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Carbon Footprint in Rail Transport

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Summary

This article discusses the concept of the carbon footprint, which represents the total sum of greenhouse gas emissions caused directly or indirectly by a given entity (person, organisation, event, or product). It characterises the currently used methods for calculating and presenting the carbon footprint, based on the ISO 14067:2018 standard and the ISO 14040:2009 series of standards. Furthermore, it presents the carbon footprint in relation to different means of transport. The analysis reveals that the highest amount of greenhouse gases originates from road transport, while the lowest comes from rail transport. However, it is important to note that for each journey and its associated carbon footprint, factors such as emissions generated during the production of components and their transportation to vehicle manufacturers, emissions from the vehicle manufacturing process and their deployment into service, as well as the construction of necessary infrastructure, must be taken into account. The article also demonstrates that the construction of new high-speed railway lines contributes to the reduction of carbon dioxide emissions in transport. Additionally, it suggests re-evaluating the feasibility of developing intermodal freight transport.

Keywords: ecological footprint, greenhouse gases, means of transport, intermodal transport

1. Introduction

The progressive warming of the climate is an undeniable fact, and it is increasingly influencing the occurrence of various extreme weather events, which until recently were confined to limited areas of the world. Scientists predict that the rate of glacier melting and water evaporation will increase, which will consequently affect the water balance of the entire Earth. This will lead to the expansion of desert areas and, as a result, contribute to the extinction of certain plant and animal species.

The average surface temperature of the Earth has already risen by 1 degree Celsius, and according to experts, within the next 80 years, it will be as much as 4 degrees higher than it was two centuries ago. Since the earliest temperature records only date back to the second half of the 17th century, scientists now have to rely on so-called indirect data obtained from the research of geologists, archaeologists, palaeontologists, and others to determine climate changes. Based on this, it has been estimated that in the past, the dynamics of change were slower and occurred over approximately 20,000 years.

However, not all scientists agree on the causes of current climate changes. Among the less popular theories is the assumption that we are currently experiencing another period of global warming that occurs cyclically on Earth, alternating with periods of glaciation, as confirmed by studies of ice layers in Greenland and Antarctica. Proponents of this theory suggest that the Sun and its activity are the most probable cause of the cycles of warming and cooling on our planet [9].

The first stance of the Intergovernmental Panel on Climate Change (IPCC), as well as assessments by various scientific bodies, indicates that the cause of the warming of the Earth's atmosphere and the resulting climate anomalies is the increase in greenhouse gas emissions, primarily anthropogenic CO_2 emissions. For this reason, in 1992, the governments of most countries signed the United Nations Framework Convention on Climate Change [23], in 1997 the Kyoto Protocol [20], and in 2015 the Paris Agreement [19], which aims to reduce the emission of harmful greenhouse gases. The objective of the conducted literature review was to gather and systematise the available knowledge on the generation of the carbon

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footprint, particularly by means of transport, and to indicate possible directions for its reduction.

2. Carbon Footprint

To standardise the measurement and continuous monitoring of global gas emission levels, the term „carbon footprint" (*CF*) was introduced. It is a measurable indicator representing the total sum of greenhouse gas emissions caused directly or indirectly by a given entity (person, organisation, event, or product) and is a type of ecological footprint.

This concept encompasses emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases expressed in CO_2 equivalents, which include fluorinated gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). The measure of the carbon footprint is: **t CO_2e** – tonne of carbon dioxide equivalent. This parameter allows for the comparison of emissions of different gases on a common scale, where one tonne of methane corresponds to 25 tonnes of CO_2e. The carbon footprint can be calculated at an enterprise or product level. The CF indicator for an enterprise includes emissions caused by all activities related to the business operations of the enterprise, including energy consumption by buildings and means of transport. The CF indicator for a product includes emissions caused by the extraction of raw materials from which the product is made, emissions from the production process, usage, storage, as well as post-consumption recycling [9].

3. Principles of Calculating and Presenting the Carbon Footprint

The presented approach means that the calculation takes into account not only direct emissions but also those occurring in the supply chain, making the data analysis process time-consuming, labour-intensive, and requiring specialised expert knowledge. Furthermore, before commencing the analysis, it is necessary to select an appropriate functional unit and define the boundaries and scope for which the CF will be calculated. This requires an understanding of the entire production process or the overall functioning of the organisation (depending on the purpose of the calculation). The following calculation scopes are applied:

- from cradle to grave, where all stages from raw material extraction to disposal are considered (using the ISO 14067:2018 [8] standard), or
- from cradle to gate, where the stages from raw material extraction to the delivery of the finished product to the client are calculated, including the transport process and using the ISO 14040:2009 [17] and ISO 14044:2009 [18] standards.

Most entrepreneurs, when deciding to calculate the CF for their products, choose the cradle-to-gate method. It is much more precise, carries a lower risk of error, and allows for a thorough examination of all processes that an expert can verify. When calculating emissions within the cradle-to-grave scope, many hypothetical scenarios must be considered, such as product usage or disposal, and average values must be assumed for situations that may or may not occur. This increases uncertainty and exposes the enterprise to potential calculation errors. Analyses within such a scope are often performed for the evaluation of economic processes or comparative analyses. The principles and guidelines outlined in the aforementioned standards are discussed below.

3.1. Calculating the Carbon Footprint According to ISO 14067:2018

The ISO 14067:2018 Greenhouse gases — Carbon footprint of products – Requirements and guidelines for quantification [8], outlines principles for calculating and applying the CFP (*carbon footprint of products*) and provides guidance on communication and qualification of CFP. The main objectives of the aforementioned standard are:

- defining requirements for CF-related methodologies,
- facilitating the identification of sources and tracking of GHG (Greenhouse Gases) emissions,
- establishing consistent and effective CF reporting procedures for all stakeholders,
- facilitating the evaluation of various product design options and production methods, from raw material selection to manufacturing technology choices and recycling assessments, to improve the implementation of strategies for planning and managing greenhouse gases throughout the product lifecycle, as well as identifying potential "savings" across the supply chain,
- enhancing the credibility of CF communications and providing information to enable clients to make informed decisions about product purchases and their impact on GHG emissions.

The determination of CF also aims to raise environmental awareness and increase the engagement of all parties involved in the supply chain, as well as to support organisations in tracking climate changes and managing these changes.

The ISO 14067 standard [8] addresses environmental aspects. The CF calculation methodology is

based on the Life Cycle Assessment (LCA) concept, and therefore it is recommended to include four fundamental research phases:
1) Goal and Scope Definition;
2) input and output analysis (materials, energy, emissions, and waste) – Life Cycle Inventory (LCI);
3) Life Cycle Impact Assessment (LCIA);
4) Life Cycle Interpretation (LCI) [10].

3.2. Calculating the Carbon Footprint According to the ISO 14040 Series of Standards

The ISO 14040 series of standards outlines requirements and principles for conducting assessments, as well as guidelines for interpreting results and templates for required documentation. The series includes the following documents:
- PN-EN ISO 14040:2009: Environmental management – Life cycle assessment – Principles and framework [17]. This standard describes the principles and framework of Life Cycle Assessment (LCA). It provides 46 definitions related to LCA studies and life cycle inventory analysis. The principles outlined in the standard should be used as guidelines for decision-making in both planning and conducting LCA.
- PN-EN ISO 14041:2002: Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis [14].
- PN-EN ISO 14043:2002: Environmental management – Life cycle assessment – Life cycle impact assessment [15].
- PN-EN ISO 14043:2002: Environmental management – Life cycle assessment – Life cycle interpretation [16].
- PN-EN ISO 14044:2009: Environmental management – Life cycle assessment – Requirements and guidelines [18]. This standard specifies requirements and provides guidelines for conducting Life Cycle Assessments. Its provisions primarily relate to the four phases of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation.
- ISO/TR 14047:2012: Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to impact assessment situations [15]. This document provides eight examples illustrating the conduct of life cycle impact assessments. The leading example allows for the full procedure of life cycle impact assessment to be traced, while the remaining examples illustrate selected issues;
- ISO/TS 14048:2002: Environmental management – Life cycle assessment – Data documentation format [5].
- ISO/TR 14049:2012: Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis [7].

3.3. Calculators for Calculating CF

To facilitate the calculation of the carbon footprint, numerous supporting computer programmes have been developed, tailored to different users (ranging from individuals interested in their own households to more specialised tools for various sectors of the economy). Consequently, these tools differ in scope, calculation methodology, and access to various databases. Whereby, as demonstrated in [10], results obtained using different calculators within the same domain (e.g., for transport) can vary by up to 100%. Nevertheless, these are highly useful tools that contribute, among other things, to raising public awareness. At the same time, it is expected that initiatives undertaken within the EU and other countries will lead to the development of modified or new, coherent programmes for calculating environmental and carbon footprints.

4. Carbon Footprint Emitted by Means of Transport

Transport is a crucial sector of the economy, accompanying humanity since the dawn of civilisation, due to the necessity of moving people and goods. Unfortunately, this sector is considered one of the most harmful to the natural environment and health [26].

As shown in the data (Fig. 1), the predominant share (approximately 74%) of all greenhouse gases emitted by this sector is generated by road transport, primarily by passenger cars, buses, and commercial vehicles. In contrast, rail transport is the least emissive means of transport in the world. It accounts for 1% of transport emissions, or 0.2% of total GHG emissions. According to averaged statistical data from the Community of European Railways and Infrastructure (CER), the amount of CO_2 emitted per passenger per kilometre (passenger-kilometre, pkm) for various means of transport is as follows:
- for train: 28 g,
- for bus: 90 g,
- for car: 102 g,
- for aircraft: 244 g CO_2/pkm.

However, it is important to consider that an accurate calculation of the carbon footprint for each journey should also account for factors such as:
- for cars: age, size (weight), fuel type, driving speed, and traffic volume,

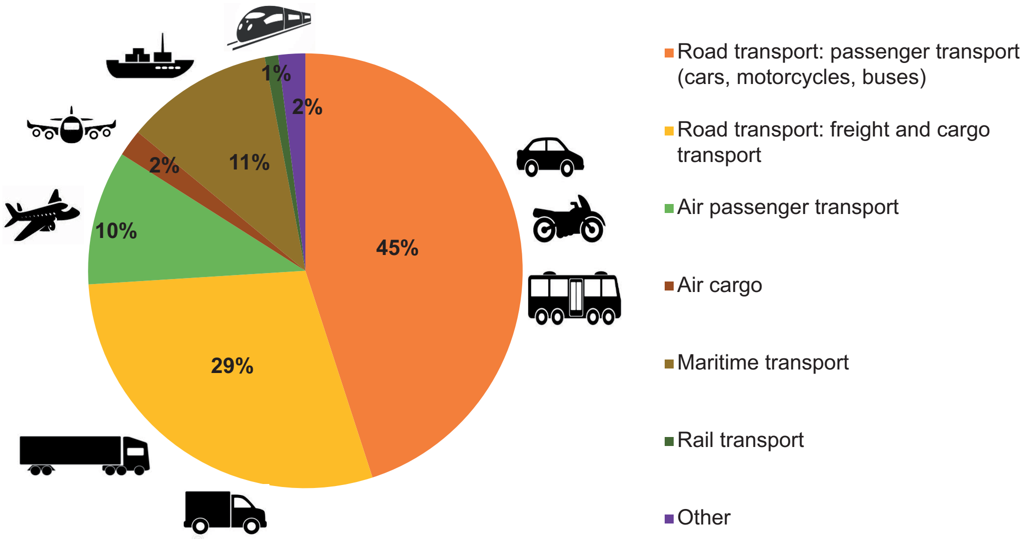

Fig. 1. Global greenhouse gas emissions per means of transport; developed by M. Łyszcz based on [24]

- for trains: the method of producing energy to power the trains (electric traction supplied by coal, nuclear, wind power plants, etc., diesel vehicles, hydrogen vehicles, or other alternative power sources) and travel speed.

For example, the French railway company SNCF reports that:
- TGV trains emit only 1.73 g CO_2/pkm,
- Intercity trains emit 5.29 g CO_2/pkm,
- Stopping trains emit 24.81 g CO_2/pkm.

Additionally, the use of low-emission nuclear energy and the high speed of TGV trains (averaging 320 km/h) allow the French carrier to claim that rail travel generates 50 times fewer emissions than car travel (with two passengers) and 80 times fewer emissions than air travel [23].

A comprehensive approach to calculating the CF indicator would also require incorporating the carbon footprint emitted during the production processes of the individual means of transport (taking into account emissions from the extraction of the individual raw materials, the manufacture of the components along with their transport to the vehicle manufacturer, emissions from the process of constructing the vehicles and putting them into service, as well as the construction of the road/airport infrastructure), thus providing a picture according to the cradle-to-gate method. On the other hand, the cradle-to-grave method necessitates the inclusion of emissions associated with the operation and disposal of means of transport. Figure 2 illustrates the sources of carbon footprint emissions for rail transport.

The UIC (*International Union of Railways*) undertook an attempt to determine the impact of railway infrastructure construction [3], as well as the construction of vehicles and infrastructure [2], on the carbon footprint of train travel.

As part of the assessment of the impact of railway infrastructure [3], the construction of 10 lines was analysed, differing in track type (ballasted and ballastless), number and size of stations, number, and length of tunnels and railway bridges, power supply, and railway traffic control systems. The data obtained from the simulations showed a particularly strong influence of tunnels and railway bridges on emissions levels. Data on the contribution of various technologies and their components, as well as the materials used, were also collected. However, it is important to note the limitations of the discussed study due to the use of different simulation tools and difficulties in obtaining complete input data, which were deemed confidential in some projects. Nevertheless, the information provided in [3] can be useful for the preliminary selection of available technological solutions in the design of low-emission infrastructure.

The authors of [2] analysed the carbon footprint of four new high-speed railway lines, two in France and two in Asia (China and Taiwan). Based on these data (in passenger-kilometres), it was shown that the carbon footprint of the High Speed railway line, including the construction phase, ranges from (3.7–4.3) g CO_2/pkm for lines in France and (6.0–8.9) g CO_2/pkm for lines in Asia. The study also presented calculations of environmental benefits resulting from the newly built LGV Mediterranée high-speed line. According to a detailed study, in 2004, 1.78 million passengers chose the LGV high-speed train, opting out of air travel to/from southern France.

This corresponds to a transport performance of 1,068 million passenger-kilometres. An additional

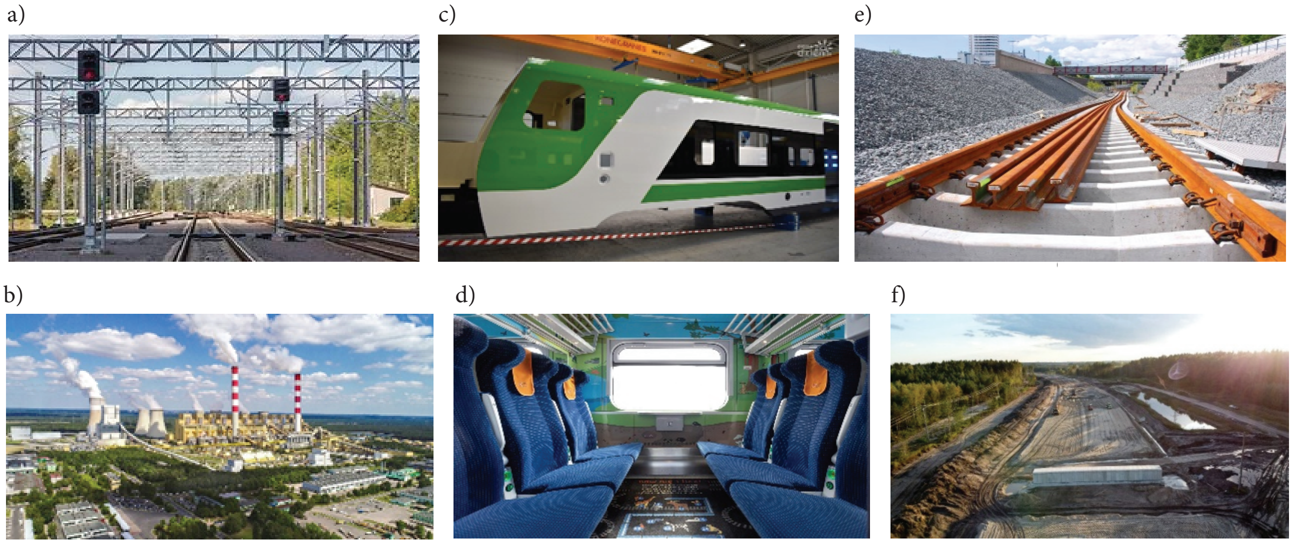

Fig. 2. Sources of greenhouse gas emissions from rail transport: a) construction of overhead lines, b) construction of power plants c) vehicle production d) rolling stock equipment e) construction of railway tracks f) construction of transport roads; developed by M. Łyszcz based on [27–31]

0.98 million passengers chose the train over the car. In this example, an emission factor of 91 g CO_2 per kWh and a load factor of 70% for LGV were applied. This makes it possible to estimate that the construction of LGV Mediterranée leads to an annual reduction of approximately 237,600 tonnes of CO_2. This example demonstrates that with the construction of new high-speed lines, countries can significantly reduce their carbon emissions in the field of transport.

Another solution that can contribute noticeably to reducing the carbon footprint is the development of intermodal and multimodal transport. In accordance with Directive 92/106/EEC [4], the predominant part of deliveries in intermodal transport should be carried out using rail, maritime, or inland waterway transport. Road transport should be used for the shortest possible distance – up to 150 km in maritime-road transport and up to 100 km in rail-road transport. Particularly advantageous solutions include the “rolling highway” (*Rollende Landstrasse*), where trucks and road vehicles are driven onto wagons (though this requires the construction of special loading ramps), and the *Piggy Back* variant. In the latter, semi-trailers and truck bodies are loaded by crane onto pocket wagons or via specialised rail wagons with rotating platforms, developed by a team from the Military University of Technology [12, 22, 25]. However, the development of intermodal transport in Poland (weakened since 2022 due to the war in Ukraine) requires the coordination of changes in road and rail transport, supported by various forms of financial assistance. These measures should also yield economic, social, and environmental benefits [1, 13, 21].

5. Conclusions

1. The fulfilment of obligations arising from the Paris Agreement and ongoing climate negotiations requires the implementation of environmental management systems and principles of sustainable development. These should become priority actions across all sectors of the economy.
2. The Life Cycle Assessment (LCA) has been recognised as the most universal tool for continuously measuring the carbon footprint (CF). This parameter, representing the total sum of greenhouse gas emissions caused directly or indirectly by a given entity, enables the measurement of the impact of products, services, and technologies on the natural environment in every sphere of human life and activity. It serves as a key decision-making tool in selecting the most advantageous solutions from among available alternatives, both economically and ecologically [11].
3. It is also desirable to introduce changes in the transport sector, particularly regarding means of travel. One potential solution is the intensive development of railway transport, with a special focus on night trains for international connections, which are regarded as an excellent alternative to air travel. This direction is already being pursued in Europe, as well as in China, which has impressively expanded its high-speed rail network over the past decade, creating 36,000 km of connections and recording 600 billion passenger-kilometres annually [24].
4. It is necessary to explore solutions that facilitate the development of intermodal and multimodal trans-

port, as well as to analyse the possibility of reintroducing the "rolling highway" initiative to reduce the carbon footprint emitted by road freight transport while simultaneously enhancing road safety.

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