factor database and the acquisition method of ground transportation speed data under different scenarios, establishing the relationship between emission factors and speed requires the coupling of traffic operation data and traffic emission data. Therefore, the emission factor database established in this paper is composed of vehicle driving condition distribution data based on specific power and measured vehicle emission rate data.

This section uses the MOVES model developed by the US Environmental Protection Agency (EPA) to establish the vehicle specific power (VSP) parameter to describe and analyze the distribution of vehicle driving conditions. VSP is defined as the output power per ton of mass (including self-weight) moved by the motor vehicle engine [25], and the calculation method is shown in the following formula:

$$VSP = \frac{Av + Bv^2 + Cv^3 + mva}{f}, \quad (8)$$

where v and a are the instantaneous speed and instantaneous acceleration of the motor vehicle, respectively, in m/s and m/s^2 ; M is the vehicle quality (t); A , B , C , and f are model constant coefficients, only relevant to the vehicle type.

The emission rate is the amount of vehicle emissions per unit time, in g/s. The collection of emission rate data is completed by the bench test based on NEDC (New European

Driving Cycle), and the test data cover CO_2 , CO , HC , NO_x , and PM of various models. Through VSP clustering and interval division, the average emission rate (g/s) of each pollutant and pollutant in each VSP interval can be obtained, that is, the mass of pollutants emitted by the motor vehicle per unit time of driving under specific operating conditions, as shown in Figure 8.

The actual driving speed on the road is an important factor affecting the emission of motor vehicles, which is often ignored in traditional emission models. Therefore, in order to accurately quantify the impact of speed on the emission factor, it is necessary to calculate the emission factor of motor vehicles based on the average speed and to establish speed correction models for emission factors of different vehicle types and fuel types. The calculation method of the emission factor in the usual emission model is shown in the following formula:

$$EF_V = \frac{3600 * \sum VSPDistribution_i * ER_i}{v}, \quad (9)$$

where EF_V represents the emission factor at average velocity v (g/km); ER_i represents the average emission rate for VSP interval i (g/s); $VSPDistribution_i$ represents the distribution ratio of VSP interval i .

To sum up, this paper established an emission factor database covering 36 vehicle types and 3 road classes, including CO , CO_2 , HC , and NO_x emissions. Emission factors for some speed ranges are shown as examples in Table 2.

4.2.2. VKT Calculation in Different Scenarios. The ground traffic flow under the influence of different scenarios is a key step to measure the emission reduction of ground transportation, and it is also the main factor affecting VKT. The ground traffic operation under the influence of the design scenario is based on the analysis of the traffic demand forecasting model established by the literature considering the impact of urban rail transit after the inversion of the subway passenger flow, while the standard scenario is based on the analysis of the current ground traffic operation. In this paper, with the help of the existing research results of the basic traffic flow diagram [26], the relationship between the three elements of the traffic flow of the road segment can be established based on the Van Aerde model, as shown in equations (10)–(12).

$$v = v_f e^{-\rho/\rho_m}, \quad (10)$$

$$q = \rho v_f e^{-\rho/\rho_m}, \quad (11)$$

$$q = -\rho_m v \ln \frac{v}{v_f}, \quad (12)$$

where q represents the hourly traffic on a single lane (veh/h); v is the average speed of the road (km/h); ρ is the average density of road sections (veh/km); v_f is the free-flow velocity of the road type to which the segment belongs (km/h); ρ_m is the road segment critical density (veh/km).

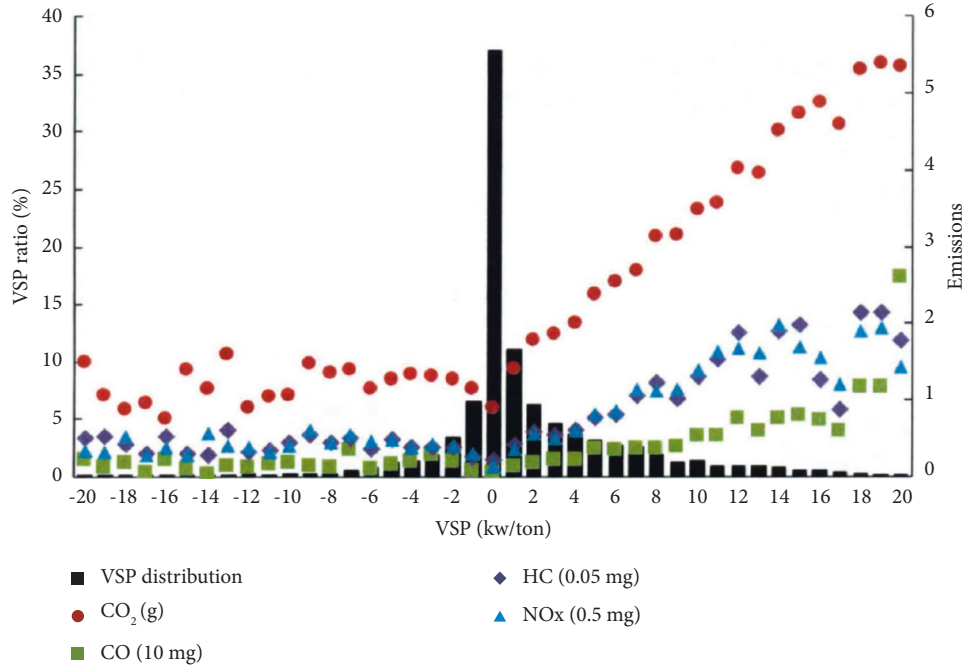


FIGURE 8: Distribution of emission rates in different VSP intervals.

TABLE 2: Sample of emission factor database.

Road type	Speed range	CO	CO ₂	THC	NO _x
11	0	42.39	5631.03	9.86	46.98
11	1	24.37	3399.37	5.53	26.83
11	2	17.59	2526.35	3.94	19.39
11	3	13.61	1966.97	3.03	14.95
11	4	11.53	1698.62	2.55	12.66
11	5	9.87	1459.58	2.17	10.81
11	6	8.8	1324.12	1.93	9.67
11	7	7.87	1188.26	1.72	8.63
11	8	7.16	1089.2	1.56	7.86
11	9	6.49	992.84	1.41	7.13
11	10	6.01	930.91	1.3	6.64

Note. Road type 11 represents the roads on the left and right sides for vehicles, with six roads on each side including motor vehicle lanes and nonmotor vehicle lanes.

According to the relationship between flow and speed established by the traffic flow basic map, this paper combines the measured floating car data in City A with the traffic flow basic map formula to carry out data regression analysis, and at the same time can calculate the speed-flow inversion method that conforms to City A, as shown in the following formula:

$$q = -\frac{v}{\delta_i} \ln \frac{v}{v_{f_i}}, i = 1, 2, 3, \quad (13)$$

where δ_i and v_{f_i} are model constant parameters; $i = 1, 2, 3$ represent expressway, main road, and sub-branch, respectively.

Due to the large differences in the emissions of the same model, after obtaining the traffic volume and length of a road section, it is necessary to analyze the model structure of the traffic volume of the road section, and then combine it with

the corresponding emission factor to calculate the emission. In the actual operation process of road traffic, the proportion of models changes in real time, but it is difficult to obtain the proportion of dynamic models. In this paper, the proportion of models in the standard scenario of fixed model ratio is used for calibration, and the proportion of models in the standard scenario is corrected to obtain the models in the design scenario.

Proportion. The proportion of vehicle models in the standard scenario in this paper is obtained by combining the video recognition data of the license plate and the vehicle management registration data. When a motor vehicle passes through a road section with a camera installed, the license plate number will be recorded. At the same time, by querying the vehicle management registration information, the vehicle model corresponding to the license plate number can be determined to obtain the model proportion data. The proportion data of some models is shown in Table 3.

5. Evaluation and Analysis of Low Carbon, Environmental Protection, Energy Saving, and Emission Reduction in Rail Transit

5.1. Rail Transit Carbon Emission Calculation. The urban rail transit energy conservation and emission-reduction evaluation model constructed in this study considers the energy consumed by rail transit in the operation process. This section takes the track lines covered by City A as the research scope. As shown in Figure 9, based on the AFC credit card data, the average transportation distance and passenger flow of different track lines are counted, and the carbon emission coefficient per person-kilometer of different track lines is combined to calculate the area of rail transit carbon

TABLE 3: Sample table of model proportion data.

Expressway, main road, and sub-branch		Highway (%)	Main road (%)	Secondary branch (%)
Bus	Class A	2.0	2.0	2.0
	Class B	1.0	1.0	1.0
	Class C	0.0	0.0	0.0
Social vehicle	Class A	0.3	0.3	0.4
	Class B	1.8	1.7	1.9
	Class C	7.5	7.4	8.3
	Class D	10.0	9.8	10.9
	Class E	41.2	40.6	45.1
	Class F	3.3	3.3	3.7

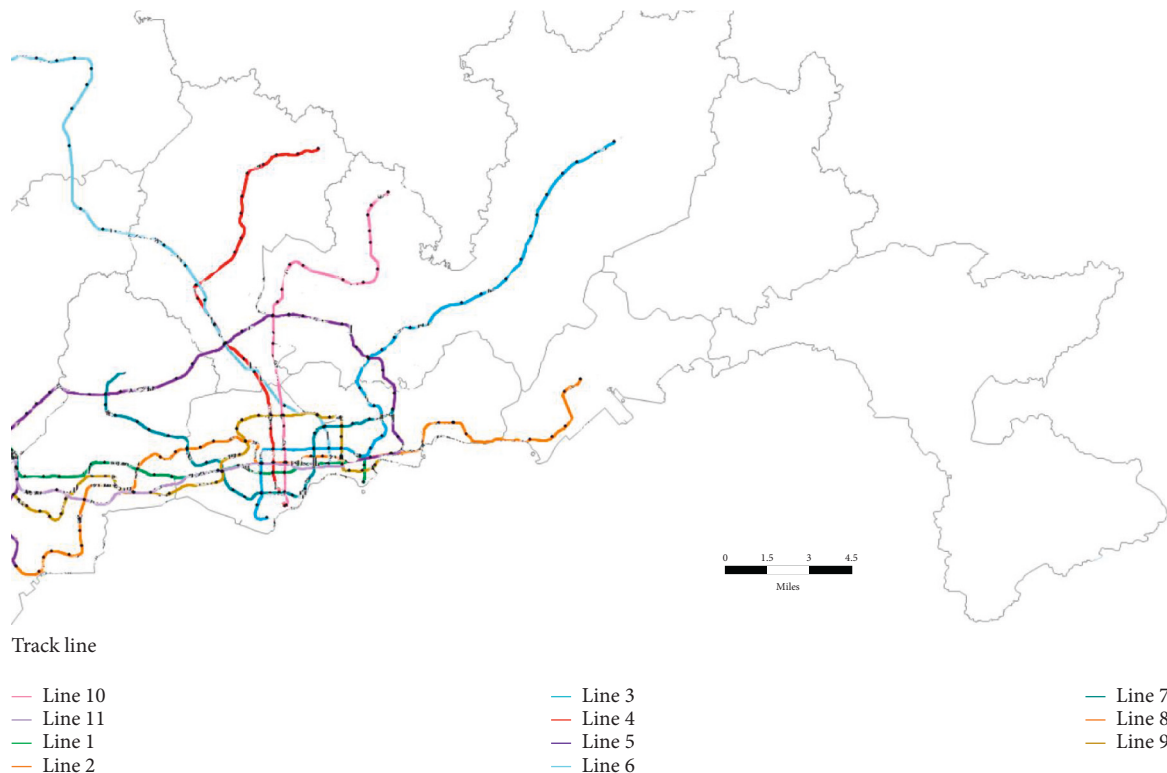


FIGURE 9: City-covered track route map.

emissions. Figure 10 shows the average transportation distance (km/person) and line occupancy ratio (ratio of average transportation distance to line length) of 11 subway lines within City A. It can be found that the average transportation distance of different lines is quite different. The average haulage occupancy ratio shows that the track occupancy ratio in the surrounding areas of City A is large, while the urban occupancy ratio is small, which is closely related to the spatial separation of passengers' work and residence, which is in line with the characteristics of passenger travel.

In this study, the energy consumption of rail transit is calculated based on the carbon emission coefficient of person-kilometers of different rail transit lines. Therefore, in addition to the average transportation distance of different lines, it is also necessary to calculate the passenger volume of each line. Generally speaking, with the change in subway

passenger flow, the subway operating company will adjust the departure interval and station service equipment, so there is a linear correlation between passenger volume and rail transit energy consumption, and considering the urban rail transit constructed in this study. The low-carbon, environmental protection, energy-saving, and emission-reduction evaluation model is based on the temporal and spatial distribution of rail transit passenger flow. Therefore, based on the AFC credit card data, I calculate the morning peak (7:00–9:00) and evening peak (17:00–19:00), respectively. The passenger flow of the line in the three periods of Pingfeng (12:00–14:00) is shown in Figures 11–13. It can be found that the passenger flow of different lines is the largest during the morning peak, the evening peak is slightly lower than the morning peak, and the passenger flow during the flat peak period drops significantly, accounting for only about 20% of the morning peak passenger flow. At

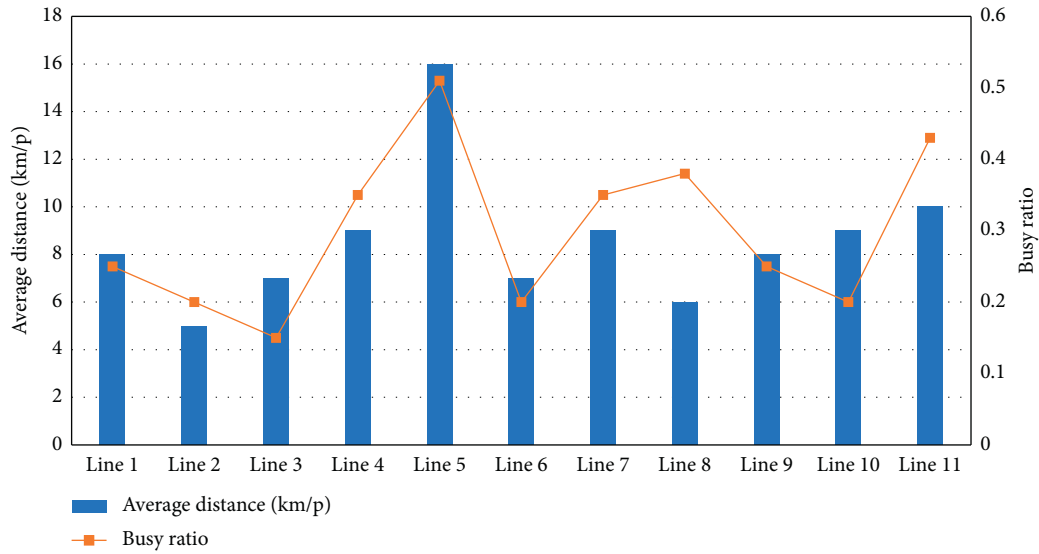


FIGURE 10: Average distance of rail transit lines in City A.

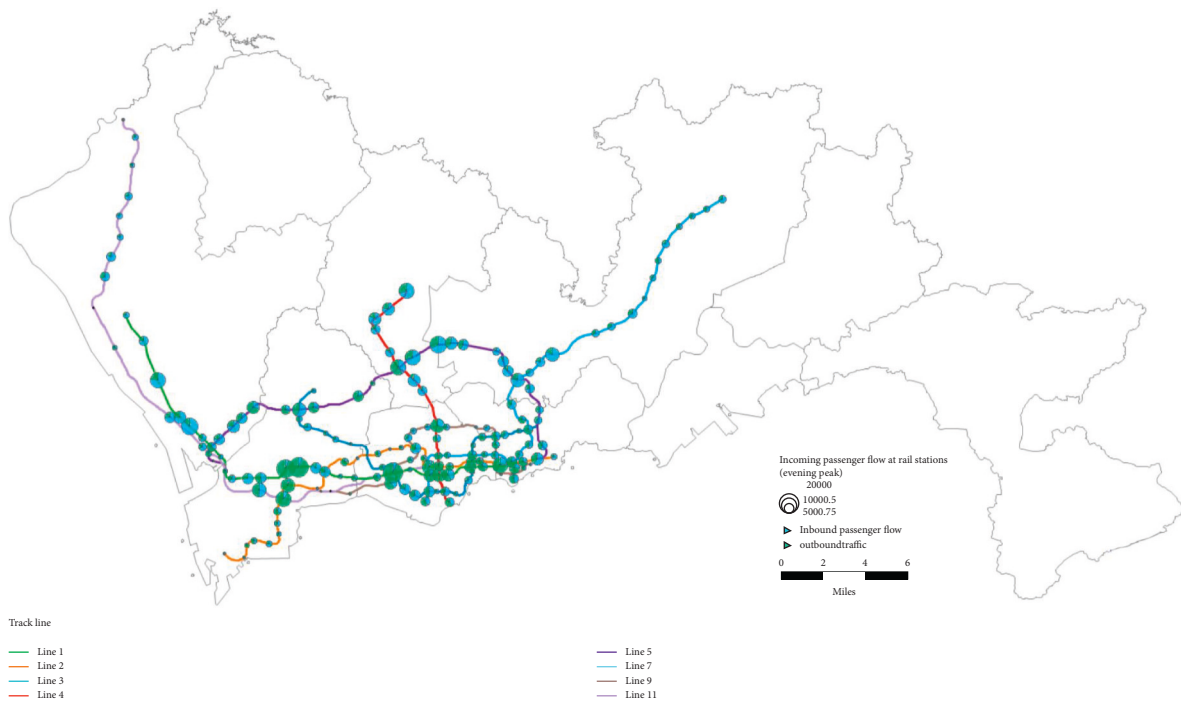


FIGURE 11: Passenger flow diagram of the rail transit lines in City A in the morning rush hour.

the same time, the difference in passenger flow between lines is also more obvious. The passenger flow of Metro Line 1 and Line 5 is the highest, the passenger flow of Line 2, Line 3, and Line 11 is relatively close, while the passenger flow of Line 4 and Line 9 is the lowest.

To sum up, this study obtained the carbon emission coefficients of 7 subway lines in City A, calculated the average transportation distance of the lines, and counted the passenger volume of each subway line in different periods according to formulas (5)–(14). The carbon emission

measurement of rail transit lines can be carried out, and the calculation results are shown in Table 4.

5.2. Energy Conservation and Emission-Reduction Assessment Results. The evaluation indicators of energy conservation and emission reduction in this study include five pollutants and emissions, including CO₂, NO_x, CO, HC, and PM. Among them, only CO₂ emissions are generated during the operation of urban rail transit itself. Therefore, the ground

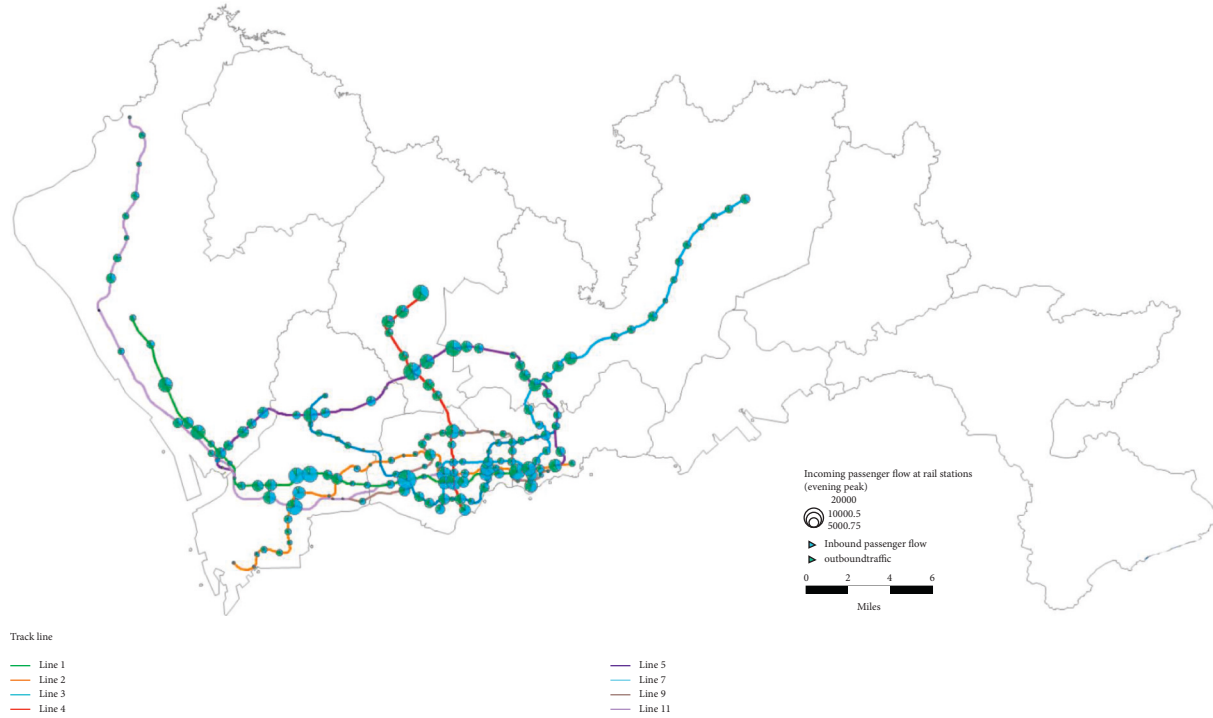


FIGURE 12: Passenger flow in and out of stations in the evening peak of the rail transit lines in City A.

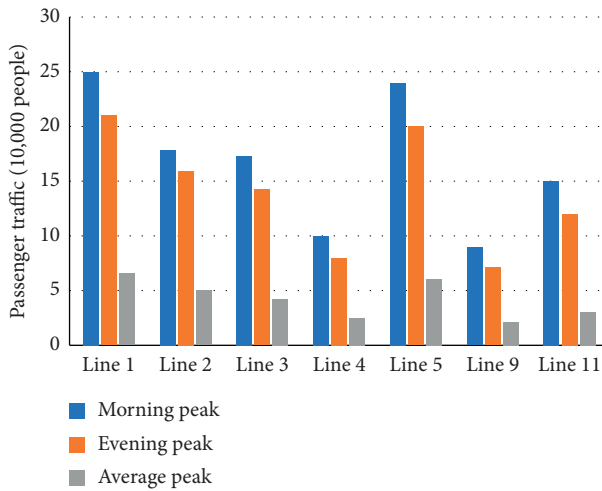


FIGURE 13: Passenger flow in different periods of rail transit lines in City A.

transportation under the influence of urban rail transit and the CO₂ emission reduction of urban rail transit to the urban transportation system need to be calculated separately, while the ground transportation emission reduction of the remaining four pollutants is the evaluation result of urban rail transit emission reduction, and the calculation methods are shown in the following formula:

$$\begin{aligned}
 E_{CO_2-save} &= (E_{B,CO_2-road} - E_{A,CO_2-road}) - (E_{A,CO_2-rail} - E_{B,CO_2-rail}), \\
 E_{Other-save} &= E_{B,Other-road} - E_{A,Other-road}
 \end{aligned}
 \tag{14}$$

TABLE 4: CO₂ emissions of rail transit lines in City A during each period.

Line	Morning peak (t)	Evening peak (t)	Average peak (t)
Line 1	59.8	50.7	15.1
Line 2	25.1	21.4	6.5
Line 3	58.2	47.2	13.8
Line 4	37.2	31.3	8.8
Line 5	62.4	52.0	3.9
Line 9	12.9	10.0	2.8
Line 10	149.7	126.1	34.2
Total	405.3	286.7	85.1

where E_{CO_2-save} represents the CO₂ emission reduction (t); $E_{Other-save}$ represent emissions of pollutants other than CO₂(t); E_A represents standard scenario emissions (t); E_B represents design scenario emissions (t).

It should be noted that the result calculated according to the above formula is the emission increase in the design scenario compared with the standard scenario, and it can be considered as the emission reduction of the standard scenario compared with the design scenario, that is, the emission reduction of urban rail transit on the urban transportation system quantity.

5.2.1. CO₂ Emission Reduction. According to formula (14), it can be found that the evaluation of energy conservation and emission reduction based on the CO₂ indicator is more complicated than that based on other emission indicators. Table 5 summarizes the CO₂ emission values and emission reductions of ground transportation in the standard and design scenarios at different time periods. It can be found

TABLE 5: CO₂ emission reduction of ground transportation under the influence of urban rail transit.

Period	Standard-ground (t)	Design-ground (t)	Ground emission reduction (t)	Ground emission-reduction ratio (%)
Morning peak	3297	4451	1154	35.0
Evening peak	3782	4778	996	26.3
Average peak	2876	3207	331	11.5

TABLE 6: CO energy saving and emission reduction under the influence of urban rail transit.

Period	Ground transportation emission reduction (t)	Rail transit emissions (t)	Rail transit emissions (t)	Total emission-reduction ratio (%)
Morning peak	1154	646	508	12.9
Evening peak	996	542	354	8.2
Average peak	331	152	179	6.1

TABLE 7: Emission reduction of other indicators under the influence of urban rail transit.

Index	Period	Standard scenario (t)	Design scenario (t)	Emission reduction (t)	Emission-reduction ratio (%)
CO	Morning peak	15.3	21.9	6.6	43
	Evening peak	18.2	24.1	5.9	32
	Average peak	10.7	12.9	2.2	21
NO _x	Morning peak	2.6	3.6	1.3	38
	Evening peak	3.1	3.9	0.8	26
	Average peak	1.7	0.3	18%	18
HC	Morning peak	1.7	2.5	0.8	47
	Evening peak	2.1	2.7	0.6	29
	Average peak	1.2	1.4	0.2	17
PM	Morning peak	0.077	0.104	0.027	35
	Evening peak	0.089	0.112	0.023	26
	Average peak	0.046	0.054	0.008	17

that in the standard scenario, the ground transportation emissions in the evening peak are 3782 t, slightly higher than the 3297 t in the morning peak. After calculating the emission reduction of ground transportation emissions in the design scenario, the emission reduction of ground transportation CO₂ reached 1154 t in the morning peak period, and the emission-reduction ratio was as high as 35%, followed by about 23% in the evening peak period. Therefore, the CO₂ emission reduction is relatively low, and the emission-reduction ratio is less than 15%. To sum up, it can be considered that urban rail transit effectively reduces the CO₂ emissions of ground transportation. This is consistent with the passenger flow distribution law of urban rail transit and the spatiotemporal distribution law of ground traffic operation under the influence of urban rail transit.

The CO₂ emission reduction of ground transportation is only a part of evaluating the effect of urban rail transit on energy conservation and emission reduction of the urban transportation system. Combined with the measurement results of rail transit carbon emissions in different time periods in Subsection 5.1, the calculation and statistics of the CO₂ emission-reduction results of urban rail transit within City A are shown in Table 6. It can be found that although rail transit generates CO₂ emissions through energy consumption, in the case of this study, urban rail transit still plays a role in reducing CO₂ emissions in the entire urban transportation system, and the emission-reduction effect in

the morning peak is still due to the other two. During this period, the total emission-reduction ratio was 12.9%, and the evening peak period was 8.2%. During the off-peak period, due to the less CO₂ emissions generated by rail transit, the total emission-reduction ratio for this period also reached 6.1%.

5.2.2. Reduction of Other Indicators. In addition to CO₂, the energy-saving and emission-reduction evaluation indicators include NO_x, CO, HC, and PM.

The emission of the above four pollutants will not be generated during the transportation operation, so the emission reduction of pollutants in the standard scenario compared with the design scenario is the emission-reduction effect of urban rail transit on the urban transportation system. Therefore, the emission-reduction effects of the above four indicators in different time periods are calculated as shown in Table 7. It can be found that in the evaluation results of the four evaluation indicators, the emissions under the urban rail transit scenario are lower than those under the no rail transit scenario. The emission-reduction effect of the four pollutants is the most obvious during the morning peak. The emission reduction of HC in the morning peak is as high as 47%, followed by the emission-reduction effect of CO, which also exceeds 40%. The emission-reduction effect of the two pollutants of PM is slightly lower, but the emission-

reduction ratio during the morning peak still reaches 38% and 35%, respectively. During the evening peak period, the emission-reduction effect of the four pollutants decreased compared with that during the early peak period, and the emission-reduction ratios of the four pollutants were all within the range of 26%–32%. Compared with the morning and evening peaks, the emission-reduction effect during the flat peak period is significantly lower, and the emission-reduction ratio is about 20% or less. From the comparison results of the emission-reduction effects of the four pollutants in different time periods, it can be found that the emission-reduction effects of different pollutants maintain a good time consistency, and this consistency is directly related to the passenger flow distribution of rail transit.

Through the above analysis of the energy-saving and emission-reduction effects of the urban rail transit network on the urban transportation system during the morning peak hours, evening peak hours, and flat peak hours, it can be found that for the ground traffic speed and flow data in the urban rail transit scenario, it is found that the urban area of City A in the rail transit network within the area effectively relieves the operating pressure of ground traffic in the area, and improves the operating conditions of ground traffic, and the improvement effect has a time-space variation law consistent with the distribution of rail transit passenger flow. For the CO₂ emissions generated by different rail transit lines in different periods of operation, it is found that the CO₂ emissions of rail transit have obvious line differences and time differences. By calculating the emissions of CO₂, NO_x, CO, HC, and PM in the presence or absence of urban rail transit, it is found that the construction and operation of urban rail transit reduces the emissions of different emissions, achieving the effect of energy saving and emission reduction. And there are temporal and spatial variation laws consistent with the distribution of rail transit passenger flow.

6. Conclusion

With the rapid development of the economy, the systematic construction and operation of urban rail transit plays a vital role in further improving business efficiency. However, with the intensification of environmental pollution and energy consumption problems, it continues to threaten the living environment of human beings and the sustainability of cities. To achieve the development goals, the research on the emission of urban rail transit has certain practical significance. This paper attempts to take the urban rail transit route as the entry point, deeply and multidimensionally analyzes many factors affecting carbon emissions, and does the following research:

- (1) Comprehensively considering the multidimensional impact of urban rail transit on the urban transportation system, a set of relatively complete mechanisms of urban rail transit energy conservation and emission reduction is established, which is the basis for the quantitative evaluation model analysis of urban rail transit low carbon, environmental protection, energy conservation, and emission reduction.

- (2) Considering the ground traffic operating speed data in different scenarios, the establishment of the relationship between the emission factor and the speed requires the coupling of the traffic operating data and the traffic emission data, getting rid of the rate for a single emission factor, the establishment of emission factor database, getting rid of the limitations of model scene application, and the improvement of the applicability of model evaluation.
- (3) The characteristics of the temporal and spatial distribution of passenger flow were analyzed, and the carbon emissions in different scenarios of morning and evening peaks were quantitatively analyzed. The temporal and spatial variation law of rail transit passenger flow distribution is consistent.

Since this paper uses a certain proportion of vehicles in the calculation of emissions, and the proportion of vehicles changes in real time during road driving, in future research, a dynamic vehicle proportion database can be established to make the calculation of emissions closer to reality.

Data Availability

The dataset can be obtained from the author upon request.

Conflicts of Interest

The author declares no conflicts of interest.

References

- [1] US Environmental Protection Agency, *User's Guide to MOBILE6.1 and MOBILE6.2*, U.S. Environmental Protection Agency, Washington, DC, USA, 2003.
- [2] L. Ntziachristos and Z. Samaras, *COPERT 4 Computer Programme to Calculate Emissions from Road Transport*, Methodology and Emission Factors, New York, NY, USA, 2007.
- [3] M. Keller and P. Wuthrich, *Handbook Emission Factors for Road Transport 3.1/3.2*, Quick Reference, Bern, Germany, 2014.
- [4] S. H. Ho, Y. D. Wong, and V. W. C. Chang, "Developing Singapore Driving Cycle for Passenger Cars to Estimate Fuel Consumption and Vehicular Emissions," *Atmospheric Environment*, vol. 97, 2014.
- [5] Sosentibile, *CO₂ Emission Reduction from Modal Shift to Railways Pre-study*, University of Bologna-Department of Transport engineering research, 2010.
- [6] T. Hodges, *Public Transportation's Role in Responding to Climate Change*, U.S. Department of Transportation Federal Transit Administration, Pennsylvania, PA, USA, 2010.
- [7] "Carbon emission from urban passenger transportation in Beijing," *Transportation Research Part D: Transport and Environment*, vol. 41, pp. 217–227, 2015.
- [8] L. Li, J. Hu, and D. Shao, "Carbon emission reduction benefit of rapid development of shanghai expo rail transit," *China Environmental Science*, vol. 32, no. 6, pp. 1141–1147, 2012.
- [9] H. Jiang and B. Fan, "Research on low carbon economy evaluation of urban rail transit," *Railway Transportation and Economy*, vol. 32, no. 9, pp. 11–15, 2010.

- [10] F. Chen, X. Shen, Z. Wang, and Y. Yang, "An evaluation of the low-carbon effects of urban rail based on mode shifts," *Sustainability*, vol. 9, no. 3, pp. 401–412, 2017.
- [11] L. Hidenori, F. Atsushi, and L. Paramet, "Measuring Emission Reduction Impacts of Mass Rapid Transit in Bangkok: The Effect of a Full Network," *13th WCTR*, vol. 11, no. 4, pp. 40–42, 2013.
- [12] Z. Wang, Y. Huo, and Z. Liu, "Prediction model on energy consumption of highway transportation in inner Mongolia based on ARMA green intelligent transportation system," in *Proceedings of the 7th International Conference on Green Intelligent Transportation System and Safety*, pp. 105–114, Springer, New York, NY, USA, June 2018.
- [13] G. Song and L. Yu, "Characteristics of low-speed vehicle-specific power distributions on urban restricted-access roadways in Beijing," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2233, no. 1, pp. 90–98, 2011.
- [14] D. Xie, G. Song, Ji. Guo, J. Sun, and L. Yu, *Development and Application of an Online Dynamic Emission Model for Traffic Networks-A Case Study of Beijing*, Present at 98th Annual Meeting of the Transportation Research Board, Washington, DC, USA, 2018.
- [15] M. F. Dziauddin, "Estimating land value uplift around light rail transit stations in Greater Kuala Lumpur: an empirical study based on geographically weighted regression (GWR)," *Research in Transportation Economics*, vol. 74, no. 5, pp. 10–20, 2019.
- [16] G. Song, F. Zhang, J. Liu, L. Yu, Y. Gao, and L. Yu, "Floating car data based method for detecting flooding incident under grade separation bridges in Beijing," *IET Intelligent Transport Systems*, vol. 9, no. 8, pp. 817–823, 2015.
- [17] S. K. Chaturvedi, P. K. Srivastava, and U. Guven, "A brief review on tsunami early warning detection using BPR approach and post analysis by SAR satellite dataset," *Journal of Ocean Engineering and Science*, vol. 2, no. 2, pp. 83–89, 2017.
- [18] T. H. DeFries, M. Sabisch, S. Kishan, F. Posada, J. German, and A. Bandivadekar, "In-use fuel economy and CO₂ emissions measurement using OBD data on US light-duty vehicles," *SAE International Journal of Engines*, vol. 7, no. 3, pp. 1382–1396, 2014.
- [19] H. C. Frey, K. Zhang, and N. M. Roupail, "Fuel use and emissions comparisons for alternative routes, time of day, road grade, and vehicles based on in-use measurements," *Environmental Science & Technology*, no. 7, pp. 2483–2489, 2008.
- [20] L. Zhang, Y. Yin, and S. Chen, "Robust signal timing optimization with environmental concerns," *Transportation Research Part C: Emerging Technologies*, vol. 29, no. 1, pp. 55–71, 2013.
- [21] C. Roncoli, N. Bekiarisliberis, and R. C. Carlson, "Special Issue on "Management of Future Motorway and Urban Traffic Systems"," *Transportation Research Part C-emerging Technologies*, vol. 96, pp. 1-2, 2018.
- [22] J. Lederer, C. Ott, P. H. Brunner, and M. Ossberger, "The life cycle energy demand and greenhouse gas emissions of high-capacity urban transport systems: a case study from Vienna's subway line U2," *International Journal of Sustainable Transportation*, vol. 10, no. 2, pp. 120–130, 2016.
- [23] Z. Yangyang, Z. Ma, Yi Yang, J. Wenhua, and J. Xinguo, "Short-Term Passenger Flow Prediction with Decomposition in Urban Railway Systems," *IEEE Access*, vol. 8, 2020.
- [24] H. Wang, X. Yang, and X. Ou, "A study on future energy consumption and carbon emissions of China's transportation sector," *Low Carbon Economy*, vol. 05, no. 04, pp. 133–138, 2014.
- [25] Z. Zhai, G. Song, H. Lu, W. He, and L. Yu, *A validation of temporal and spatial consistency of facility- and speed-specific VSP distribution for emissions estimation: a case study in Beijing*, Present at 95th Annual Meeting of the Transportation Research Board, Washington, DC, USA, 2016.
- [26] Y. Yue, *Research on the Basic Map of Multi-Level Traffic Flow in Beijing Based on Multi-Source Data*, Beijing Jiaotong University, Beijing, China, 2015.