

## Carbon footprint of rail vehicles

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### ABSTRACT

The article presents the essence of carbon footprint, defined as the sum of greenhouse gas emission, caused directly or indirectly by a person, organisation, product or event. Transport accounts for about 20% of global CO<sub>2</sub> emission, ranking third after the energy sector (40%) and industry (25%). Therefore, in the era of railway development, especially high-speed rail, the issue of CO<sub>2</sub> emission is of particular importance. High-speed vehicles require new, more durable materials, including composites, which generate a carbon footprint more than twice as large as that of steel. The carbon footprint of a rail vehicle is measured by the total amount of greenhouse gases emitted throughout its life cycle, generated by the product (i.e. a rail vehicle) from the extraction of raw materials to the end-of-life stage of that product. The system boundaries used in the analysis of the carbon footprint of a product may vary, as was demonstrated in this article using the example of train carriages. The most comprehensive scope is 'cradle-to-cradle', as this model of product design encompasses all aspects of a product life. The study showed that the use of this model in the manufacture of new carriages decreases the carbon footprint four-fold. The paper presents the collected and processed data regarding CO<sub>2</sub> emission according to events, which indicates that the largest CO<sub>2</sub> emissions occur within Scope 3 – other indirect emissions that concern activity throughout the entire value chain, e.g. transport products and processes, material production or even business travel, which account for 75–85% of total emissions. CO<sub>2</sub> emissions are presented for different life-cycle stages of a vehicle and types of vehicles, as well as for construction materials used in the production of rail vehicles, including tram and metro carriages.

**Keywords:** carbon footprint, rail vehicles, carbon footprint assessment models, CO<sub>2</sub> emissions of rail vehicles.

### INTRODUCTION

Every product, (machine, device, building) undergoes four key phases in its life cycle, starting with design, production, operation and recycling. In addition to the operational stage, which is the longest, the design stage is crucial, as it determines the key characteristics of a product. The following characteristics are distinguished: geometric, material, dynamic, reliability, durability, safety and environmental. Today, when ecological concerns are gaining strategic importance in the life of man, the environmental characteristic has become a decisive competitive advantage.

The term 'ecology' derives from the Greek word *oikos* – 'living area', 'household', 'environment' and *lógos* – 'word', 'mind', 'study', 'knowledge'. Ecology is therefore the science that

examines the structure and functioning of nature at various levels of organisation. Broadly speaking, ecology is the study of order and disorder in nature and the consequences resulting from this order and disorder for the existence of biosphere and humans [1]. In the context of transport-related (mechanistic) issues, ecology is understood primarily as the impact on the environment of human habitat through pollution: noise, vibrations, exhaust gases, particulate particles, etc.

Science and the world, including various international and non-governmental organisations (such as Greenpeace, WWF and Friends of the Earth International) play a key role in addressing global environmental challenges. Particular attention should be given to the International Union for Conservation of Nature (IUCN). It is

a membership union comprising governments and civil society organisations. It harnesses the experience, resources and reach of more than 1,400 member organisations, and the input of over 17,000 experts. This variety and tremendous knowledge make the IUCN a global authority on the natural world status and resources necessary for its protection [2, 3].

Scientific research and studies have shown that human activity and greenhouse gas emissions should be blamed for global warming. Industry and its dynamic growth accounts for over 70% of global CO<sub>2</sub> emissions. As major emitters, companies bear the responsibility for reducing their carbon footprint. Given a significant contribution of industry to climate change, enterprises must take concrete steps to reduce greenhouse gas emissions.

Rail vehicles are a key element of sustainable transport, and their design and operation require both energy optimisation and CO<sub>2</sub> reduction. This paper analysed the carbon footprint of rail vehicles, including materials and processes used in their manufacture, operation, and recycling. The paper presents Scope 3 CO<sub>2</sub> emission data – indirect emissions across activity in the entire value chain, e.g. transport products and processes, material production emissions, or even business travel, which make up about 80% of total CO<sub>2</sub> emissions of rail vehicles.

The majority of existing studies focuses on the analysis of railway infrastructure, traction energy emissions, or comparisons of rail transport with other modes of transport. The railway rolling stock; especially electric, diesel, and hybrid locomotives, lacks systematic studies and data regarding their carbon footprint that would cover the full life cycle from raw material production, through operation, to recycling and reuse of materials (cradle-to-cradle). Existing studies tend to consider high-speed rail only [5, 6, 7].

The main objective of this research was to present the mechanisms of carbon footprint generation in the transport sector using rail vehicles as an example, as well as to identify opportunities for emission reduction. The study employed the following research methods: analysis of research material using literature review, internet resource studies, documentation analysis, calculation and analysis of data obtained from industrial enterprises. To estimate the carbon footprint of rail vehicles a bottom-up approach based on process data was used. This method involves summing up all individual emissions from individual process

or product stages, from raw materials to decommission. It is calculated by multiplying the amount of each material used or activity performed by its corresponding emission factor (activity × emission factor) and adding up the results. This is a detailed approach used, among others, in life-cycle assessment (LCA) to calculate the product carbon footprint (PCF) [8].

## ESSENCE OF CARBON FOOTPRINT

A carbon footprint is the total amount of greenhouse gas emission caused directly or indirectly by an individual, organisation, even or product [9]. It is a type of ecological footprint. Carbon footprint encompasses the emission of carbon dioxide, methane, nitrous oxide and other greenhouse gases, expressed in units of carbon dioxide equivalent CO<sub>2</sub>e. The measure of carbon footprint is CO<sub>2</sub>e – a tonne of carbon dioxide equivalent. Various greenhouse gases have varying global warming potentials, whereas carbon dioxide equivalent allows for a comparison of various gases on a common scale. For example, one tonne of methane has the same impact as approximately 25 tonnes of CO<sub>2</sub>e.

The carbon footprint over the life cycle of a product is measured as the total amount of greenhouse gases emitted by the product, from extraction of raw materials to the end of its life cycle. It is expressed in carbon dioxide equivalents (CO<sub>2</sub>e). The carbon footprint of products should be related to the scope or boundaries (Figure 1). The common system boundaries are [10]:

- cradle-to-gate; typically used for business-to-business (B2B) products. It measures total emission of greenhouse gases from extraction of raw material, through production, up to the gate of the enterprise,
- cradle-to-grave; generally applied to business-to-consumer (B2C) products. It measures total emission of greenhouse gases from extraction of raw materials to production, distribution, use and final disposal of the product,
- cradle-to-cradle; a model of product design that considers all aspects of its life. It focuses on sustainable environmental and social development of the invention in five key areas: material health, material reuse, renewable energy and carbon management, responsible water management and social fairness, as well as the implementation of a circular economy (CE).

The carbon footprint, representing the total of greenhouse gas emissions over a full life-cycle of an individual, is expressed in carbon dioxide equivalent (CO<sub>2</sub>e) and is one of key indicators of the impact of human activity on the environment.

The carbon footprint of a product is the amount of greenhouse gas emissions that are associated with the production, transport, use and disposal of that product. Calculating this measure allows assessing the environmental influence of a product and enables customers to make informed, eco-friendly choices.

Water footprint measures the amount of water used or polluted. It defines the amount of water used directly or indirectly. Water is used directly to drink, wash-up, wash, clean. Water can also be used indirectly, it is so-called ‘virtual water’, necessary for the production of food, goods and services for the society.

Material footprint is the total quantity of biotic (e.g. plants) and abiotic (e.g. minerals) resources, extracted at each stage of the life cycle of products or services.

Ecological footprint, a tool used to assess the environmental impact of a product or enterprise (regardless of their size or industry). It helps compare similar products based on their environmental efficiency.

Carbon footprint, along with water and material footprint, is also an element of environmental (ecological) footprint. In other words, it analyses humanity’s demand for natural resources. In this case, human consumption of natural resources is compared to the ability of our planet to regenerate them. Environmental footprint is the estimated number of hectares of land and sea area, necessary to compensate for the resources consumed and the absorption of waste. It is measured in global hectares (gha) per person.

The United Kingdom was the first country to calculate carbon footprint for both products and organisations. Initially, British companies decided to calculate the value of the carbon footprint,

and subsequently – having a measurable indicator – they reduced their emissions and monitored progress in this aspect. Today, enterprises around the world, including those in Poland, undertake to calculate the carbon footprint for various reasons. Currently, market exerts the pressure on companies to do it. Entrepreneurs who cooperate with international companies (especially with UK-based firms), are required to calculate the carbon footprint for their activities or products [13, 14].

## ORIGIN OF CARBON FOOTPRINT

Carbon footprint in the world comes from various sectors, each contributing to the emission of greenhouse gas emissions to a different extent. According to verified data and reports, the division of global carbon dioxide emissions by sector is as follows [15]:

- energy sector (power plants, heating, production of electricity) – 35–40%. This is due to the combustion of fossil fuels (coal, oil, gas) in power plants and heating plants. Historical changes in CO<sub>2</sub> emission are shown in Figure 2.
- industry – about 25%; CO<sub>2</sub> emissions are primarily associated with cement, steel, chemical and plastic production, since industrial processes require large amounts of energy,
- transport – 15–20%; road transport has the largest share in CO<sub>2</sub> emissions, followed by air, maritime and rail transport,
- agriculture and land use –15–20%; it is related to livestock farming (methane emission), deforestation (the loss of natural CO<sub>2</sub> sinks), production of fertilisers and soil degradation,
- building construction and operation – 5–10%; emissions originate from heating, air conditioning of buildings, lighting and production of construction materials,
- natural sources – trace amounts of CO<sub>2</sub>; they are a result of natural emissions, e.g. volcanoes, decaying vegetation, oceans. However, forests,



Figure 1. Boundaries of the carbon footprint of a product [11, 12]

vegetation, soils and oceans act as significant carbon sinks, absorbing large amounts of CO<sub>2</sub>.

Historical changes in CO<sub>2</sub> concentration [based on 4]:

- about 50 million years ago CO<sub>2</sub> concentration increased to 1.600 ppm, resulting in a temperature increase by 12 °C,
- during the Mesozoic era, 65 million years ago, CO<sub>2</sub> concentration was 16 times higher than today,
- during the Pliocene Epoch, 3 million years ago, CO<sub>2</sub> levels were similar to those observed today.

Increase in CO<sub>2</sub> concentration during the Industrial Era:

- since the beginning of the Industrial Era in the 18th, century CO<sub>2</sub> concentration has increased by 50%,
- by the mid-20th century, CO<sub>2</sub> emissions had reached about 5 gigatonnes per year,
- by the end of the 20th century, CO<sub>2</sub> emissions had exceeded 35 gigatonnes per year.

Current increase in CO<sub>2</sub> concentration:

- since 1880 CO<sub>2</sub> concentration has risen by approximately 99 ppm,
- in the last 25 years, humanity has emitted as much carbon dioxide as between the beginning of the Industrial Revolution and the 1980s.

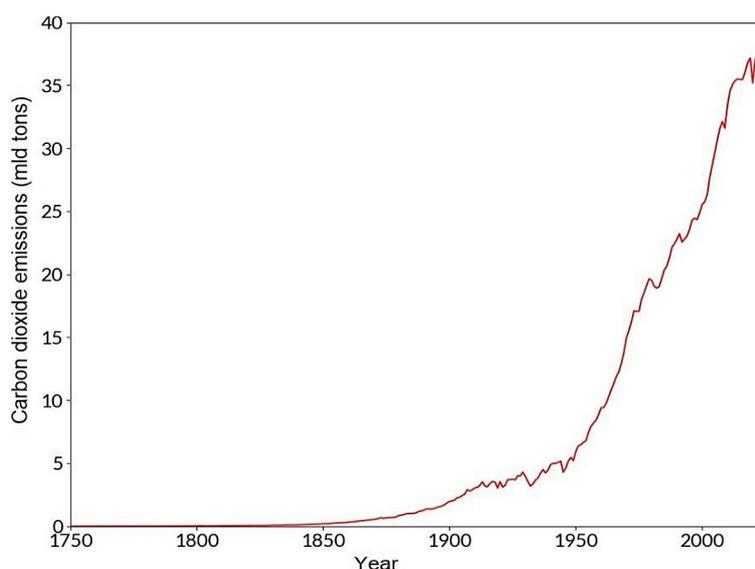
Historical changes in CO<sub>2</sub> emission are shown in Figure 3.

According to recent global data, carbon dioxide emissions from the combustion of fossil fuels continue to grow, contributing to global warming. In 2025, the CO<sub>2</sub> emissions reached a record level of 37.5 billion tonnes, representing a 1% increase compared to 2021. In 2024, CO<sub>2</sub> emissions from fossil fuels totalled approximately 37.4 billion tonnes [11].

Nature emits enormous quantities of carbon dioxide (CO<sub>2</sub>) through natural processes, but also absorbs nearly equivalent amounts, maintaining an approximate carbon balance under natural conditions. Unfortunately, this balance, due to human activity, is beginning to be disturbed. Natural sources of CO<sub>2</sub> emission include [8]:

- respiration of living organisms – about 60 gigatonnes of CO<sub>2</sub> per year, emitted by vegetation, animals, microorganisms and humans through cellular respiration.
- decomposition of organic matter– about 220 gigatonnes of CO<sub>2</sub> per year; dying plants, trees and microorganisms decompose, releasing CO<sub>2</sub>.
- volcanoes – approximately 0.3-0.4 gigatonnes of CO<sub>2</sub>, per year eruptions and volcanic activity release CO<sub>2</sub>, but in relatively small amounts compared to other sources,
- oceans – roughly 330 gigatonnes of CO<sub>2</sub> per year, emitted during natural gas exchange but also acting as major carbon sinks.

In total, nature emits about 750 gigatonnes of CO<sub>2</sub> annually. However, it also absorbs almost as much CO<sub>2</sub> through:



**Figure 2.** Changes in carbon dioxide emissions from the combustion of fossil fuels between 1751–2012 – the black line; the light grey line represents an exponential function, growing at a rate of 2.8% per year (i.e. doubling every 25 years) [16]

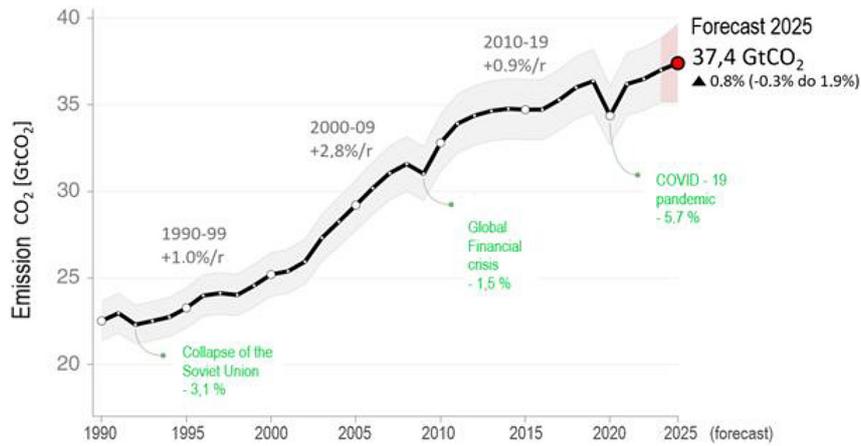


Figure 3. Changes in the carbon dioxide emission coming from fossil fuel combustion between 1990–2024 [11]

- photosynthesis of plants and phytoplankton – about 450 gigatonnes of CO<sub>2</sub> per year,
- oceanic absorption – about 300 gigatonnes of CO<sub>2</sub> per year.

In total, nature absorbs 750 gigatonnes of CO<sub>2</sub> per year, which means that in the natural state that system was balanced.

Currently, however, human activity adds about 40 gigatonnes of CO<sub>2</sub> per year, mainly from fossil fuel combustion and deforestation. Nature is unable to absorb this surplus, leading to an accumulation of CO<sub>2</sub> in the atmosphere and climate.

### PRODUCT CARBON FOOTPRINT GENERATION

Product Carbon Footprint (PCF) is the measure of total emission of greenhouse gases (GHG),

generated by a given product at all stages of a product lifespan. It enables identification of most emission-intensive phases of the life cycle and the implementation of actions aiming at their reduction. GHG are the gases that transmit most solar radiation (the so-called short-wave radiation) reaching the Earth. Figure 4 presents the phases of product carbon footprint generation [4, 9].

Research has allowed distinguishing the daily life areas that have the greatest influence on greenhouse gas emissions. These are: mobility, food and housing (including emissions related to building construction and energy use). Mobility emissions (transport) account for about 24% of all greenhouse gas emissions in Poland [16]. About two-thirds of these emissions come from passenger transport, which means significant potential for emission reduction through changes in mobility methods. Therefore, one of key elements of the reduction of

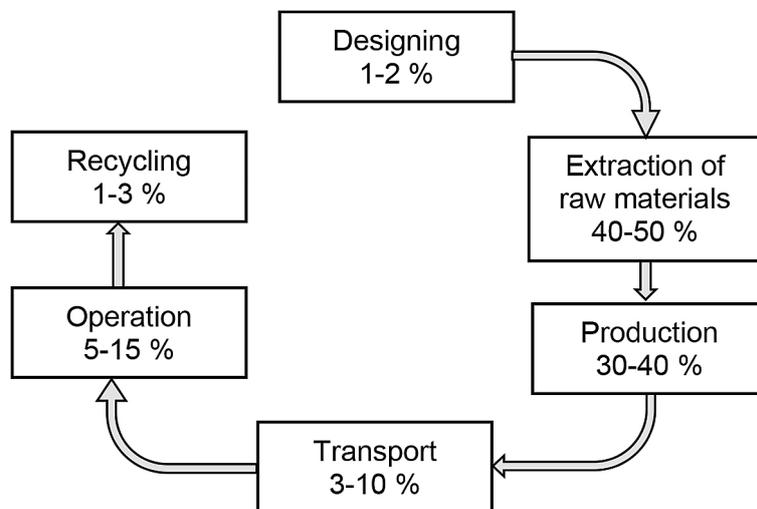


Figure 4. Phases of the carbon footprint generation of a product [4]

greenhouse gas emission is the change in mobility methods and designing vehicles that generate the lowest possible carbon footprint.

As it was mentioned before, the most important stage of a product lifespan is the design stage, during which construction features are determined, including: geometry, material, dynamic, reliability, durability, safety, and environmental. A detailed description of concepts related to design and construction is given by Dietrych [17]: ‘An engineering work is characterised by the process of constructing, the process of designing a product as an artificial material system. The direct product of this process is a special type of creation – a construction...’. A vital element of the construction process is the choice of construction features. Geometric, material and dynamic construction features are distinguished. In the summary, Dietrych says: ‘The basic definition of a construction is the following statement. A construction is a system of limits for the allowable states of a product, determined by a set of features with regard to a specific effect’. Many publications use the term ‘design’, which according to the definition above is ‘the process of designing a product as an artificial material system’.

According to the descriptions of the concepts considered, the subject of designing could be a machine, process, feature etc. – in other words something that is designed, but which does not have to be realisable. On the other hand, the subject of construction is a specific structure for which construction features are determined (geometric, material and dynamic). Therefore, this subject must be physically realisable [18].

The process of conceiving a product as an artificial material system, i.e. designing, should be directed at considering pro-environmental features and calculating carbon footprint of products.

Cradle to cradle – a model of product design that takes into account all aspects of its life. The name relates to the assumption of ‘cradle to grave’ design, where ‘grave’ is replaced with another ‘cradle’, to demonstrate the essence of a circular economy. The main assumption of ‘cradle to cradle’ is designing and manufacturing products for its widest possible use, including after the end of its life, minimising negative effects of production and maximising the positive impact on the environment and people’s health.

The cradle to cradle products should be recyclable after their use in a closed loop within one of two cycles: technological and biological. In the

first cycle, materials are reused to manufacture new products. In the biological cycle, it is of key importance to process materials so that they can be used as e.g. fertiliser.

Cradle to cradle is a set of five rules a company should follow, if they want to introduce this model in their activity:

- health safety – all materials must obtain a positive assessment in criteria regarding the environment and human health.
- drive to reuse as many materials as possible. They may be used as treatment components in industrial production (technical zone) or fertiliser (biosphere).
- use of renewable energy.
- responsible and effective water management.
- acting with care for employees and social responsibility in the entire value chain.

From the perspective of minimising the environmental impact of a product and reducing its carbon footprint, it is important to calculate the carbon footprint within the cradle-to-cradle scope, that is by using a form of Circular Economy and the concept of Industry 4.0.

One of the basic concepts of Industry 4.0 is sustainable design and manufacture, according to which higher effectiveness indicators must be accompanied by environmental protection. Therefore, in industry 4.0, the reduction of time, resources and energy necessary to manufacture a given unit are key environmental aspects.

## ANALYSIS OF THE CARBON FOOTPRINT OF PRODUCTS

The basis for carbon footprint analysis is the family of ISO 14060 norms [8], which ensures clarity and consistency for quantifying, monitoring, reporting and validating or verifying emissions and removals of GHG in order to support sustainable development through a low-carbon economy. It is also beneficial for organisations, designers and stakeholders worldwide by ensuring clarity and consistency for quantifying, monitoring, reporting and validating or verifying emissions and removals of GHG. The use of ISO 14060 leads to (Figure 5):

- higher environmental integrity for quantifying GHG;

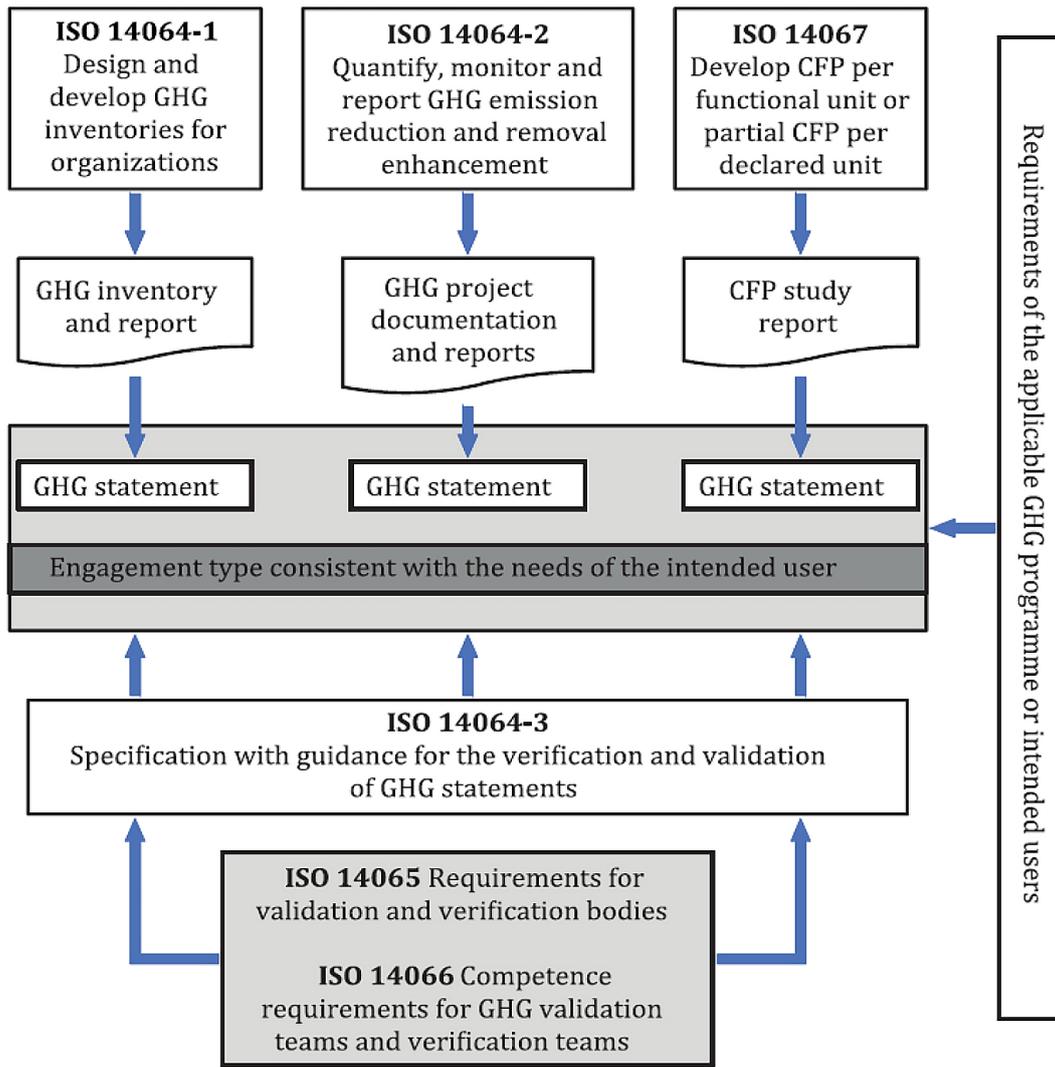


Figure 5. Relationship between the family of ISO 14060 standards regarding greenhouse gases [8]

- increased reliability, consistency and clarity for quantifying, monitoring, reporting, validating and verifying GHG;
- enhanced development and implementation of strategies and plans of GHG management;
- facilitated development and implementation of neutralising activities through reduction of emissions or improvement in removal;
- facilitates tracking efficiency and progress in reduction of greenhouse gases and/or increase of GHG removal.

ISO 14067:2018 standard: Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification [8] shows rules or calculating and the use of PCF (product carbon footprint), as well guidelines for communication and PCF qualification. The standard aims at, among others:

- defining requirements for methods connected with PCF,
- facilitating identification of sources and tracking GHG emissions,
- creating consistent and effective PCF information procedures for all sides concerned,
- facilitating assessment of different variation of designing products and methods of their production, starting with the choice of raw materials, to the choice of manufacturing technologies, to assessment of recycling in order to improve the strategies of GHG planning and management in the whole life-cycle of a product, as well as identification of potential ‘savings’ in the whole chain of delivery,
- increasing reliability of PCF communication and providing information that enables consumers to make conscious purchase decisions of products and their impact on GHG emissions.

To facilitate the calculation of the product carbon footprint (PCF) numerous software tools have been developed for various users – both business entities and households. For an accurate analysis of the carbon footprint, every stage of the life cycle of a product must be identified and the corresponding emission sources must be assigned to each of them. Every process – from extraction of raw materials, through transport, production to disposal – should be thoroughly documented, and emissions generated as a result should be recorded. At present, such a requirement applies companies in the energy, industry and transport sectors.

### CARBON FOOTPRINT OF A RAIL VEHICLE

Designing the structure (a rail vehicle) with minimal carbon footprint requires a holistic approach, including [19, 20]:

- analysis of life-cycle of materials (LCA – life cycle assessment) – assessment of CO<sub>2</sub> emission, from extraction of raw materials, through production, operation to recycling,
- optimisation of material use – structural weight reduction through smart design and use of modern materials and technologies,
- choice of low carbon footprint materials – use of low-carbon steel, plastics, wood and other certified construction components,
- energy-saving production processes – minimisation of energy use and waste at the stage of production,
- module designing and recycling – ease of dis-assembly and reuse of components.

Table 1 presents the values of density, tensile strength and CO<sub>2</sub> emissions for the production of 1 kg of materials used in the construction of rail vehicles. Steel is low-cost and has moderate CO<sub>2</sub> emission, aluminium is lighter, but more emissive, while carbon fibre offers the best strength, but generates the highest CO<sub>2</sub> emission. Composites allow for the balance between mass and emission. Analysis of CO<sub>2</sub> emission should cover the following scopes of events in the carbon footprint calculation:

- Scope 1 (direct emissions): emissions generated directly as a result of activity, e.g. fuel combustion in vehicles, boilers, during manufacturing and production processes.
- Scope 2 (indirect emissions from energy): emissions from the consumption of electricity, heat or cooling provided by suppliers.
- Scope 3 (other indirect emissions): emissions related to the activity in the entire value chain, e.g. products and transport processes, emissions from material production or even business travel.

Table 2 presents CO<sub>2</sub> carbon footprint share according to the scopes presented above [21, 22]. The highest carbon footprint – 75 to 85% comes from Scope 3. It is generated primarily by key deliverers of material, components and subsets production for vehicles, e.g. combustion engines, compressors, etc. Table 3 presents the division of CO<sub>2</sub> emission (carbon footprint) for individual stages of the life cycle of a vehicle [23,24]. Calculation of CO<sub>2</sub> emissions (carbon footprint) in various phases of the life cycle of a rail vehicle should include the following components:

**Table 1.** Example data on materials used in the construction of rail vehicles [19]

Material	Density (kg/m <sup>3</sup> )	Tensile strength (MPa)	CO <sub>2</sub> emission (CO <sub>2</sub> /kg)
Steel	7.850	400–550	2.00
Aluminium	2.700	200–300	8.10
Carbon fibre	1.600	3.000–6.000	25.00
Composite	1.500-2.000	500–1500	5.00
Old materials (e.g. cast iron)	7.200	150–300	2.50

**Table 2.** Division of CO<sub>2</sub> emissions according to scope of events [21, 22]

Scope of events	Share in total carbon footprint of a vehicle in %
Scope 1 – direct emissions	10–15%
Scope 2 – indirect emissions from purchased energy	5–10%
Scope 3 – other indirect emissions	75–85%

**Table 3.** Division of CO<sub>2</sub> emission by the life cycle of a vehicle [23, 24]

Stage of life cycle	Share in total carbon footprint of a vehicle in %
Material and component production	40–50%
Making payments	5–10%
Use (fuel and/or energy consumption by vehicle operators)	40–50%
Service and maintenance	3–5%
Recycling and end of life cycle of a vehicle	2–5%

a) Production of a vehicle:

- extraction (steel, aluminium, copper, composites) – calculation of emission related to their extraction and processing,
- production and manufacturing (engines, braking systems, electronics, etc.),
- transport of parts and components to production plants,
- production process – energy consumption in the plant and generation of production waste.

b) Operation of the vehicle:

- energy use – emissions resulting from energy consumption (depending on whether the energy comes from renewable sources or fossil fuels),
- maintenance and repairs – replacement of faulty components, lubrication, use of consumables,
- operating conditions (loads) – carbon footprint per passenger-kilometre.

c) Disposal and recycling:

- disassembly and material sorting,
- recycling or storage – emissions of substances from the use of metals and plastics (production of one tonne of prime steel generates on average about 2.0 tonnes of CO<sub>2</sub>, whereas recycled steel generates 0.6 tonne of CO<sub>2</sub>).

Carbon footprint generated by individual types of rail vehicles is presented in Table 4. Average CO<sub>2</sub> emissions in the production of individual types of rail vehicles are presented in Table 5.

The largest carbon footprint is generated by Diesel locomotives and passenger electric multiple units. However, the number of Diesel locomotives has a falling tendency.

Since the largest carbon footprint comes from Scope 3 – 75–85% (Table 2), Table 6 presents indirect emissions from the production and processing of materials used in the construction of rail vehicles.

**Table 4.** Average CO<sub>2</sub> emissions for rail vehicles [own elaboration based on 25, 26, 27, 28, 29]

Type of rail vehicle	Carbon footprint in production (tCO <sub>2</sub> /vehicle)	Carbon footprint in use (gCO <sub>2</sub> /pkm*)	Total carbon footprint in life cycle (tCO <sub>2</sub> )
Electric train (RES)	500–1.500	5–10	3.000–5.000
Electric train (EU energy mix)	500–1.500	30–50	4.000–7.000
Combustion engine train (Diesel)	500–1.500	80–120	6.000–10.000
Tram/metro (electric, RES)	100–500	5–15	500–2.000

**Note:** \* pkm – passenger-kilometre.

**Table 5.** Average CO<sub>2</sub> emissions for types of rail vehicles [own elaboration based on 25, 26, 27, 28, 29]

Type of rail vehicle	Production carbon footprint (tCO <sub>2</sub> /vehicle)
Passenger train (electric multiple unit)	500–1 500 tonnes of CO <sub>2</sub>
Passenger train (Diesel multiple unit)	500–1 600 tonnes of CO <sub>2</sub>
Freight train (electric locomotive)	600–1 500 tonnes of CO <sub>2</sub>
Freight train (Diesel locomotive)	700–1 800 tonnes of CO <sub>2</sub>
Passenger carriages	50–300 tonnes of CO <sub>2</sub>
Freight carriages	30–200 tonnes of CO <sub>2</sub>
Tramway	100–500 tonnes of CO <sub>2</sub>
Metro	200–600 tonnes of CO <sub>2</sub>

The design of a minimal carbon footprint structure requires a pro-ecological and holistic approach that encompasses:

- Life cycle assessment of CO<sub>2</sub> emission, from the extraction of raw materials, through production and use, to recycling,
- Optimisation of material use – the reduction of the structure weight through smart design and the application of innovative technologies,
- Selection of low-carbon footprint materials – use of low-emission steel, low-emission concrete, certified construction timber,
- Energy-efficient production processes – minimisation of energy and waste consumption during the production stage,
- Modular design and recycling – ease of disassembly and reuse of components.

As it was mentioned in this paper, the design is a crucial stage of the life cycle of a product. During this stage, it is necessary to consider the features listed above, as well as the recyclability

of a product, including the use of appropriate recycling symbols on the structural components of the vehicle (Table 6). Recycling worn-out components of rail vehicles will significantly reduce the carbon footprint over their life cycle.

Below are examples of the carbon footprint reductions achieved for selected construction materials used in rail vehicles [30, 31]:

- Steel;
  - primary production – 1.9 to 2.5 CO<sub>2</sub>e/kg,
  - recycled steel – 0.3 to 0.7 CO<sub>2</sub>e/kg,
  - emission reduction 60–85%.
- Aluminium;
  - primary production – 8 to 12 CO<sub>2</sub>e/kg,
  - recycled steel – 0.5 to 1 CO<sub>2</sub>e/kg,
  - emission reduction to 95%.
- Copper;
  - primary production – 3 to 5 CO<sub>2</sub>e/kg,
  - recycled steel – 0.4 to 1 CO<sub>2</sub>e/kg,
  - emission reduction to 80%.
- plastics, depending on the type and recovery quality – reduction 30 to 70%. (Figure 6).

**Table 6.** Average CO<sub>2</sub> emissions for individual construction materials for rail vehicles [own elaboration based on 25, 26, 27, 28, 29]

Material	Average CO <sub>2</sub> e emission (kg CO <sub>2</sub> e/t)	Average material use (t/ vehicle)	CO <sub>2</sub> e emissions (t CO <sub>2</sub> e)
Construction steel	1.800–2.500	50–150	90–375
Stainless steel	5.000–6.000	10–30	50–180
Aluminium	10.000–12.000	5–20	50–240
Plastics	3.000–6.000	1–10	3–6
Glass	1.000–1.500	0.5–5	0.5–7.5
Copper (wires, electronics)	4.000–5.000	1–5	4–25
Batteries (tramways, hybrid trains)	60,000–80,000		



**Figure 6.** Symbols used in recycling [31]

## Example

According to the Polish Statistical Yearbook, in 1990 the Polish State Railways operated 89,940 freight carriages. By 2000, this number had decreased to 66,370 carriages, meaning 23,570 carriages were withdrawn [32]. In 2023, the number of freight carriages rose again to 83,497 – an increase of 17,127 carriages. Assuming an average weight of 20 tonnes per freight carriage, and that the 17,127 new carriages were produced using primary steel production, the resulting carbon footprint (assuming 2.0 tonnes of CO<sub>2</sub>e) would be approximately 34,254 tonnes of CO<sub>2</sub>e. However, if the decommissioned carriages removed from service by 2000 were recycled, the carbon footprint (assuming 0.6 tonnes of CO<sub>2</sub>e) would amount to approximately 10,276 tonnes of CO<sub>2</sub>e. Using recycled steel from old carriages in the production of new ones would therefore result in a CO<sub>2</sub>e emission reduction of around 70%.

## CONCLUSIONS

The article presented the essence of carbon footprint, defined as the total amount of greenhouse gas emissions, directly or indirectly caused by a person, organisation, product or event. Transport accounts for about 20% of total CO<sub>2</sub> emission, ranking third after energy (40%) and industry (25%). Therefore, in the era of railway development, especially high-speed rail, the issue of CO<sub>2</sub> emission is of great significance. High-speed vehicles require new, more durable materials, particularly composites, which generate carbon footprint almost twice as high as that of steel.

The product carbon footprint of a rail vehicle is measured by the total greenhouse gas emissions generated by the product from the extraction of raw materials to the end of its life. The boundaries adopted in life cycle carbon footprint analyses vary, as shown in the article using the example of rail carriages. The most comprehensive scope is cradle-to-cradle – a model of product design that includes all aspects of its life cycle. The article demonstrates that applying this model to the production of a new carriage can reduce the carbon footprint fourfold.

The paper presented the collected and calculated data on CO<sub>2</sub> emission by event, indicating that the largest share of CO<sub>2</sub> emissions concern Scope 3 – other indirect emissions related to

activities across the entire value chain, e.g. transport products and processes, material production or even business travel – 75–85% (Table 2). CO<sub>2</sub> emissions are also presented for individual stages of the life cycle of a rail vehicle and types and categories of vehicles, and for the construction materials used in the manufacture of rail vehicles, including tramways and metro cars.

Designing a new rail vehicle structure with a minimal carbon footprint requires a comprehensive approach that includes material selection, efficient production processes, and recycling strategies. The example of using recycled steel from decommissioned carriages to manufacture new one shows that the carbon footprint can be reduced by about 75%, along with lower energy and mineral resource consumption and less environmental degradation resulting from raw materials extraction.

- using the cradle-to-cradle model in rail vehicle design and executing a full product life cycle, including production, use, and recycling, can reduce emissions by a factor of four, providing significant environmental benefits,
- recycling is key to reducing CO<sub>2</sub> emissions. Using recycled materials, such as steel from dismantled railcars, can significantly reduce the carbon footprint of new vehicles. This approach can reduce the raw material consumption, the waste, and support the circular economy strategy, which is consistent with global sustainability trends.

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