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An Evaluation of the Low-Carbon Effects of Urban Rail Based on Mode Shifts

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Abstract: Urban rail is widely considered to be a form of low-carbon green transportation, but there is a lack of specific quantitative research to support this. By comparing the mode, distance, and corresponding energy consumption of residents before and after the opening of rail transit, this paper establishes a carbon reduction method for rail transit. A measurement model takes the passenger carbon emissions before the line is opened as the baseline and compares them with the standard after the opening, determining the carbon emissions reduction. The model requires a combination of a large amount of research data, transit smart card data, and GIS network measurement tools as measured data and parameters. The model is then applied to rail transit lines that have opened in Beijing in recent years. The emissions reductions of four different routes are estimated and the carbon emissions reduction effect of rail transit is evaluated.

Keywords: urban rail; mode shift; carbon reduction; smart card data

1. Introduction

The transportation industry consumes a large amount of energy; it is one of the main sources of greenhouse gas emissions, but also the main source of environmental pollution. Rail transport is considered to be a green transportation mode capable of saving energy and reducing emissions, and its low-carbon characteristics play an important role in this regard. However, there are no reliable data to support the energy-saving and emission-reducing potential of rail transit. To optimize the urban rail transit passenger traffic structure, provide a pre-assessment method and theoretical basis for formulating and implementing low-carbon transportation policies, and promote energy conservation and emissions reduction in the transportation field, a calculation method is necessary for quantifying carbon reduction [1].

Relatively little research has been done on urban rail carbon emissions reduction. Typically, simple assumptions are used for rail transit traffic according to the proportion of city or passenger transport structure assigned to different modes of transport. Assessing emissions reductions according to the difference between emissions before and after implementation of rail systems suffers from poor reliability [2,3]. Sostenibile [4] considered that the transformation of traffic patterns is the first and foremost way of determining alternative modes of rail transit. At the same time, it is necessary to define travel time and travel distance. The Methodology for Clean Development Mechanism ACM0016 [5] developed a methodology for estimating carbon emissions reductions for large-capacity rapid transit projects using a bottom-up approach based primarily on human kilometer emission parameters and comparing project input emissions. However, there are problems in the calibration of parameters and the reliability of the calculations.

The study of carbon emissions from various means of urban passenger transportation can also provide a reference for urban rail emissions reduction calculation. Nejadkoork et al. [6] developed a model for calculating emissions from urban traffic by integrating three independent models to calculate the CO_2 emissions of urban road traffic and visualized the emissions model. Hiroshi [7] introduced the general situation and operating conditions of the metropolitan rail transit network in Tokyo and obtained the CO_2 emissions factor according to the energy consumption data obtained by different transportation modes. Zhang [8] obtained the average fuel consumption per hundred kilometers (L/100 km), the bearing rate of passenger cars and taxis, and the number of passengers per 100 km according to actual travel distance and the total number of passengers for cars and private cars. Walsh et al. [9] studied the direct carbon emissions and indirect energy consumption of various modes of transportation in Dublin, Ireland and derived the direct emissions factors for various modes of transport. Chen et al. [10] calculated the carbon emissions of Shanghai's urban transportation according to the number of vehicles, vehicle mileage, vehicle fuel consumption, and energy carbon emissions factors.

Whether urban rail saves energy and reduces emissions, if so to what extent, and what kind of measurement standards are appropriate remain open questions. The existing studies do not provide reliable quantitative methods. The proposed model is applied here to newly opened routes, allowing emissions reduction effects of different lines to be quantitatively evaluated from the point of view of the transfer mode of residents' travel; the effects of carbon emissions reduction are thereby analyzed. This provides a method for quantitative assessment of carbon emissions reduction in urban rail transit and provides a basis for formulating urban carbon emissions reduction policies.

2. Materials and Methods

2.1. Dataset

Detailed measurement of emissions from the perspective of travel and travel distance requires a large amount of basic data. These data include emissions parameters, energy calorific value parameters, and power-related parameters; but also traffic, travel distances of various modes of transportation, and energy efficiency. Different data must be obtained from different sources. The sources of the parameters in this study involve two aspects: access to international or national releases of data obtained from the government transport sector and questionnaires.

Data on energy-related emissions parameters, energy consumption of urban rails, and passenger traffic can be obtained from public reports by contacting the transport department. The power grid emissions factor is the baseline emissions factor calculated by the National Development and Reform Commission (NDRC) based on the net electricity consumption, fuel type, and total fuel consumption of all power plants in the power system. This value is commonly used in power system carbon emissions reduction calculations. The Intergovernmental Panel on Climate Change (IPCC) released CO_2 emissions coefficients that are widely used. Calorific value refers to the heat released during the complete combustion of 1 kg (or 1 m^3 of gas) of a material, and different national energy compositions of calorific value parameters are generally used in the National Energy Statistical Yearbook of published data. The passenger volume, average distance, station energy consumption, and vehicle energy consumption of urban rail transit are obtained through the subway operation management department. The energy consumption, number of vehicles, and operating mileage of buses using different fuels are obtained through public transport groups. The source of these parameters were summarized in Table 1. The proportion of different types of taxis is obtained through the city taxi management department.

Table 1. Parameter data sources.

Parameter	Definition (Type)	Reference
$EF_{grid,cm}$	National grid emissions factor	National Development and Reform Commission
$EF_{CO2,X}$	Ratio of gasoline CO_2 emissions	IPCC (2006) [11]
	Ratio of diesel CO_2 emissions	
	Ratio of natural gas CO_2 emissions	
$\gamma_x(\rho_x)$	Net calorific value of gasoline (density)	China Energy Statistics (2014) [12]
Q_l	Metro *l* Total passenger volume	Retrieved from smart card data
d_l	Metro *l* Average distance	
W_l	Metro *l* Station energy consumption	Metro operation company 2014
$E_{km,x}$	Metro *l* Traction energy consumption	City bus company 2014
$E_{km,x}$	Energy consumption of natural gas buses by kilometers	Bus operation company 2014
	Energy consumption of diesel buses by kilometers	
	Energy consumption of electric buses by kilometers	
	Proportion of buses using different fuel types	
p_i	Proportion of different types of taxis	Taxi management department

Passengers' trip origin and destination on urban rail network were recorded by card data, so trip distances on urban rail can be extracted from smart card data and network data. While passengers' trip information before the new urban rail line came into service, and the trip information of the access to and egress from the new urban rail line were collected by questionnaires in field survey, as shown in Table 2. Here we gave a description of the main content and the sample allocation of the survey. The objective of this survey is to obtain the trip chains before and after the new urban rail service, including origin, destination, all the modes, line numbers, and interchange nodes, so that trip length of each mode can be calculated. Therefore, questions pertaining to personal characteristics, trip information about this trip, and the trip before this new line are designed in the questionnaire. At first, we included a lot of questions like a normal travel survey [10], but it takes too long to finish the survey by stopping passengers on a platform or on board in our pilot survey [11], so we cut the questionnaire to cover only gender, trip information such as trip purpose, OD, and interchange nodes. With regard to sample, first we determined the sample size by a pilot study, then we allocated the sample in accordance to the demand of different stations at different times because the travel demand of a metro line is not evenly distributed for different times of a day, days of a week, and for different stations [13]. Some passengers may travel on the new urban rail line with neither alighting nor boarding on it. These trips are hard to be captured because surveys are normally done on platform. For this, we carried out our survey on board, in addition to being on platform, trying to cover these trips. In this study, we finally collected 7401 passengers' personal and trip information on the platform and on board four urban rail lines that have newly come into service. Travel paths involving taxis and private car passengers also provide load factors and vehicle energy consumption level data.

Table 2. Data obtained from the field survey.

Parameter	Definition (Type)	Reference
Q_y	Number of samples of passengers surveyed	Sample determination method
d_i	The use of buses, taxis, private cars, and subway travel distance	Passenger sample survey
OC_i	Passenger load factor for taxis Passenger load factor for private cars Passenger load factor for public utility vehicles	Passenger sample survey Passenger sample survey Visual estimate or ticket statistics
$E_{km,x}$	Energy consumption level of taxis per kilometer Energy consumption level of private cars per kilometer	Taxi sample survey Passenger sample survey

It is worth mentioning the original mode share of the four target lines. The essence of the emissions reduction effect of urban rail is mode shift, thus, the original mode share of the urban rail passengers affects the emissions reduction very much. The original mode share of the four lines studied is illustrated in Figure 1. It is not surprising that most of the metro demand was shifted from bus, which is also a low-emission mode. The share of buses ranges from 40% to 60%. The second is a mixed mode, bus and metro, indicating lots of passengers just change their route choices on the rail network, and the existing urban rail network in Beijing accounts a large part of urban mobility. The third is car. Normally, this mode contributes the most for the carbon reduction effect of urban rail. Line 6 attracted more passengers from car driving compared the other three lines. The influence of the original mode share on the final carbon reduction will be further examined in the results.

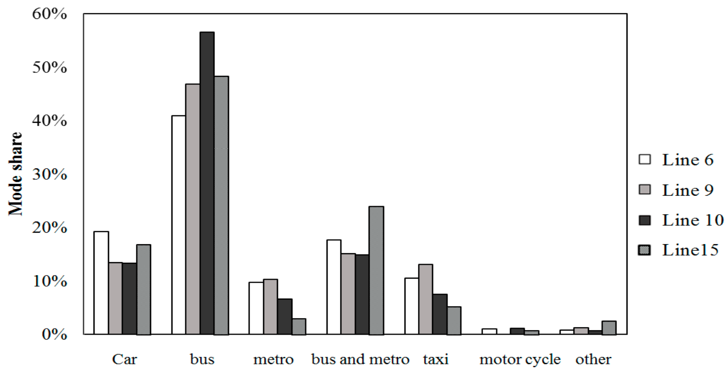

Figure 1. Original mode traffic share with the shift toward urban rail.

2.2. Calculation and Extraction of Travel Distance Data Based on GIS

In this study, we used a network analysis method to calculate the travel distances of passengers for different modes of transportation in geographic information system (GIS). First, GIS data for Beijing's road network (including road grades), bus line network, rail transit network, bus stations, rail transit stations, and other road elements are extracted from the latest online electronic maps using the tools we developed, as shown in Figure 2; these are then transformed into a comprehensive graph consisting of edges and nodes. This integrated graph played as a road network for route choice. The geocoded passenger OD points from field study are loaded onto a map. Thus, with OD points and the interchange nodes collected from field study, respondents' route choice can be generated on the integrated network, and the corresponding distances traveled using various modes along the passengers' trip chains can be calculated.

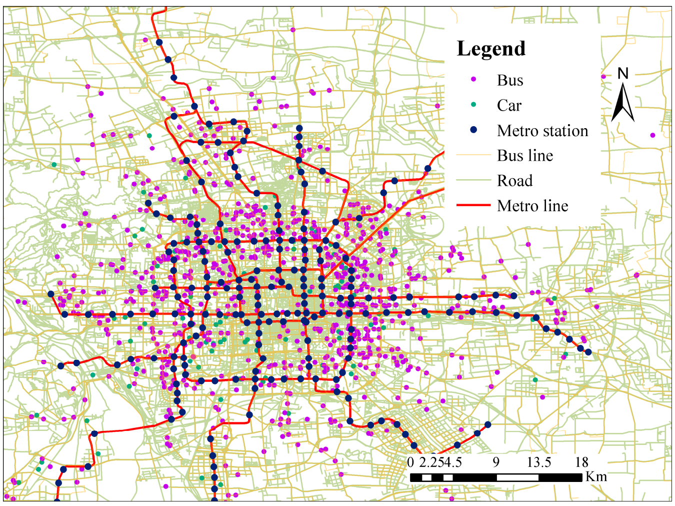

Figure 2. Respondents' origins and road networks visualized in GIS.

To illustrate trip distance calculation in GIS using a graph method, the calculation of the access distance for passenger taking a bus to ride rail transit was taken as an example. The respondents' origin bus stops and the rail stations they boarding were collected in field survey and geocoded in GIS. Then, on the bus line network, the routes from their origins to the corresponding rail stations were generated, shown as blue lines in Figure 3. The lengths of the blue lines are the bus trip distances for those who choose bus to get access to their nearest rail stations. These distances can be used to calculate emissions in combination with the emissions factor of buses. For cars and taxis, the trip distances can be generated on road network. All the trip chains we recorded as points in the field survey were transferred into length.

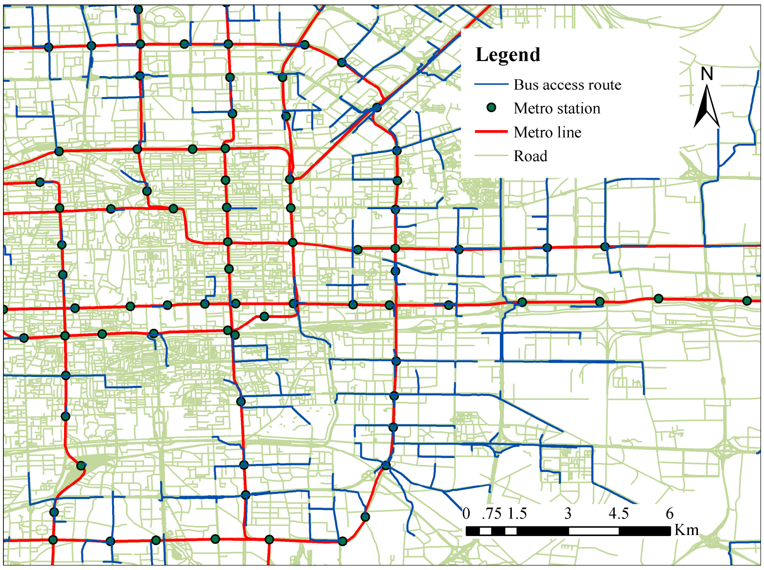

Figure 3. Illustration of the calculation of bus access distances using GIS tools.

2.3. Calculation Model for Urban Rail Carbon Emissions Reduction

The method adopted in this work is very straightforward, just comparing the current emissions of the passengers of a new urban rail line and the original emissions of this same collection of passengers when this new line does not exist. What is available is a record of the total electricity consumption of a rail line, so the emissions when passengers travel on the new rail line can be easily drawn. However, the emissions of the original trips of these passengers on the new rail line and the emissions of the trips going to and from the rail line are unavailable. They must be estimated by a bottom-up method from trip information: travel mode and trip distance. To obtain trip information, two approaches can be applied. First, one can turn to the transport model of the whole city. Any new transport infrastructure can change the accessibility and thus the mode share of the whole city, residents will respond to it by changing travel behavior such as mode choice, route choice, so a traditional four-stage model can be used to capture the change. However, this method needs too much data and a city-level model, which is normally unavailable to researchers. Also, individual travel characteristics are not captured in this method. Therefore, a direct sample expanding method was adopted here. We just collected trip information required from a field survey for a sample out of the total passengers of the new rail line, and then expanded this sample to the total demand. The trip origins, destinations, modes, and distances of the sample passengers were used as a proxy for the whole collection of the passengers riding the new rail line, and thus for the corresponding emission, with an expanding factor. The expanding factor is the ratio of the total demand to the sample.

2.3.1. Urban Rail Transit Carbon Emissions Reduction

The opening of a new urban rail line caused residents to change their travel mode. The original emissions are taken as baseline emissions compared to the standard level. The difference between the emissions levels before and after changing to rail transit is defined as the emissions reduction:

$$R_{ce} = B_{ce} - P_{ce} \tag{1}$$

R_{ce}: Urban rail transit carbon emissions reduction (g CO_2)
B_{ce}: Baseline carbon emissions (g CO_2)
P_{ce}: Current carbon emissions (g CO_2)

2.3.2. Baseline Emissions

The baseline emissions of the sample passengers are obtained by a sample survey, and the weighted average is obtained for per capita baseline carbon emissions. This is multiplied by the total passenger flow of the target subway line to obtain the baseline carbon emissions. The baseline total carbon emissions level is calculated as shown in Equation (2) below:

$$B_{ce} = \frac{Q_p}{Q_s} \sum_i \sum_j d_{ij} \times EF_j \tag{2}$$

B_{ce}: Baseline emissions (g CO_2)
Q_p: Total passenger flow of a subway line under investigation (number of passengers)
Q_s: Number of passengers being investigated
d_{ij}: Baseline travel distance of the *i*th investigated passenger using travel mode *j* (km)
EF_j: Carbon emissions factor of travel mode *j* (g/km), which is calculated based on the emissions parameters defined by IPCC 2006 [14] and China's energy characteristics (obtained from the National Bureau of Statistics of China, 2013 [15–17], and General Administration of Quality Supervision, 2012 [18]).

2.3.3. Current Emissions

Current emissions refers to the emissions of passengers using the target metro line, including direct emissions and synergistic emissions, which are converted emissions from the urban rail system itself. This includes energy consumption traction trains and other electrical and mechanical equipment energy consumption. The latter is the use of the target line of passengers from the starting point to the target subway line station entrance and from the target subway line station exits to destinations using public transport and other modes of transport-generated emissions.

Calculation of project period emissions proceeds using the following equation

$$P_{ce} = D_{ce} + ND_{ce} = W \times EF_{grid,cm} + \frac{Q_p}{Q_s} \sum_i \sum_j d_{ij}' \times EF_j \tag{3}$$

D_{ce}: Direct carbon emissions (g CO_2)
ND_{ce}: Indirect carbon emissions (g CO_2)
d_{ij}': Baseline travel distance of the *i*th investigated passenger using travel mode *j* (km)
W: Total electricity consumption of urban rail, including the traction energy consumption and electromechanical energy consumption (kWh)
$EF_{grid,cm}$: Carbon emissions factor of electricity generation for the power grid based on the comprehensive margin (g/kWh), which is determined using the baseline emissions of regional power grids issued by National Development and Reform Commission of China in 2013 [16].

2.3.4. Emissions Factor

An important parameter in the above model is the km emissions factor for a given mode of transport. Examples in this study include urban rail, electric-powered and general buses, taxis, private cars, motorcycles, and electric bicycles (e-bikes).

Based on the fuel carbon emissions factor per unit volume or mass combined with the carrying capacity, we can calculate the human-kilometer carbon emissions factors of various modes of transportation. The layout of different urban rail lines, electromechanical equipment types, passenger flow, and so on vary greatly, so the lines must use difference factors for human-kilometers, which are calculated using Equation (4)

$$EF_l = \frac{(W_p + W_v) \times EF_{grid,cm}}{Q_l \times d_l} \tag{4}$$

where EF_l represents the carbon emissions of Line l; W_{pl} and W_{vl} represent the dynamic energy consumption and traction energy consumption, respectively; and Q_l and d_l represent the passenger flow and average transport distance of the line, respectively, which are obtained on the basis of smart card data.

Finally, we obtain a variety of modes of transport used in 2014, and the human-kilometer emissions factors are as shown in Table 3, where urban rail is only part of the subway line factor.

Table 3. Carbon emissions factors in terms of PKM for each mode.

Transportation Type	CO_2 Emissions Factor per Passenger Kilometer (g/pkm)	
E-bike	7.14	
Motorcycle	54.4	
Privately owned car	Sample value	
Taxi	165.04/Number of passengers	
Public bus	Fuel bus	49.32
	Electric bus	36.50
Metro	Line 1	31.96
	Line 2	28.35
	Line 4	40.91
	Line 5	36.30
	Line 6	57.12

3. Results and Discussion

The model and parameters are used to estimate the carbon reduction effect of selected typical lines. First, we calculated the baseline emissions before the existence of urban rail systems and the number of passengers using other alternative travel routes and their corresponding carbon emissions. The current emissions were then estimated. The difference between the two emissions levels was calculated, along with the resulting emissions reductions.

3.1. Baseline Carbon Emissions

Based on the calculation formula for baseline carbon emissions, this study calculated the carbon emissions of four target subway lines by using the carbon emissions reduction calculation model and obtained relevant information such as travel modes and travel distances of passengers not using the target metro line. The results are shown in Table 4.

Baseline carbon emissions vary great from line to line. The reason is that different lines are located in different areas in the city, so the demand and its original trip modes and distances are quite distinct, generating different emissions reductions from the perspective of mode shift. As for total emissions, apparently it is determined by the total demand. The annual baseline emissions of Line 10 reached to 670.6 thousand t CO_2, ranking first out of the four lines, while that of Line 15 is lowest due to the lower annual demand. If the total annual emissions is averaged on each passenger, more will be revealed. The Per capita emissions for Line 10 is much lower than the others, roughly equaling two-thirds of Lines 6 and 9, just over half of Line 15. The explanation is that the public transport network in the surrounding areas of the line is relatively mature. There are more electric buses and other subway lines in the main city region. Passengers had more public transportation lines available, and their travel distances were shorter than that of suburban line passengers. Line 15 is more like a suburban line, connecting the center of the city with a remote sub-center. When this line did not exist, the main choices of its passengers were buses and car trips, and the average travel distance was longer, so the average baseline carbon emissions is the highest.

Table 4. Annual carbon emissions of baseline scenario for Metro Lines 6, 9, 10, and 15.

Metro Line	Unit	Line 6	Line 9	Line 10	Line 15
Total emissions of the sample	kg CO_2	2168.06	1941.13	4681.5	779.21
Sample size	persons	1440	1215	4305	410
Baseline carbon emissions per passenger	g CO_2/person	1505.6	1597.6	1087.5	1900.5
Annual demand	million persons	219.57	168.15	616.585	54.52
Baseline carbon emissions	thousand t CO_2	330.58	268.65	670.50	103.61

3.2. Current Emissions

Based on the annual operating energy consumption of the subway system in 2014 and the carbon emissions factor of the baseline for the North China Power Grid, direct carbon emissions were calculated, as shown in Table 5.

Table 5. Direct carbon emissions of Metro Lines 6, 9, 10, and 15.

Metro Line	Unit	Line 6	Line 9	Line 10	Line 15
Total annual direct carbon emissions	thousand t CO_2	113.99	42.84	164.24	45.25

Since direction emissions are drawn directly from the electricity consumption of the line, including station electricity consumption and vehicle electricity consumption, the total emissions is determined by the total demand, length, and station number of the line. It is not surprising that Line 10 has the highest carbon emissions due to its 57 km length and 45 stations moving more than two million passengers daily. Line 6 ranks at the second place due to its 42 km lengths and eight-car trains, while the other three lines only run six-car trains. Line 15 has the same line length as Line 6, but the number of stations along Line 15 is fewer, the train is shorter, and the train kilometers traveled is fewer due to lower demand. Therefore, the total amount of direct carbon emissions for Line 15 was relatively lower.

As for the indirect emissions, the emissions before passenger boarding and after alighting of the new urban rail line studies were calculated using survey data. The trip modes of the respondents' trip chain not falling on the new urban rail line including walking, bicycles, electric bicycles, motorcycles, urban rails, buses, cars, taxis, and a combination of the above. According to the travel distance of each mode and the corresponding carbon emissions factors, the indirect carbon emissions per person per trip were calculated, and the results were summarized in Table 6.

Table 6. Indirect carbon emissions of Metro Lines 6, 9, 10, and 15.

Metro Line	Unit	Line 6	Line 9	Line 10	Line 15
Total emissions of the sample	kg CO_2	564.90	810.10	1732.82	232.69
Sample size	person	1440	1215	4305	410
Indirect carbon emissions per passenger	g CO_2/person	392.3	666.8	402.5	567.5
Total demand	million person	219.57	168.15	616.585	54.52
Total indirect carbon emissions	thousand t CO_2	86.13	112.12	248.18	30.94

The situation of indirect emissions is more complex. This part of the emissions is not related to the baseline emissions or direction emissions. It is estimated by the part of the trip chain out of the target line, so the connection of the target line to other transport infrastructure plays an important role. If the passengers have to travel a long way to from their origins to the target line and also a long way from the line to their destinations, the corresponding average emissions will definitely be higher. It is the just the case for Line 9 and Line 15, both playing as a link, and moving passengers from a suburban center to the edge of the city center. When passengers arrive at the terminal stations, they normally will change to other rail lines. The feature of such lines is that they have a very high ratio of interchanges even with other urban rail lines. For instance, there are 69% of the total passengers on Line 15 change for Line 13 after their alighting. Then, the emissions when they are on Line 13 is treated as indirect emissions. Line 6 running through the city center and has more passengers with both OD around its stations, so the indirect emissions per passenger is only a half of that of Line 15 and Line 9.

3.3. Emissions Reduction

Based on the baseline carbon emissions, direct carbon emissions, and indirect carbon emissions, the emissions reductions of the urban rail lines were calculated. The four lines in Beijing in 2014 were estimated to reduce 0.529 million t CO_2. The results are shown in Table 7.

The total emissions reduction of a line is directly related its annual demand. Thus, when the carbon reduction is average on a passenger, regardless of the trip modes and distances before or after the urban rail line, the differences are much lower compared to average baseline, direction, and indirect emission. The highest is Line 9, which shifts more car trips, while the lowest is Line 10, which is totally located in the central area and shifts more bus or urban rail trips.

Table 7. Expected total annual emissions reduction of Metro Lines 6, 9, 10, and 15.

Metro Line	Unit	Line 6	Line 9	Line 10	Line 15
Annual emissions reduction	million t CO_2	0.130	0.114	0.258	0.027
Annual passenger volume	million person	219.57	168.15	616.58	54.52
Carbon emissions reduction per passenger	g CO_2/person	594.1	676.1	418.6	503.0

3.4. Sensitivity Analysis

Sensitivity analysis is significant in two aspects. First, data quality plays a significant role on the results. Although we did a lot to increase the reliability of the data, there is still some uncertainty on the data from multiple sources. Sensitivity analysis can reveal the effect of data uncertainty on the final results. Second, the impact of the changes of various parameters on the carbon reduction of urban rail can be determined, which can provide evidence for policy makers to come up measures aiming at carbon reduction.

We tested the influence of emissions factors on final results at first, and found that carbon reduction is quite sensitive to the electricity emissions factors, while the emissions factors of gasoline are not so sensitive. Taking Line 15 as an example, when the electricity factor decreases by 10%, the carbon reduction of this line will increase as much as 16.5%, as shown in Table 8. The reason is quite simple. Electricity consumption of an urban rail line is huge, especially for full underground lines, because a lot energy is consumed for illumination and environment control. The annual energy consumption of Line 15 was 56.60 million kWh in 2014. It reached 205.43 million kWh for Line 10. Therefore, even a little change of this factor will lead a large variation of the carbon reduction. The good news is that electricity carbon emissions factor is decreasing very year.

The carbon reduction from urban rail is also very sensitive to the mode share of the line's ridership when the line does not exist, especially the car trip share. Taking Line 15 as an example, if the share of car trip decreases by only 1 percent with other modes decreasing by 1%, the carbon reduction will increase by more than 6.17%. Therefore, the filed survey is very important in the estimation. That is why we deliberated so much time and fund on the data collection. It also implies that if urban rail lines shift more car trips other than buses or cycling, the carbon reduction effect will be very much enhanced.

Table 8. Sensitivity analysis of emissions factors and original mode share for Line 15.

Change of Electricity Emissions Factor in Percent	Change of Carbon Reduction	Change of Car Trip Share	Change of Carbon Reduction
15%	−24.75%	1%	6.17%
10%	−16.50%	0.5%	3.29%
5%	−8.25%	0%	0%
0%	0.00%	−0.5%	−2.30%
−5%	8.25%	−1%	−4.60%
−10%	16.50%	−1.5%	−7.98%
−15%	24.75%	−3%	−13.85%

3.5. Policy Implications

According to the results we estimated, urban rail does reduce carbon emission, but the reduction amount is not so much as generally considered. In this work, emissions reductions for target lines are determined by baseline carbon emissions, direct carbon emissions, and indirect carbon emissions. The combination of energy emissions factor, passenger traffic, trip distances, emissions factors for different modes, mode shifts, and other factors can affect the results. From the results and the sensitivity analysis, some policy implications can be drawn for transport practitioners and emissions reduction authorities.

Firstly, large scale construction of urban rail lines does not necessarily generate large carbon reductions. The full realization of reduction effects needs transport policies on mode share. The key is the shift of high-emission modes to low-emission modes. According to sensitivity analysis, the total carbon reduction from urban rail lines is very sensitive to the original mode share, especially the sharing of car or taxi trips. If a new urban rail line only attracts bus trips or even active modes such as cycling, then the carbon reduction will be very low. This is the case in Beijing. In the last decade, the urban rail of Beijing increased rapidly from 114 km to 554 km, and the share of it also soared from 5.8% to 20.0% [18]. At the same time, the share of cycling plunged from 27.7% to 13.4%. However, the share of cars and taxis did not decrease, even under strict car purchasing and use limitations. Rapidly developing metro actually shifted greening modes such as cycling and bus. To reverse the trend, more limitations on car usage, such as car congestion charges, together with facilities such as park and ride lot (P+R) around suburban metro stations, are needed. In fact, Beijing is considering congestion charges for car users in the central area, and 45 new P+R facilities are in planning.

Secondly, emissions reduction effects of urban rail can be strongly enhanced by energy structure and technologies. Sensitivity analysis reveals that emissions factors play an important role in emissions reduction, especially the electricity carbon emissions factor. The electricity consumption of urban rail is very huge. In additional to the energy consumption of train, the energy consumed by stations is also very big, and can account for 50% of the total energy consumption [19]. This is quite different from other modes. In Beijing, the carbon emissions factor of electricity is very high, because in Northern China nearly all the electricity is generated by fossil fuel, mainly coal. The carbon emissions during the last step fossil fuel consumption in power station (equivalent to gasoline consumed by car) is very large. If the energy structure is optimized by increasing more clean energy, if more electricity is from hydro or nuclear sources like in Southern China, urban rail will achieve a higher carbon reduction. According to sensitivity analysis, a 5 percent decrease of the electricity carbon emissions factor will lead to a more than 8 percent carbon reduction for this case.

4. Conclusions and Recommendations

In regard to the widely-believed carbon reduction effect of urban rail lines, this paper discussed the principle of carbon emissions reduction of rail transit, and established a carbon emissions reduction estimation model for rail transit lines based on mode shift effect, comparison of the scenarios before and after the rail transit existence, and current data availability. According to the travel mode and distance-related parameters required by the model, the passenger travel paths of typical lines were investigated in detail. The carbon emissions reductions of some rail transit lines in Beijing were calculated and the corresponding conclusions were obtained using the model and combining the results with emissions parameters.

(a) A model of rail transportation carbon emissions reduction based on transportation mode transfer was established. After the opening of a rail transit line, passengers previously using cars, buses, and other modes of transport switched to rail transit, which lead to emissions reductions. Based on this, the scope of the calculation was defined as emissions from energy consumption in the operational phase of the vehicles considered and the emissions from electricity during fossil fuel consumption at power stations. The emissions reductions were calculated by comparing the emissions differences corresponding to the passenger travel paths when using rail transit or not.

(b) The carbon emissions reductions of four typical rail transit lines in Beijing were estimated. This study established a set of surveys to extract passenger travel patterns and travel distances through a field survey and GIS-based data processing methods. Based on the model and the travels of sample passengers, the annual carbon emissions reduction and emissions intensity indices of Beijing Metro Lines 6, 9, 10, and 15 were calculated. The results show that four subway lines in 2014 in Beijing reduced 0.529 million t CO_2 in total. This study used more detailed data to demonstrate the effect of urban rail carbon emissions reduction rather than rule of thumb.

(c) The results and the sensitivity analysis show that the carbon reduction of urban rail was closely related the carbon emissions factor of electricity, and the mode share of an urban rail line's passengers before the line come into use (original mode share), especially the car trip share. The high share of coal source electricity increases the emissions factor and thus decreases the emissions reduction to a great extent. Clean energy policy of electricity will enhance the carbon reduction of urban rail vastly. As for original mode share, if urban rail systems shift many passengers from low-emission modes (or even from green mode, such as cycling), the emissions reduction effect will be significantly reduced. For various reasons, new lines constructed in the last decade shifted quite a share of bicycle travelers leading to low emissions reduction. More car usage limitation including congestion charge, and "P+R" facilities around suburban rail stations, will definitely enhance the carbon reduction effect of urban rail systems in the transport field.

This study did not consider the use of urban rail transit to ease traffic congestion on the road and other factors, and it is clear that the transfer of part of the car travel proportion to rail can improve road congestion. This is bound to further reduce the amount of road traffic not yet transferred. For some of the emissions parameters, including car and bus km emissions parameters, this study used the total conversion method without considering the impact of transit speed. These considerations will constitute the next step in this study, including the use of taxi GPS data to establish a more accurate road speed based on a road traffic carbon emissions measurement model.

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