Fine calculation method for carbon emission of urban rail transit

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Abstract. As an important part of modern integrated transportation system, urban rail transit generates carbon emissions mainly by consuming electric energy. Aiming at the problems such as single index and weak accuracy of the current carbon emissions accounting method for urban rail transit, this study builds a refined carbon emissions calculation model based on existing industry standards and norms, puts forward refined carbon emissions calculation factors under different conditions, and designs efficient algorithms to solve them. The research hopes to provide a basis for differentiated policy formulation for urban rail transit operators, so as to facilitate urban rail transit operators to obtain more say in carbon trading, complete carbon quotas more scientifically and rationally, and better help urban rail transit enterprises to complete the strategic goal of "carbon neutrality" and "carbon peak".

1. Introduction

Since 2006, China has been the world's largest emitter of carbon dioxide, and the transport sector, as one of the major sources of greenhouse gas emissions, occupies the third place among the emissions of all sectors, with an emissions share of 13.1% [1]. Urban rail transit includes a variety of standards, with high transportation efficiency, low environmental pollution properties, is the construction of digital transportation, green transportation, constitute an important part of modern comprehensive transportation system. In October 2021, The State Council issued the "Action Plan for Carbon Peaking before 2030", which includes the fifth point on "Green and low-carbon action for transport". To comply with this national policy, the China Urban Rail Transit Association released the "China Urban Rail Transit Green Urban Rail Development Action Plan" in August 2022. At present, some places like Shenzhen and Zhejiang Province have implemented carbon-inclusive methodologies and carbon emissions reduction policies [2]. However, at present, there is a lack of accurate carbon emission calculation methods, and the demand and requirements for accounting corporate greenhouse gas emissions with relatively uniform standards are rising. The accounting methods of corporate greenhouse gas emissions based on industry characteristics are being widely concerned. Extending to the enterprise value chain and focusing on the internal facilities of the enterprise are the two current trends. The fine accounting of urban rail transit is an accurate calculation process of carbon emissions under different circumstances based on statistical data and equipment parameters combined with actual travel conditions after comprehensive consideration of regional, climate, equipment, passenger flow, operation and other conditions of urban rail transit system. Through the detailed accounting of carbon emissions under specific circumstances, urban rail transit operators can have a clearer and more accurate understanding of the carbon emissions of their operating lines, in order to better cooperate with the implementation of the national "dual carbon" strategy.

2. Influencing factors of carbon emissions in urban rail transit

2.1. Main methods of carbon emissions accounting

At present, the emission factor method is the most widely and most commonly used carbon accounting method. It is a carbon emissions estimation method proposed by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations [3]. It can be simply understood as energy consumption plus an emission factor, which is a coefficient corresponding to energy consumption. In the greenhouse gas emission accounting practice of enterprises, the most commonly used method for the calculation of carbon dioxide emissions generated by the purchase and use of electricity is also the emission factor estimation method, which means that the purchase and use of electricity is multiplied by the grid carbon emission factor to obtain the corresponding carbon emissions. Therefore, whether the grid carbon emission factor is used reasonably and its value is appropriate greatly affects the quality of greenhouse gas emission accounting, which is of great significance for the accurate assessment of carbon emissions (or carbon emissions reduction) of various regions, enterprises and projects, as well as the development of high-quality carbon peak and carbon neutral implementation plans. At present, the grid carbon emission factor is not updated in a timely manner, and the

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spatial and temporal resolution is not enough. It is urgent to establish an objective, intuitive and accurate grid carbon emission factor system to provide scientific data reference for monitoring carbon emissions dynamics and implementing carbon reduction actions.

2.2 Analysis of influencing factors of urban rail transit energy consumption

Since the main form of energy used in the operation of urban rail transit is electric energy, carbon emissions generated by urban rail mainly come from purchased electricity. Discussing the influencing factors of carbon emissions of urban rail is equivalent to discussing the influencing factors of energy consumption of urban rail. Urban rail energy consumption refers to the energy consumption generated by urban rail passenger transport and related transportation auxiliary activities such as scheduling, locomotives and works. Taking metro as an example, its power consumption is mainly divided into two parts: train energy consumption and station energy consumption [4,5]. Some scholars have carried out qualitative analysis and identification of subway energy consumption and its influencing factors [6]. Some scholars have explored it, and some factors are listed in Table 1 below.

Table 1. Factors affecting energy consumption in subway operation.

<table>
<thead>
<tr>
<th>Influencing factors of train energy consumption</th>
<th>Influencing factors of station energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle type, train formation, driving mode, ramp design, curve radius, station spacing, passenger flow, season, laying train weight, passenger number, mode, mode of the station volume, laying mode, season, environmental control system, motor type, station spacing, locomotive traction characteristics, operation and the section routing.</td>
<td></td>
</tr>
</tbody>
</table>

2.3. Selection of influencing factors for fine calculation of carbon emission of urban rail transit

This study takes the metro lines that have been opened as the research object, and selects factors of carbon emission. Based on the analysis of the influencing factors of energy consumption and the actual situation, the station type, vehicle type, season factor and period factor are selected as the influencing factors for fine calculation, and the corresponding line conditions are listed.

2.3.1 Line conditions.

(1) Station type factor. The station type is related to the laying mode of the station. Under the same vehicle and passenger flow conditions, underground stations have more energy consumption in terms of ventilation, elevator, lighting, etc., so the underground station has greater energy consumption than the overground station. In this paper, the overground station type means that more than 50% of the stations in the line are overground stations.

(2) Vehicle type factor. Due to differences in vehicle width, self-weight, operating speed, and other technical indicators, the energy consumption of urban rail vehicles varies greatly between different types and models. This paper mainly discusses and analyses the two most widely used models: Type A and Type B.

2.3.2 Season and period conditions.

(1) Seasonal factor. The seasonal influence is mainly reflected in the power consumption of stations. Based on the data from Beijing Metro Line 5, the monthly energy consumption of stations equipped with an underground closed platform screen door system is significantly higher from June to October compared to other months. This paper discusses the impact of North China's hot summers and cold winters on station energy consumption due to noticeable changes in seasons. According to previous studies on temperature's effect on station energy consumption, November to May of the following year is classified as the cold season, while June to October is classified as the warm season.

(2) Period factor. The metro operates on different schedules during peak hours, low peak hours on weekdays, and rest days. The train departure frequency and intervals vary for each schedule, resulting in differences in train operation energy consumption. This paper distinguishes between these three situations.

Table 2 shows the influencing factors for the fine calculation of the four urban rail transit operation energy consumption selected in this paper, where $I$, $J$, $K$ and $L$ represent the types of the station type, vehicle type, season factor and period factor, respectively.

Table 2. Influencing factors of subway operation energy consumption.

<table>
<thead>
<tr>
<th>Line conditions</th>
<th>Season and period conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station type $I$</td>
<td>Vehicle type $J$</td>
</tr>
<tr>
<td>Overground station Type A</td>
<td>Cold season</td>
</tr>
<tr>
<td>Underground station Type B</td>
<td>Warm season</td>
</tr>
<tr>
<td>-</td>
<td>Rest day</td>
</tr>
</tbody>
</table>

2.3.3 Carbon emission factor

This research model was established based on the relevant formulas and contents in Shenzhen Low-carbon Public Travel Carbon Inclusive Methodology (Trial) and the White Paper of Urban Green Travel Index of Zhejiang Province. Both of them propose to use the average passenger-kilometer emission factor to calculate personal carbon emissions of passengers in the project scenario, as shown below.

$$E_p = \left(ER_x \times AC_x \right) / Q$$ (1)
3.2. Modeling

The carbon emission based on total power consumption \( E_a \) is calculated according to the internationally accepted emission factor method, the calculation formula is as follows.

\[
E_a = \sum_{r=1}^{n} W_r \cdot EF_r
\]  

Where, \( E_a \) is the total annual carbon emissions from power consumption of all lines, kg. \( W_r \) is the total annual power consumption per line, kWh. \( EF_r \) is the national grid carbon emission factor, kgCO2/kWh. \( R \) stands for number of subway lines.

The basic average carbon emission factor was obtained according to the total energy consumption and mileage of rail transit operation. Its calculation formula is as follows.

\[
e = \sum_{r=1}^{n} W_r \cdot EF_r / \sum_{r=1}^{n} D_r
\]  

Where, \( e \) is the base average carbon emission factor, kg/km. \( D_r \) is the total annual kilometers travelled by each line, km.

Carbon emissions generated by rail transit line operation are related to line conditions and line mileage, and the corresponding carbon emission factors of the same line under the same line conditions are the same. The total carbon emission \( E_b \) of the line is calculated as follows.

\[
E_b = \sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} \cdot d_{ijkl} \cdot e
\]  

Where, \( E_b \) is the sum of all line condition carbon emissions, kg. \( \alpha_{ijkl} \) is the first line carbon emission allocation factor, \( d_{ijkl} \) is the kilometers of the line under the first condition, km.

3.3. Constraint

The first type of constraint in this model is that all line carbon emission factors are positive and less than \( m \).

\[
0 < \sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} < m
\]  

The second type of constraint is the plus, which is equivalent to all factors taking one without considering different line conditions, so all the carbon emission factors of the lines must add up to the total number of types of carbon emission factors of the lines.

\[
\sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} = ijkl
\]  

The third type of constraint is the station type carbon emission constraint, according to the existing literature, the annual energy consumption of underground stations in the northern region is more than that of overground stations, so the annual carbon emission of underground stations should be greater than that of overground stations.

\[
\sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e \geq \sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e
\]  

The fourth constraint is the carbon emission constraint of vehicle type. The carbon emission of type A car is usually greater than that of type B car because of its large body and large passenger capacity.

\[
\sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e \geq \sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e
\]  

The fifth constraint is the seasonal carbon emission constraint. In northern cities, the total carbon emission of stations in summer is higher than that in winter.

\[
\sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e \geq \sum_{i=1}^{l} \sum_{j=1}^{k} \sum_{r=1}^{n} \alpha_{ijkl} d_{ijkl} e
\]  

The sixth type of constraint is carbon emission constraint in period. The train frequency is high in peak hours, and the number of trains is much higher than that in low peak hours and rest days, so the train operation carbon emission is high.


\[ \sum_{i,j,k} c_{ijk} \geq \sum_{i,j,k} d_{ijk} \geq \sum_{i,j,k} e_{ijk} \]

(12)

4. Example analysis

This study does not consider the climate differences between different regions, so it mainly takes northern cities with hot summer and cold winter as the research object. Based on some subways in Beijing, Taiyuan and Qingdao, the corresponding data are selected for example analysis, and genetic algorithm is adopted to solve the problem.

Among them, the running kilometers data of train refer to the Annual Report of Beijing Transportation Development and other documents, and the sub-periods running kilometers data refer to the subway timetable combined with the train operation mileage. The value of \( m \) is 5.

Table 3 shows the calculation result of the carbon emission factors of the lines, and the objective function value is 0.0000000000, which meets the requirements.

<table>
<thead>
<tr>
<th>Season and period conditions</th>
<th>Cold season - weekday peak hours</th>
<th>Cold season - weekday low peak hours</th>
<th>Cold season - all other days</th>
<th>Warm Season - weekday peak hours</th>
<th>Warm Season - weekday low peak hours</th>
<th>Warm Season - all other days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overground station - type A</td>
<td>1.3860</td>
<td>0.7702</td>
<td>0.3960</td>
<td>0.7427</td>
<td>0.5677</td>
<td>0.4178</td>
</tr>
<tr>
<td>Overground station - type B</td>
<td>0.7770</td>
<td>1.2641</td>
<td>0.2924</td>
<td>0.7524</td>
<td>0.1091</td>
<td>0.0382</td>
</tr>
<tr>
<td>Underground station - type A</td>
<td>3.1066</td>
<td>1.1255</td>
<td>2.2264</td>
<td>2.5896</td>
<td>1.2384</td>
<td>1.9277</td>
</tr>
<tr>
<td>Underground station - type B</td>
<td>0.6667</td>
<td>0.5529</td>
<td>0.5549</td>
<td>1.0291</td>
<td>0.6399</td>
<td>0.8286</td>
</tr>
</tbody>
</table>

The line carbon emission factors provided in this study can enable urban rail operators to make fine calculations according to the characteristics of the lines under their control, and can also obtain different carbon emissions in different periods and seasons, which is convenient for enterprises to analyze their own emission behavior and formulate emission measures more targeted based on the analysis results, so as to better participate in carbon trading. The fine calculation method of urban rail operation enterprises is as follows.

\[ CE = W \cdot EF \cdot \alpha \]  

(13)

Where, \( CE \) is the carbon emission of the line, kg. \( \alpha \) is the carbon emission factor of the line under the condition.

Next, Jinan Metro Line 2 is taken as an example for example analysis. It belongs to the situation of underground station - type B, and the climate of Jinan city is consistent with the model situation in this paper. Table 4 shows the carbon emission calculation results of Jinan Metro Line 2.

<table>
<thead>
<tr>
<th>Carbon emission factors of the line</th>
<th>Cold season - weekday peak hours</th>
<th>Cold season - weekday low peak hours</th>
<th>Cold season - all other days</th>
<th>Warm Season - weekday peak hours</th>
<th>Warm Season - weekday low peak hours</th>
<th>Warm Season - all other days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon emission factors of the line</td>
<td>0.6667</td>
<td>0.5529</td>
<td>0.5549</td>
<td>1.0291</td>
<td>0.6399</td>
<td>0.8286</td>
</tr>
<tr>
<td>Fine calculation of total annual carbon emissions (kg)</td>
<td>7115037.50</td>
<td>836744.54</td>
<td>1180725.00</td>
<td>21858593.08</td>
<td>10192434.77</td>
<td>17519193.08</td>
</tr>
</tbody>
</table>

5. Conclusion

The paper first analyzes the factors that affect the energy consumption of urban rail transit, which mainly include train energy consumption and station energy consumption. Then, the fine calculation model of urban rail transit carbon emissions is constructed, and the line carbon emission factors under 16 conditions are distinguished and solved. The carbon emission of different lines and different periods of urban rail transit are calculated using the emission factor method. This corrected the defects of imprecise calculation caused by the use of national unified grid carbon emission factors. Finally, it estimates the carbon emissions of Jinan Metro Line 2 using the fine calculation method and provides fine calculation results for different periods’ carbon emissions. The method proposed in this paper accurately evaluates the carbon emissions of urban rail transit and contributes to developing more scientific and reasonable strategies for reducing carbon emissions by operating enterprises.
References


