Original Research Article

Carbon emission of urban transport with different data sources

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Abstract: The identification of critical sectors at the provincial level is important for achieving China' s CO_2 mitigation target. To scientifically subdivide the target of emission peak and carbon neutrality in public transport, this article employs a decision tree, taking into a combination of "top-down" and "bottom-up" approaches, to determine selection rules for carbon emission calculation under different data sources. The stepwise regression analysis determines length of vehicle is the key factor affecting bus 100 km energy consumption. The results reveal that, with 383.0 million tons of carbon dioxide being emit, the highest carbon emission from Inner Mongolia ground buses system happened in 2013. The results show that measures including replacing conventional vehicles with electric vehicles could effectively facilitate the road transport sector to gradually approach zero carbon emissions.

Keywords: urban traffic; carbon emissions; decision model; electric vehicles; stepwise regression

1. Introduction

With the increase of global greenhouse gases emission, the environment and human life is influenced, such as long droughts, global warming, devastating floods, and so on[1]. Climate change has become an important issue affecting human development, and reducing greenhouse gas emissions has become a global consensus. Transport energy consumption is about one-fifth of the final energy consumption of the world, with over 70% of these emissions from on-road vehicles[2,3]. China's total carbon emissions are about 10 billion tons/year accounting for 1/3 of the global carbon dioxide emissions[4]. The transportation sector is the third largest source of carbon dioxide emissions after industry and construction in China, of which road transport carbon emissions account for more than 50%. China has promised the international community to achieve a carbon peak by 2030 and carbon neutrality by 2060[5,6]. The report of the 20th National Congress of the Communist Party of China (NCCPC) clearly proposed to build "a country with strong transportation network" and focused on "green traffic" in China[7]. It is imperative to use renewable energy to replace gasoline and diesel and prioritize the development of public transportation systems[8].

The Communist Party of China Central Committee and the State Council on Sunday jointly unveiled a guiding document on the country's work to achieve carbon peaking by 2030 and carbon neutrality by 2060, laying out key targets and measures for the coming decades. The achievement possibility of carbon peak goals and the specific effectiveness of measures are lacking, especially when the transport field of considered[9]. Currently, the energy consumption statistic of railway, civil aviation, and waterway transportation in China is relatively sound. However, there is still a lack of reliable primary data and a unified and standardized statistical accounting system in road transportation and urban passenger transport.

As for the carbon measurement methods of the urban public transport industry, previous studies[10–12] mostly adopted two methods in IPCC 2019 National Greenhouse Gas Inventory Guidelines[13] according to available data sources. Up-bottom method: using energy consumption data multiplied by fuel carbon emission coefficient to calculate. Bottom-up method: using activity level data and unit carbon emission factor to

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calculate carbon emissions is the most commonly used method to calculate carbon emissions of public transportation at home and abroad. Due to the imperfection of the statistical system, as well as researchers' greater autonomy in the selection of emission factors and activity level data, the accuracy and comparability of results will be affected to a certain extent.

Whats more, the calculation of previous studies is mainly aimed at national level, large and medium-sized cities or urban public transportation enterprises, under the background that carbon emissions are included in the quantitative assessment of provincial governments as binding indicators, there are few studies on measuring regional carbon emissions. It is an effective way for China to reach the peak before 2030 to promote the developed regions to advance the peak from the provincial level. Thus, it is necessary to identify critical sectors at the provincial level rather than the national level to enhance carbon emission mitigation policies[14]. Therefore, this paper will conduct empirical research at the regional level, analyze the development laws and characteristics, and judge the peak year and value.

In 2022, the total energy consumption in Inner Mongolia was 250 million tons of standard coal, and the total economic output of the whole region only accounted for 1.7% of the entire country, consuming 5.2% of the whole country's energy. Due to the significant differences in the development of public transportation in different regions of Inner Mongolia, there is not only Hohhot city, a national transit metropolis, but also cities with substandard bus sharing rates, which are represented in terms of economic development level, spatial structure, and passenger transportation system. Taking Inner Mongolia as an example, the research on carbon emission measurement method and the carbon peak of urban public transportation based on different development levels has essential reference significance for analyzing the characteristics of various places, especially at the provincial level, and proposing carbon reduction paths.

Focusing on the achievement of carbon peak goals, this study aims at address the following questions:

(i) How to calculate carbon emission of urban transport with different data sources at the provincial level?

(ii) When and what is the peak of Inner Mongolia's CO_2 emission?

(iii) Does the current policy effectively facilitate road transport sector to gradually approach zero carbon emissions?

2. Materials and methods

This analysis combines: (i) a decision model of carbon emission measurement method of urban public transport base on different data sources; (ii) the fitting relationship between the vehicle length and fuel consumption per 100 km.

2.1. Research boundary

Before the calculation, it was necessary to clarify the boundary of the urban transport system. Firstly, greenhouse gas emissions from urban public transportation are divided into direct and indirect emissions. Direct emissions refer to carbon dioxide emissions generated by the complete combustion of fossil fuels such as gasoline, diesel oil, and natural gas with oxygen in various mobile source equipment. Indirect emissions refer to indirect emissions of greenhouse gases caused by the purchased electricity consumed by vehicles (such as the electricity consumed by charging pure electric and plug-in hybrid vehicles). Because indirect emissions are included in the calculation of power systems in the local greenhouse gas emission inventory, this paper only considers direct emissions, and for electric vehicles, their carbon emissions are not calculated. For plug-in hybrid buses, only the carbon emissions generated by consuming fossil energy are calculated.

2.2. The structure and scope of the model

A schematic overview of the method selected for the study is provided in **Figure 1**.

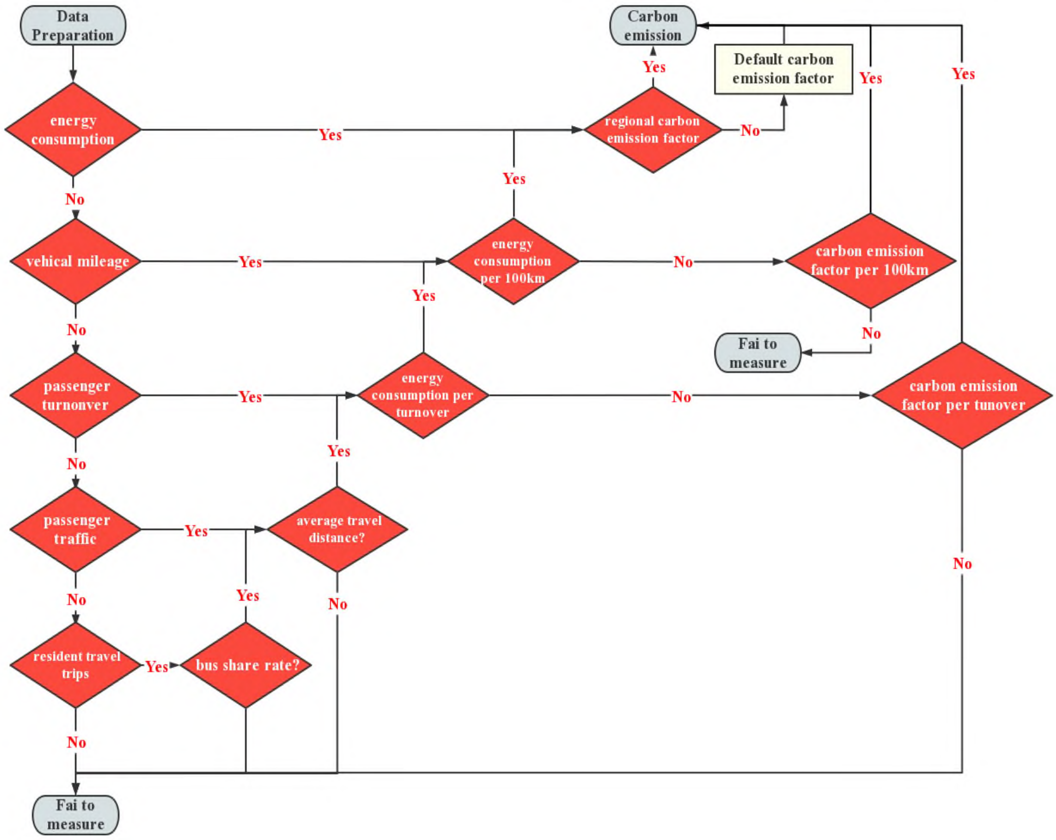

Figure 1. Decision model of carbon emission measurement method of urban public transport.

As shown in **Figure 1**, the decision-making model of urban public transport carbon emission measurement method can be divided into five types according to the operational indicators. **Table 1** shows the summary of previous studies related to carbon emission of urban transport. Researchers can choose the calculation method according to the available data and structure in urban public transportation. The more decision nodes, the more indicators obtained by calculation and estimation, and the higher the possibility of data errors. In this paper, urban public transport industry indicators are divided into operation indicators and efficiency indicators. Operation indicators include passenger volume, turnover, vehicle mileage, fuel consumption, etc. Efficiency indicators include fuel consumption per 100 km, fuel consumption per unit turnover, average travel distance of passengers, etc.

Table 1. Summary of previous studies related to carbon emission of urban transport.

Strategy	Reference	Year	Result
1	[10]	2022	The results reveal that carbon emission from Qingdao's passenger transport in 2020 was 8.15 million tons.
2	[11]	2023	Using Ruicheng County, Shanxi, China as an example, county-level planning of the road transport sector is conducted in terms of quantifying energy consumption and CO_2 emissions.
3	[12]	2023	Transport Sector Energy Model based on Türkiye Energy Model is designed, the transport sector is analyzed.
4	[15]	2019	The urban transport CO_2 emissions between 1960 and 2001 from 46 global cities are calculated.
5	[16]	2014	Carbon emission intensity of Shanghais urban transport declined steadily from 1.66 kg/trip to 1.55 kg/trip.

As indicated in **Table 2**, the influencing factors of carbon emission are identified.

Table 2. Nomenclature.

C	Carbon emission	f	Energy consumption per turnover
i	Energy types	V_{bus}	Bus volume
Q	Energy consumption	$V_{society}$	Resident travel volume
EF	Carbon emission factor	d	Average travel distance
m	Mileage	p	Bus share rate
t	Passenger turnover	-	-

$$C = \sum Q_i EF_i \tag{1}$$

where (i) C represents the total carbon emission from the bus system; (ii) Q_i represents the amount of energy consumed by vehicle for public transport passengers; (iii) i denotes for fuel types, including gasoline, diesel oil, natural gas; (iv) EF_i is carbon emission factor.

The default values provided in the IPCC 2019 Guidelines for National Greenhouse Gas Inventories and the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories are shown in Equation (2):

$$EF_i = a_i b_i c_i \theta \tag{2}$$

where (i) EF_i represents carbon emission factor; (ii) a_i is the average low calorific value of the first energy source; (iii) b_i is the carbon content per unit heat of the first energy source, TJ = 10^3 GJ = 10^9 KJ; (iv) c_i is the oxidation rate when the first energy is burned; (v) θ is the molecular weight ratio of carbon dioxide to carbon, which is equal to 44 g CO_2/12gce, which is about 3.6667.

The calculation results are shown in **Table 3**.

Table 3. Carbon emissions coefficient of different energy sources.

Type of fuel	a_i **kJ/kg**	b_i **t-ce/TJ**	c_i **%**	θ	**kg-CO_2/kg**
Gasoline	43,070	18.9	98	3.6667	2.9251
Diesel fuel	42,652	20.2	98	3.6667	3.0959
Natural gas	38,931	15.3	99	3.6667	2.1623

Strategy 1: For fuel consumption data, the most direct and accurate way is to obtain it by inquiring about vehicle refueling records. In recent years, with the rapid popularization information systems, entrepreneur enterprise-level data are becoming more and more perfect, which improves the accuracy and verifiability of inventory compilation.

Strategy 2: Vehicle mileage data can be obtained. The decision node of fuel consumption per 100 km in strategy 2 is the critical node to distinguish the two methods of top-down and bottom-up in the Guide.

If 100 km fuel consumption can be obtained, Equation (1) Q_i is calculated using the product of vehicle mileage and 100 km fuel consumption, as shown in Equation (3).

$$Q_i = \sum m_i y_i \tag{3}$$

where (i) Q_i represents the consumption of the first fuel; (ii) i represents the fuel type, gasoline, diesel oil, natural gas, hybrid power, etc.; (iii) m_i represents the mileage of vehicles with the fuel type i; (iv) y_i is the 100 km consumption of vehicles with fuel type i.

If 100 km fuel consumption is unavailable, the carbon emission is calculated by multiplying the vehicle mileage and the 100 km fuel carbon emission factor, as shown in Equation (4).

$$C = \sum m_i EF_{mile,i} \tag{4}$$

where (i) C represents the total carbon emission from bus system; (ii) i is the fuel type, gasoline, diesel oil, natural gas, hybrid power; (iii) m_i is the mileage of vehicles with fuel type i; (iv) $EF_{mile,i}$ is the unit turnover emission factor of fuel i.

Strategy 3: Passenger turnover data can be obtained. In strategy 3, fuel consumption per unit turnover becomes the critical decision node.

If the fuel consumption per unit turnover is available, Equation (1) Q_i is calculated using the product of passenger turnover and fuel consumption per unit of turnover, as shown in Equation (5).

$$Q_i = \sum t_i f_i \tag{5}$$

where (i) Q_i represents the consumption of the i fuel; (ii) i is the fuel type, gasoline, diesel oil, natural gas, hybrid power; (iii) t_i is the passenger turnover of *i* fuel vehicle; (iv) f_i is the fuel consumption per turnover for *i* fuel vehicle.

If fuel consumption per unit turnover is not available, the product of passenger turnover and the emission factor per unit turnover is used to calculate carbon emissions, as shown in Equation (6).

$$C_{bus} = \sum m_i EF_{turnover,i} \tag{6}$$

where (i) C represents the total carbon emissions from bus system; (ii) i is the fuel type, gasoline, diesel oil, natural gas, hybrid power; (iii) m_i is the mileage of the *i* fuel vehicles; (iv) $EF_{turnover}$ is the emission factor per unit turnover of the i fuel.

Strategy 4: Use the product of passenger volume and per capital km to replace the passenger turnover, as shown in Equation (7), and then implement strategy 3.

$$t = v_{bus} \times d \tag{7}$$

where (i) *t* is the passenger turnover of urban public transport; (ii) v_{bus} is the amount of urban public transport passenger volume; (iii) d is the average travel distance of passengers.

Strategy 5: Use the product of the total amount of social trips and the proportion of public transportation to replace the passenger volume of public transit, as shown in Equation (8), and then implement strategy 4 and strategy 3.

$$v_{bus} = v_{society} \times p \tag{8}$$

where (i) v_{bus} is the amount of urban public transport passenger traffic; (ii) $v_{society}$ is the amount of city passenger traffic; (iii) p is the share rate of bus.

2.3. Data analysis

2.3.1. Strategy 1 (2011–2014, 2020–2022)

According to the investigation, in 2009, the state set up a special fund for bus, requiring enterprises to establish files, record the basic information such as vehicles, mileage, and oil consumption entirely and accurately, and declare the application funds through the system, and the accuracy of data has increased year by year. Since 2015, the state has determined the promotion and application targets and operating subsidy standards of electric vehicles, revised the subsidy for fuel buses, and declared the basic situation and operating mileage of vehicles utilizing fixed subsidies for vehicles instead of fuel consumption. Therefore public transport fuel consumption for 2011–2014 can be extracted through the transportation management department of Inner Mongolia, details on these data is tabulated in **Table 4**.

The Statistical Report of urban Passenger Transport is approved by the Ministry of Transport and National Bureau of Statistics, which has robust data caliber and index stability. As shown in **Table 4** since 2020, indicators have been changed in terms of new statistical system. Therefore public transport fuel consumption for 2020–2022 can be extracted from annual statistical report of urban passenger transport.

2.3.2. Strategy 2 (2015–2019)

Because the terminal fuel consumption from 2015 to 2019 (**Table 4**) cannot be obtained, according to the carbon emission calculation model of urban public transportation (**Figure 1**), the second strategy is selected for calculation (Equation (2)).

m_i can be inquired in the Passenger Transport Statistics Report;

Among the cities, the vehicle emission factors were remarkably different (the highest is 50%–90% higher than the lowest) owing to their distinct local features and vehicle technology levels, and the major contributors to total vehicle emissions were also different[17]. Lü et al.[18] calculated the carbon dioxide emission factors of 31 provinces in China, but only calculated the unit passenger turnover emission factors of diesel buses in the field of public transport. Hence, this paper regarded the regional carbon emission factors as unavailable. Therefore, EF_i sets the default value (**Table 3**).

This paper explores the method of determining y_i.

1) Stepwise regression analysis of crucial influencing factors

In this section, five quantifiable attributes, namely, approved passenger capacity, vehicle length, power, displacement, and vehicle age, in the fuel subsidy declaration system are taken as the research objects and the influencing factors of bus fuel consumption per 100 km y_i are discussed. Based on the stepwise regression analysis method, a regression model of influencing factors of bus fuel consumption is established as shown in Equation (9):

$$y_{ij} = \sum (a_{ijk} x_{ijk} + \varepsilon_{ij}) \tag{9}$$

where (i) *i* represents the energy type, gasoline, diesel oil, and natural gas, in the empirical data, the sample size of hybrid vehicles is small, the types of vehicles are concentrated, and the variables are not different, so regression analysis is not done; (ii) *j* is the number of samples; (iii) *k* is the number of influencing factors; (iv) y_{ij} is the 100 km consumption value of the *j*-th sample of the *i*-th fuel; (v) x_{ijk} is the *k*-th influencing factor of the 100 km consumption value of the *j* sample of the ith fuel; (vi) α_{ijk} is the coefficient; (vii)ε_{ij} is the perturbation term.

The calculation results are shown in **Table 5**. Under three different fuel types, the factor that contributes the most to the fuel consumption per 100 km is the vehicle length. In models 2 and 3 obtained by further regression, although the models have been further optimized, the effect is weak. Therefore, this study chooses the factor of vehicle length as the influencing factor of fuel consumption per 100 km. Taking the diesel bus with the largest sample size as an example, as shown in **Table 6**, the *p*-values are all smaller than 0.01 and can be considered highly significant. Bus length is the largest among the three modes.

Table 4. Inner Mongolia urban transport statistics report from 2011 to 2022.

	Index		**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
1.Vehicle	1.1 Vehicle		8204	8336	9816	10,236	10,251	10,602	11,644	11,543	12,203	12,380	12,233	11,498
	1.2 Standard vehicle		7767	8102	9843	10,405	10,512	10,868	12,354	12,354	13,338	13,602	13,659	12,048
	1.3 Vehicle length	≤5m	1027	969	957	1037	991	969	924	830	827	725	674	537
		>5 m and ≤7 m	2099	1872	1993	2000	1906	2000	1798	1869	1628	1507	1230	1050
		>7 m and ≤10 m	2741	2847	3280	3032	3049	3254	3360	3052	3185	3582	3336	3290
		>10 m and ≤13 m	2328	2619	3530	4111	4249	4323	5510	5740	6511	6514	6941	6545
		>13 m and ≤16 m	3	3	0	0	0	0	0	0	0	0	0	54
		>16 m and ≤18 m	4	4	34	34	34	34	30	30	30	30	30	0
		>18 m	0	0	0	0	0	0	0	0	0	0	0	0
		Double vehicle	2	22	22	22	22	22	22	22	22	22	22	11
		≤5 m	1027	969	957	1037	991	969	924	830	827	725	674	537
	1.4 Fuel type	Gasoline vehicle	1861	1841	1692	1531	1368	978	960	951	892	806	766	567
		Diesel vehicle	4390	3991	4320	4262	3993	3944	3529	3144	2782	2386	2025	1679
		Natural gas vehicle	459	590	2500	3534	4390	4229	4269	3981	3839	3393	2832	2417
		Double fuel vehicle	1494	1904	1304	375	277	564	463	181	224	209	288	291
		Electric vehicle	0	0	0	0	42	431	1292	2146	3321	4515	5201	5443
		Hybrid vehicle	0	0	0	534	181	456	1131	1140	1145	1071	1071	1073
		Hydrogen vehicle	-	-	-	-	-	-	-	-	-	-	50	28
2.Service	2.1 Passenger volume/million		1053	1128	1247	1281	1294	1291	1279	1162	1195	667	721	467
	2.2 Mileage/million km		625	682	736	697	704	705	669	648	644	525	581	455
		Gasoline vehicle	-	-	-	-	-	-	-	-	-	52	47	30
		Diesel vehicle	-	-	-	-	-	-	-	-	-	118	100	70
		Compressed natural gas vehicle	-	-	-	-	-	-	-	-	-	122	100	72
		Liquefied natural gas vehicle	-	-	-	-	-	-	-	-	-	29	22	16
		Double fuel vehicle	-	-	-	-	-	-	-	-	-	-	18	16
		Electric vehicle	-	-	-	-	-	-	-	-	-	170	257	220
		Hybrid vehicle	-	-	-	-	-	-	-	-	-	33	37	31
		Others	-	-	-	-	-	-	-	-	-	0	0	0
3.Energy	Consumption		-	-	-	-	-	-	-	-	-	132,533	139,343	99,822
		Gasoline/ton	-	-	-	-	-	-	-	-	-	5210	4703	2881
		Diesel/ton	-	-	-	-	-	-	-	-	-	23,339	20,584	14,761
		Natural gas/million m³	-	-	-	-	-	-	-	-	-	-	-	-
		Compressed natural gas/million m³	-	-	-	-	-	-	-	-	-	41	38	26
		Liquefied natural gas/kg standard coal	-	-	-	-	-	-	-	-	-	6973	5725	4399
		Hybrid vehicle/kg standard coal	-	-	-	-	-	-	-	-	-	11,384	16,853	10,865
		Double fuel vehicle/million m³	-	-	-	-	-	-	-	-	-	-	2705	2340
		Others/million m³	-	-	-	-	-	-	-	-	-	0	93	88

Table 5. Summary of stepwise regression model of influencing factors of bus fuel consumption.

Fuel type	Model	R	R-squared	Adjustment of R-side	Standard error	Forecast variables
Gasoline	A	0.959a	0.920	0.920	2.638	A. Vehicle length (mm)
	B	0.962b	0.925	0.925	2.555	B. Vehicle length (mm), displacement (mL)
	C	0.963c	0.927	0.926	2.523	C. Vehicle length (mm), displacement (mL), vehicle age (y)
Diesel fuel	A	0.820a	0.673	0.673	3.892	A. Vehicle length (mm)
	B	0.824b	0.679	0.679	3.855	B. Vehicle length (mm), passenger capacity (persons)
	C	0.826c	0.682	0.681	3.840	C. Vehicle length (mm), passenger capacity (person), power (kW)
Natural gas	A	0.857a	0.735	0.735	3.320	A. Vehicle length (mm)
	B	0.862b	0.743	0.743	3.271	B. Vehicle length (mm), displacement (mL)
	C	0.869c	0.755	0.755	3.193	C. Vehicle length (mm), displacement (mL), vehicle age (y)

Table 6. Parameter of stepwise regression model of influencing factors of bus diesel consumption.

Model	Influencing factors	Standardization factor beta	*t*	*p*-value
A	Vehicle length (mm)	0.820	95.816	0.000
B	Vehicle length (mm)	0.719	52.528	0.000
	Passenger capacity (p)	0.128	9.375	0.000
C	Vehicle length (mm)	0.662	40.095	0.000
	Passenger capacity (p)	0.136	9.955	0.000
	Power (kw)	0.073	6.141	0.000

2) Length threshold layer reference value

The calculation can be carried out if the data source includes vehicle fuel type and vehicle length. However, because the data of the national fuel subsidy declaration system is not open, it is difficult to obtain the data. The plan was suspended in 2020, and detailed data will not be accepted in the coming year. Therefore, studying a more universally applicable calculation method of fuel consumption per 100 km is necessary.

Considering that the Statistical Report of Urban Passenger Transport contains the data indicators divided by layers of bus captains, the data sources are stable. At the same time, to improve the model's applicability and achieve the catalog of carbon emission calculation through a small sample survey without obtaining statistical data, it is also of practical significance to study and design a stratified sampling framework. Therefore, the next step is to research and calculate the reference value of fuel consumption per 100 km based on the threshold division of vehicle length.

Firstly, vehicle length and diesel fuel consumption of 100 km was visualized using the historical data in 2014, as shown in **Figure 2**, with vehicle lengths of 7045, 10,000, and 11,600 mm as the change points; regarding the vehicle length of buses, the vehicle length thresholds of the Statistical Report of Urban Passenger Transport were divided into (0, 5], (5, 7], (7, 10], (10, 13], (13, 16], (16, 18], (18, +∞), and double-decker. The data statistics of Inner Mongolia buses from 2015–2022 show that the average number of bus vehicles with lengths below 5 m and above 13 m accounts for less than 8%, so this paper divides the vehicle length thresholds into combined strata as (0, 7], (7, 10], and (10, +∞).

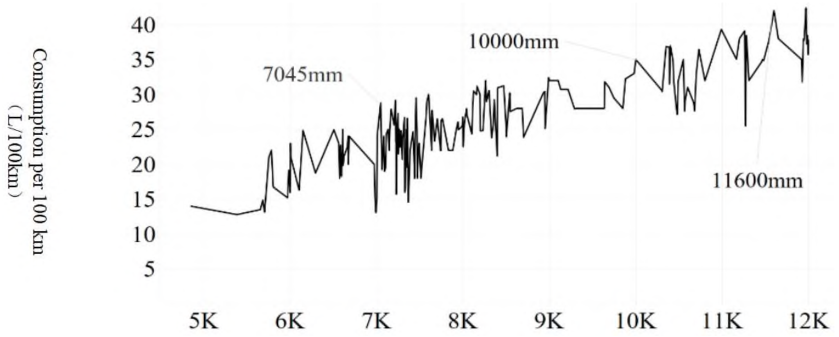

Figure 2. The line of length and diesel oil consumption of 100 km.

Thus, Equation (2) can be further optimized to Equation (10).

$$f_{ij} = \sum m_{ij} y_{ij} \tag{10}$$

where (i) f_{ij} is the consumption of the *i* fuel, *j* vehicle layer; (ii) *i* refer to fuel type, gasoline, diesel oil, natural gas, hybrid power; (iii) *j* is the stratification of the car length; (iv) m_{ij} is the mileage of the *i* fuel type, *j* vehicle layer; (v) y_{ij} is the consumption value per 100 km for *i* fuel type, *j* vehicle layer.

After calculation, the fuel consumption per 100 km of buses divided by lengths is obtained (as shown in **Table 4**). Among them, hybrid vehicles in the empirical data are all gas-electric hybrid vehicles, and fuel subsidies are received by reporting natural gas consumption data. The changing range of vehicle length is 10.5 m to 12.0 m, which aligns with the stratification range of vehicle length (10, +∞).

Because the purpose of this study is to investigate the relatively precise total amount, structure, and evolution trend of carbon emissions from urban public transportation, neither the influence of motor vehicle energy consumption technology level, traffic conditions, and other factors on carbon emissions, it is assumed that the energy consumption level per unit driving distance will remain unchanged during the investigation period that is the fuel consumption per 100 km of vehicles will remain unchanged (**Table 7**).

Table 7. Energy consumption of 100 km of different lengths.

Type of fuel	**(0, 7]**	**(7, 10]**	**(10, +∞)**
Gasoline vehicle (L)	8.7335	21.7336	22.2022
Diesel vehicle (L)	15.5436	21.8931	27.8002
Natural gas vehicle (m^3)	15.5522	22.8214	25.6923
Gas-electric hybrid vehicle (m^3)	-	-	22.5745

3. Results

3.1. CO_2 emissions

The target of carbon peaking includes peak year and peak value. It is calculated that from 2011 to 2022, the urban public transport industry in Inner Mongolia had the highest carbon emission in 2013, which is 383,000 tons.

Therefore, after 2013, when the number of bus vehicles increased at an annual rate of 5.7%, the carbon emissions decreased by an average rate of 2.6% per year until 2022.

While the total emission of the urban public transport industry in Inner Mongolia has increased rapidly, its structure has also significantly changed. As shown in **Figure 3**, the types of vehicle energy have changed significantly. The carbon emission of urban public transportation in the early stage mainly came from diesel oil consumption, accounting for 53.5%, and then declined steadily. The proportion of carbon emissions generated by natural gas consumption has increased yearly from 20% in 2011 and has been equal to diesel oil since 2015, becoming the primary source of carbon emissions. By 2022, the proportion has reached 48.7%, making it the most significant urban public transportation carbon source. Since 2011, the proportion of carbon emissions from gasoline consumption has decreased yearly, from 7.4% to 1.1%, showing a trend of gradually withdrawing from the urban public transport market.

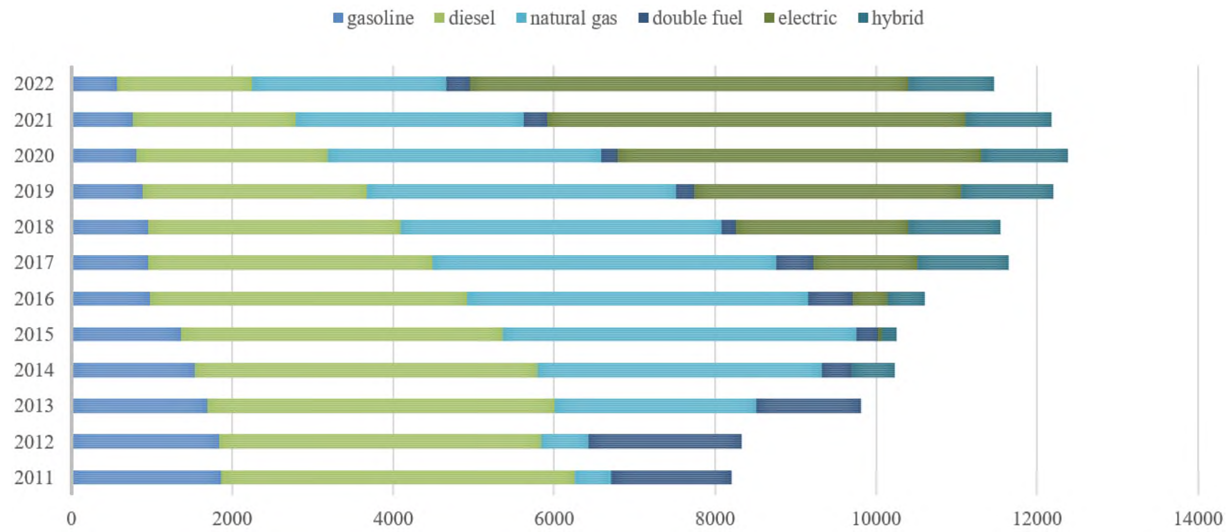

Figure 3. Carbon emissions of different energy in Inner Mongolia from 2011 to 2022.

At the mean time, low-emission gas-electric hybrid buses and zero-emission pure electric vehicles entered the Inner Mongolia market in 2014 and 2015, respectively, their carbon reduction benefits were directly presented in the following year (decreased by 8.8% and 6.8% respectively in 2015 and 2016, respectively), increased rapidly after 2014, replaced a number of fossil electric vehicles. The push toward decarbonization of the power industry is essential for reducing the peak value of carbon emissions[19]. The Chinese government carried out and implement a list of policy promoting the use of electric vehicles, including purchasing subsidy, the operating subsidy, charging infrastructure construction subsidy, to ensure the regular operation of new electric vehicles.

3.2. Strength conditions

As shown in **Figure 4**, from 2011 to 2022, the intensity indicators showed a downward trend in general, in which the per capital and per vehicle carbon emissions decreased rapidly, with an average annual decline of about 5% and 12%.

Comprehensively improve urban public transport services, reduce residents' dependence on passenger cars, and optimize the per capital efficiency index of urban public transport, thereby reducing the overall carbon emissions of urban transportation systems.

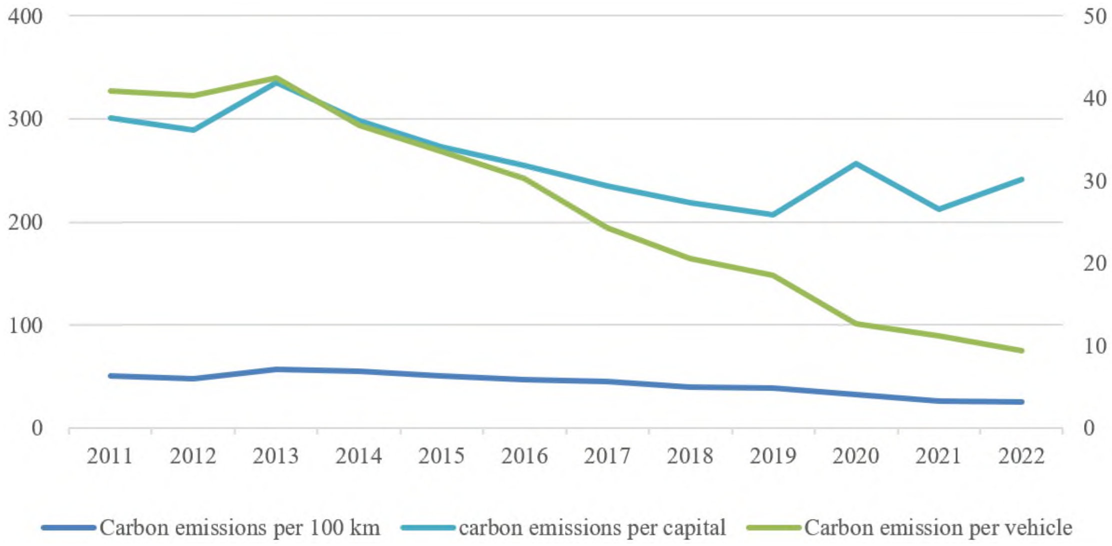

Figure 4. Carbon intensity.

In the context of the growing requirements for CO_2 emission reductions in China, the optimization of the industrial structure is an important way to reduce CO_2 emissions.

4. Conclusion

Reasonable statistical structure and accurate statistical data are critical factors in calculating the energy consumption and carbon emission of urban public transportation. In this study, a carbon emission measurement method for urban public transportation based on different data sources was established. The carbon emission calculation model of urban public transportation based on different data is effective and can be used for government decision-making reference, and internal control of enterprises at the macro-provincial, meso-city, and micro-enterprise levels.

This study obtained the relationship between the vehicle length and fuel consumption per 100 km, which is helpful for internal control of enterprises and decision-making reference of governments.

The urban public transport industry's carbon emissions in Inner Mongolia peaked in 2013 (383,000 tons). From 2013 to 2022, buses increased by 5.7% annually, while carbon emissions decreased by 2.6% annually. The subsidy policy for new electric vehicles operations has a remarkable carbon reduction effect. In the second year after the introduction to the policy, electric vehicles accounted for 33% of the newly added and replaced buses in Inner Mongolia, and the proportion was over 80% from 2015 to 2022.

There are some limitations in this study. This paper only considers direct emissions, and for electric vehicles, their carbon emissions are not calculated. For plug-in hybrid buses, only the carbon emissions generated by consuming fossil energy are calculated. This study focuses on the carbon emissions generated by fossil energy consumption in urban public transport terminals and does not consider other energy consumption in the life cycle, such as infrastructure construction, operation, and maintenance.

Author contributions

Conceptualization, methodology, RW and CS; software,validation, RW and XW; formal analysis, investigation, resources, data curation, RW and CS; writing—original draft preparation, RW; writing—review and editing, XW and XY; visualization, XW; supervision, funding acquisition, CS. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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