Methodological approaches to the CO₂ emissions estimation in rail transport

Anna Bezdudnaya*, Olga Kol, Roman Smirnov, Marina Treyman

Saint Petersburg State University of Economics, Saint Petersburg, Russia

Abstract. Today there is a growing interest in the problems of assessing the impact of greenhouse gases on the environment. Modern methods for estimating the volume of CO₂ emissions from cargo transportation processes are inaccurate. The study aims to develop a methodology for calculating and estimating the volume of CO₂ emissions generated by rail transport during the transportation of goods and its subsequent validation. Research methods – analysis of Russian and international regulatory documents, scientific and practical methodological approaches to determine the volume of CO₂ emissions for rail transport. It is substantiated that the actual methodological approach should consider direct emissions, indirect emissions and specific parameters: carbon intensity and cargo intensity, mass of transported cargo. The result of study is a methodology for calculating the volume of CO₂ emissions during the transportation of building materials by rail between St. Petersburg and Murmansk is given. The proposed methodology makes it possible to include the amount of estimated CO₂ emissions in the service, which will facilitate the introduction of "green" certificates for customers.

Keywords: transport and logistics sector, rail transport, greenhouse gases, volumes of net carbon dioxide

1 Introduction

The transportation and logistics sector is one of the main sources of CO₂ emissions into the atmosphere. Experts estimate that the transportation industry – aviation, railroads, shipping, and trucking – is responsible for about 17% of global greenhouse gas emissions. Therefore, its decarbonization should significantly improve the quality of the environment and contribute to climate risk reduction. At the same time, rail transport is the “cleanest” in terms of greenhouse gas emissions. For example, according to the Long-Term Development Program of JSC “Russian Railways” until 2025, the reduction of the specific level of greenhouse gas emissions in relation to 2018 will be 4.5% [1].

The development of such a concept as “carbon-neutral” transport occurred in the transport and logistics sector from 2009 to 2015. Today, the carbon neutrality of vehicles,
facilities and services in international practice is measured by significantly minimizing or achieving zero CO$_2$ emissions through renewable energy sources and participation in balancing CO$_2$ emissions through compensation in the direction of their capture, removal and absorption.

One of the key tasks here is to develop a methodology for calculating and estimating CO$_2$ emissions in freight transportation by various modes of transport, including railways. Solving this problem will not only allow to monitor air pollution but also to assess the damage caused to the environment and prevent the negative impact of trucking processes on the environment. It is necessary to consider the direct (Scope 1) and indirect (Scope 2 and Scope 3) CO$_2$ emissions, which contribute to the total air pollution in the process of cargo transportation. As an example, we can calculate emissions for all three covers of the second largest transcontinental railroad in North America after the Union Pacific Corporation BNSF (Burlington Northern Santa Fe Corporation) Railway (Table 1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Scope 1</th>
<th>Scope 2</th>
<th>Scope 3</th>
<th>Overall volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>11,300,797</td>
<td>368,943</td>
<td>3,624,596</td>
<td>15,294,336</td>
</tr>
<tr>
<td>2019</td>
<td>10,184,713</td>
<td>315,994</td>
<td>3,226,663</td>
<td>13,727,370</td>
</tr>
<tr>
<td>2020</td>
<td>8,979,288</td>
<td>301,504</td>
<td>2,844,836</td>
<td>12,125,628</td>
</tr>
<tr>
<td>……</td>
<td>……….</td>
<td>……….</td>
<td>……….</td>
<td>……….</td>
</tr>
<tr>
<td>2030</td>
<td>8,630,864</td>
<td>320,269</td>
<td>1,807,221</td>
<td>10,758,354</td>
</tr>
</tbody>
</table>

Methodological approaches to the volumes of greenhouse gas emissions by individual modes of transport, including railway transport, are given in the “Guidelines for national greenhouse gas inventories of the IPCC” [3]. Today there are 18 standards for calculating CO$_2$ emissions abroad, a combination of standards supported by the state and standards independently developed by various associations, recommendations of research bodies, regional approaches and standards for individual modes of transport. In addition to official documents regulating the assessment of CO$_2$ emissions in the transport and logistics industry as a whole and concerning individual modes of transport, foreign scientific literature also proposes the following methodological approaches:

- methods of multidimensional power distribution [4];
- distribution based on income [5];
- game-theoretic approaches to distribution [6];
- approach based on allocating proportional distance as a limiting factor in the supply chain by analogy with the useful body volume of trucks (or TEU) [7].

Currently, the most actively used methodological approach proposed by the Swiss scientist Peter Wild is based on ton-kilometers [8].

As O.D. Kohl points out that at present, JSC “Russian Railways” has developed and is in force the “Methodology for determining the amount of greenhouse gas emissions in JSC “Russian Railways” since 2017 [9]. However, given the requirements for estimating greenhouse gas emissions by coverage type, Scope-1 and Scope-2 requires serious refinement. In addition, the development of transport and logistics services of the company in the direction of offering its customers multimodal transportation involves the creation of appropriate assessment methodology and a single information platform to account for a single “transport footprint” in the delivery of goods [10].

Given the above, the purpose of this study can be formulated as follows: development of a methodology for calculating greenhouse gas emissions in cargo transportation on the example of rail transport.
2 Materials and methods

After analyzing regulatory and legal documents, standards at the Russian and international levels, conclusions were made on the need to develop a more accurate methodology for calculating and estimating CO₂ emissions for implementing cargo transportation by rail. First of all, the calculations must be as accurate as possible and consider both direct (Scope 1) and indirect emissions (Scope 2) and the specific parameters that contribute to pollution, which include such indicators as carbon intensity and cargo intensity, the weight of the transported cargo, must also be taken into account. Direct emissions come from rolling stock operating on electric traction and diesel traction.

This approach allows to shift responsibility from the cargo carrier to the customer, i.e., to include the volume of calculated CO₂ emissions in the service and subsequently introduce such an important tool as “green” certificates for customers. Therefore, the calculation of the volume of CO₂ emissions from the planned on route of cargo transportation by rail should be based on the formula (1):

\[
\zeta_{\text{route}} = \sum_k (\zeta_{\text{fr.trans.el.trac.} \ k} \times \Theta_{\text{el.section} \ k} \times M + E_{\text{fr.trans.loc.tract} \ k} \times \Theta_{\text{section loco.tract} \ k} \times M),
\]

where \(\zeta_{\text{route}}\) – the predicted value of the volume of GHG emissions that will be generated from the transportation of cargo along the route, t CO₂-eq;

\(\zeta_{\text{fr.trans.el.trac.} \ k}\) – carbon intensity of freight transportation within the boundaries of the \(k\)-th railroad for electric traction, t CO₂-eq/t-km gross;

\(\Theta_{\text{el.section} \ k}\) – predicted distance of the corresponding cargo transportation by electric traction within the boundaries of the \(k\)-th railroad, km;

\(\zeta_{\text{fr.trans.loc.tract} \ k}\) – carbon intensity of freight transportation within the boundaries of the \(k\)-th railroad for diesel traction, t CO₂-eq/t-km gross;

\(\Theta_{\text{section loco.tract} \ k}\) – the predicted distance in the transportation of the corresponding freight by diesel traction within the boundaries of the \(k\)-th railroad, km;

\(M\) – the gross weight of the transported cargo, t gross. Determined by the shipper, then following the cargo selected type of car with the appropriate tare weight.

In this case, it is necessary to consider the specifics of rail transport: the railway network has electrified and non-electrified sections, and the accounting of CO₂ emissions occurs differently in freight transport.

Evaluation of electrified areas is carried out according to the following formulas (2-3):

\[
\Theta_{\text{el.section} \ k} = \Theta_{\text{section} \ k} \times \frac{\Theta_{\text{total el. sections} \ k}}{\Theta_{\text{oper.} \ k}},
\]

\[
\Theta_{\text{locos.section} \ k} = \Theta_{\text{section} \ k} \times \frac{\Theta_{\text{total non-el. sections} \ k}}{\Theta_{\text{oper.} \ k}},
\]
where $\Theta_{\text{section } k}$ – predicted distance in the transportation of the corresponding cargo within the boundaries of the $k$-th railroad, km;

$\Theta_{\text{total non-el. sections } k}$ – total length of non-electrified sections within the boundaries of the $k$-th railroad, km;

$\Theta_{\text{oper. } k}$ – operating track length of the $k$-th railroad, km.

These indicators should be calculated for each railroad separately. Table 2 gives an example of the sources of information for determining the value of the above indicators (formulas 4-6).

**Table 2.** Sources of information and calculation of the value of indicators for the n-railway of JSC “Russian Railways”.

<table>
<thead>
<tr>
<th>Indicator name</th>
<th>Designation of the indicator from the formula</th>
<th>Sources of information and formulas for calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of electrified sections within the boundaries of the n-railway per year, km</td>
<td>$\Theta_{\text{total el. sections } k}$</td>
<td>Reference value from the information system of JSC “Russian Railways”.</td>
</tr>
<tr>
<td>Total length of non-electrified sections within the boundaries of the n-railway per year, km</td>
<td>$\Theta_{\text{total non-el. sections } k}$</td>
<td>Reference value from the information system of JSC “Russian Railways”.</td>
</tr>
<tr>
<td>Total operating length of all sections within the boundaries of the n-railroad per year, km</td>
<td>$\Theta_{\text{total all sections } k}$</td>
<td>$\Theta_{\text{total all sections } k} = \Theta_{\text{total non-el. sections } k} + \Theta_{\text{total el. sections } k}$, (4)</td>
</tr>
<tr>
<td>The value of load intensity of electrified sections within the boundaries of the n-railway for the past year, million tons-km gr/km per year</td>
<td>$\Gamma_{\text{el. sections } k}$</td>
<td>$A_{\text{freight el. traction } k}$ – freight work (freight turnover) performed by electric traction within the boundaries of the $k$-th railroad, mln t-km gross; $\Theta_{\text{total el. sections } k}$ – total length of electrified sections within the boundaries of the $k$-th railroad, km.</td>
</tr>
<tr>
<td>The value of freight intensity of non-electrified sections within the boundaries of the n-railway for the past year, million tons-km gr/km per year</td>
<td>$\Gamma_{\text{loco. section } k}$</td>
<td>The formula from Order No. 28p of 13.01.2020 determines the load capacity for non-electrified sections’ calculated value. “On the approved Methodology of Classification and Specialization of Railway Lines of JSC Russian Railways.” $A_{\text{cargo on loco. traction } k}$ – freight work (freight turnover) performed by diesel traction within the boundaries of the $k$-th railroad, mln t-km gross;</td>
</tr>
</tbody>
</table>
The next indicator to be determined is the carbon intensity of freight transportation. It is also calculated separately for diesel and electric traction. Calculation of the carbon intensity of freight transportation for diesel traction is carried out by the formula (7):

\[
\zeta_{fr.\text{trans.locotract} \, k} = \frac{\zeta_{\text{direct freight} \, k}}{A_{\text{cargo on loco.tract} \, k}} \times 10^{-6}, \tag{7}
\]

where \(\zeta_{fr.\text{trans.locotract} \, k}\) – the carbon intensity of freight transportation for diesel traction within the boundaries of the \(k\)-th railroad, t CO₂-eq/t-km gross;

\(\zeta_{\text{direct freight} \, k}\) – direct GHG emissions from combustion of diesel fuel when performing freight transportation within the boundaries of the \(k\)-th railroad, t CO₂-eq;

\(A_{\text{cargo on loco.tract} \, k}\) – freight work (freight turnover) performed by diesel traction within the boundaries of the \(k\)-th railroad, mln t-km gross.

Next, it is necessary to determine the indirect CO₂ emissions from freight transportation by rail. Estimation of indirect CO₂ emissions from railroad freight transportation is carried out according to formulas (9-10):

\[
\zeta_{fr.\text{trans.eltract} \, k} = \frac{\zeta_{\text{indirect freight} \, k}}{A_{\text{cargo on eltract} \, k}} \times 10^{-6}, \tag{8}
\]

where \(\zeta_{fr.\text{trans.eltract} \, k}\) – the carbon intensity of freight transportation for electric traction within the boundaries of the \(k\)-th railroad, t CO₂-eq./t-km gross;

\(\zeta_{\text{indirect freight} \, k}\) – indirect GHG energy emissions from electricity consumption by electric locomotives during freight traffic within the boundaries of the \(k\)-th railroad, t CO₂-eq;

\(A_{\text{cargo on eltract} \, k}\) – freight work (freight turnover) performed by electric traction within the boundaries of the \(k\)-th railroad, mln t-km gross;

\(k\) – railway of JSC “Russian Railways”.

Next, it is necessary to determine the indirect CO₂ emissions from freight transportation by rail. Estimation of indirect CO₂ emissions from railroad freight transportation is carried out according to formulas (9-10):

\[
\zeta_{fr.\text{trans.eltract} \, i} = F_{el} \times EF_{el \, m} \times \frac{\Theta}{\text{el.section} \, i}, \tag{9}
\]

where \(F_{el}\) – the consumption of electrical energy, kWh;

\(EF_{el \, m}\) – coefficient of indirect energy emissions for the route section \(m\), t CO₂/MW·h;

\(\Theta_{\text{el.section} \, i}\) – the distance traveled when transporting the corresponding cargo on electric traction on the \(i\)-th section of the circulation, km.

\[
\zeta_{fr.\text{trans.locotract} \, j} = FC_{\text{dies.fuel}} \times NCV_{\text{dies.fuel}} \times EF_{\text{dies.fuel} \, i} \times GWP_{\text{i}} \times \frac{\Theta_{\text{loco. section} \, j}}{\text{section} \, j}, \tag{10}
\]

where \(FC_{\text{dies.fuel}}\) – diesel fuel consumption, tons of fuel;
\( NCV_{\text{diesel fuel}} \) – the lower heating value of diesel fuel, equal to 42.5 TJ/kt;
\( EF_{\text{diesel fuel} i} \) – emission factor of the \( i \)-th greenhouse gas from combustion of diesel fuel, kg \( \text{CO}_2/\text{TJ} \);
\( GWP_i \) – the global warming potential for the \( i \)-th gas;
\( \Theta_{\text{loco. section } j} \) – the distance traveled during transportation of the corresponding freight by diesel traction on the \( j \)-th section of the circulation, km.

3 Results

The above method was tested on the route St. Petersburg – Murmansk (distance 1420 km), operated by Oktyabrskaya Railways – a branch of Russian Railways, during the transportation of construction materials weighing 60 tons.

Table 3 shows the values of the indicators needed to calculate the direct and indirect \( \text{CO}_2 \) emissions during cargo transportation.

Table 3. Value of indicators for Oktyabrskaya Railway – a branch of Russian Railways in 2022.

<table>
<thead>
<tr>
<th>Indicator name</th>
<th>Indicator designation from the formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of electrified sections within the boundaries of the Oktyabrskaya railroad per year, km</td>
<td>( \Theta_{\text{total el. sections } k} )</td>
<td>4,448.049</td>
</tr>
<tr>
<td>Total length of non-electrified sections within the Oktyabrskaya railroad per year, km</td>
<td>( \Theta_{\text{total non-el. sections } k} )</td>
<td>5,992.851</td>
</tr>
<tr>
<td>Total operating length of all sections within the boundaries of the Oktyabrskaya railroad per year, km</td>
<td>( \Theta_{\text{total all sections } k} )</td>
<td>10,440.9</td>
</tr>
</tbody>
</table>

The following direct and indirect emissions were calculated for electric traction and diesel traction rolling stock:

\[
\Theta_{\text{el. section } k} = \Theta_{\text{section } k} \times \frac{\Theta_{\text{total el. sections } k}}{L_{\text{oper. } k}} = 1420 \times \frac{4448.049}{10440.9} = 604.96 \text{ km}
\]

\[
\Theta_{\text{loco. section } k} = \Theta_{\text{section } k} \times \frac{\Theta_{\text{total non-el. sections } k}}{L_{\text{oper. } k}} = 1420 \times \frac{5992.851}{10440.9} = 815.04 \text{ km}
\]

Values of indicators necessary for further calculation of \( \text{CO}_2 \) emissions are shown in Table 4.

Table 4. Values of indicators for Oktyabrskaya Railway – a branch of Russian Railways in 2022.

<table>
<thead>
<tr>
<th>Indicator name</th>
<th>Indicator value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of diesel fuel consumed in physical units during freight transportation within the boundaries of the Oktyabrskaya Railroad, thousand tons.</td>
<td>162.47</td>
</tr>
<tr>
<td>Cargo work (freight turnover) performed by diesel traction within the boundaries of the Oktyabrskaya Railroad, mln t-km gross</td>
<td>64,165</td>
</tr>
<tr>
<td>Cargo work (freight turnover) performed by electric traction within the boundaries of the Oktyabrskaya Railroad, mln t-km gross</td>
<td>209,967</td>
</tr>
<tr>
<td>Quantity of electric energy consumed during freight transportation within the boundaries of Oktyabrskaya Railroad, MW·h</td>
<td>1,775,085</td>
</tr>
</tbody>
</table>

The carbon intensity of freight transportation of construction materials using locomotive traction was as follows:
The carbon intensity of freight transportation of this type of cargo based on electric traction was determined as follows:

\[ \zeta_{fr.\,trans.\,loc.\,traction\,k} = \frac{511\,658}{64\,165} \times 10^{-6} = 7.97 \times 10^{-6} \]

The volume of direct greenhouse gas emissions (Scope 1) from the combustion of diesel fuel during transportation of construction materials along the route St. Petersburg – Murmansk was

\[ \zeta_{direct\,freight\,k} = 162\,470\,\text{tonn} \times 42.5 \times 74100 \times 10^{-3} \times 1 = 511,658\,\text{tons of CO}_2 \]

As a result, the carbon footprint from the transportation of one carload of construction materials weighing 60 tons along the route St. Petersburg – Murmansk:

\[ \zeta_{route\,\text{CO}_2} = 2.1 \times 10^{-6} \times 604.96 \times 60 \times 7.97 \times 10^{-6} \times 815.04 \times 60 \times 0.076 + 0.386 = 0.462\,\text{t CO}_2\text{-eq.} \]

4 Discussion

Currently, there are many methodologies for assessing and calculating CO\(_2\) emissions for various types of transportation systems, mostly based on regulations and legislation, as well as affecting international regulations [11, 12]. A 2018 study conducted by Interreg. Central Europe’s “TOOLBOX ELEMENT: CO\(_2\) CALCULATOR” [13] is devoted to analyzing the most known CO\(_2\) emission calculators for different modes of transport. The authors of the study combine them into two groups:

- general calculation method or activity-based method (activity-based approach), which uses the average CO\(_2\) emission factor per ton-kilometer by mode of transport, vehicle body volume, and average transportation distance by mode of transport;
- energy-based approach (energy approach) evaluates the actual amount of work performed and energy consumed per unit of output. “Output” of freight transport operations is usually measured in ton-kilometers, energy consumption in liters of fuel or kilowatt-hours of electricity used per ton-kilometer, and a fuel/energy CO\(_2\) emission factor.

The most difficult point when using the second approach is establishing the most appropriate emission factor when carrying out freight transport for each mode of transport and a particular mode of transport in a particular country (per the standard EN 16258) [14].

The results obtained in the approbation of the above methodological approach show that due to the electrification of railway transportation alone, there was a significant reduction in CO\(_2\) emissions, which significantly reduced the negative impact of rail transport on the environment. And this, in turn, allowed to significantly increase the level of the greening of freight transportation of JSC “Russian Railways” [15-17].

The main results of the study are shown in Table 5.

**Table 5.** Results of CO\(_2\) emissions calculation for cargo shipments along the St. Petersburg – Murmansk route.

<table>
<thead>
<tr>
<th>Indicator name</th>
<th>Unit of measurement</th>
<th>Resulting value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7
According to the assessment, the volume of CO₂ emissions along the route St. Petersburg – Murmansk will be 0.462 tons of CO₂-eq, which is significantly less than the calculation according to the approved methodology of 5.267 tons of CO₂-eq [9]. Consequently, the above methodology allows a more accurate assessment of the volume of CO₂ emissions, as it considers additional parameters – carbon intensity, cargo intensity, and the isolation of electrified and non-electrified sections of the railroad.

5 Conclusion

This study is aimed at examining various approaches to calculating the volume of CO₂ emissions in freight transportation on the railroad. The following conclusions can be made based on the results obtained:

- at present, the problem of greenhouse gases is still relevant in various sectors and spheres of economic activity; the transport and logistics sectors significantly pollute the natural environment and make a significant “contribution” to the volume of greenhouse gas emissions, including CO₂ emissions;
- assessment of CO₂ emissions is an important and multi-component component for various processes and will subsequently achieve the principles of sustainable development at the regional level;
- currently, there are many Russian and foreign methodological approaches to calculating the volume of CO₂ emissions, which are based on the calculation of specific CO₂ emissions from rail transport, as well as direct and indirect accounting of emissions, which allows considering the indirect impact of technology on the environment.

References

10. O. Kol, Main directions for the use of digitalization tools in the transport under the conditions of decarbonization. Sup. Chain Manag. J. 13(2), 26-33 (2022)
11. O. S. Korobova, Formation of an economic mechanism for realizing the potential of reducing greenhouse gas emissions (Moscow State Mining University, Moscow, 2011)
12. S. M. Semenov, Greenhouse gases and the modern climate of the Earth (Meteorology and hydrology, Moscow, 2004)
15. B. S. Ksenofontov, Greenhouse gases: utilization using biotechnological installations (Infra-M, Moscow, 2023)
17. S. F. Abdulin, Environmental impact of hazardous emissions from nickel mining and smelting plants on humans and the environment. (Publishing house of OmSTU, Omsk, 2012)