

Article

Locomotives vs. Heavy Road Freight Vehicle Combinations: A Case Study of the Energy Intensity and WTW CO₂e Emissions of Freight Transport

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Abstract

This study quantifies, based on real-world operational measurements, the energy intensity and greenhouse gas emissions of selected vehicle types in rail and road freight transport on the Brno–Břeclav corridor. Measurements were conducted on several generations of electric locomotives, one upgraded diesel locomotive, and two heavy road freight vehicle combinations. Energy flows were converted to a common basis, and both energy intensity and greenhouse gas emissions were assessed on a well-to-wheel (WTW) basis. Unlike many previous studies, this research focuses on a comparison of specific, currently operated vehicles rather than on an aggregated comparison of transport modes. The results reveal substantial differences not only between rail and road freight transport, but also within rail traction itself, where pronounced differences were identified among individual locomotive generations. At the same time, they confirm that, even when diesel traction is used, rail freight transport remains more energy-efficient and exhibits lower greenhouse gas emissions than heavy road freight vehicle combinations, both per gross and per net tonne-kilometre. Overall, the findings indicate that the environmental performance of freight transport is determined not only by the transport mode itself, but also by vehicle technology, traction type, and the structure of transport performance.

Keywords: energy intensity; greenhouse gas emissions; freight transport; well-to-wheel

1. Introduction

Optimizing the energy and emissions intensity of freight transport is an urgent issue, yet its broad-based implementation is constrained primarily by the differing infrastructure conditions across countries. The efficiency of individual transport modes is determined by many factors, such as the composition and age of the vehicle fleet, the share of electric traction, and route/line profiles, as well as the energy mix and the way in which energy is generated. This study provides a data-driven perspective on the energy and emissions intensity of rail and road transport along a corridor where a motorway section and a railway line run in parallel. The analysis covers commonly used vehicle types in long-distance road and rail freight transport, for which both energy consumption and CO₂e emissions were assessed using a WTW approach that accounts for operational impacts as well as the impacts of producing the energy consumed by the investigated vehicles.

Transport is a key element of the functioning of society and the economy, and the quality of life of the population is closely linked to its efficiency and accessibility; at



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the same time, transport is among the three most significant sources of greenhouse gas emissions, together with the energy sector and the metallurgical industry [1]. Road and rail freight transport form the backbone of European logistics; however, their energy and emissions efficiency is not universally fixed and depends on specific technical and operational parameters. Comparative studies show that the results are sensitive to the applied methodology, local conditions, and the selection of input data [2]. Transport is one of the major factors affecting the environment and contributing to climate change. Globally, transport accounts for approximately 23% of energy-related CO₂e emissions; total sectoral emissions reached almost 8 Gt CO₂ in 2022, and energy-related emissions continued to increase in 2023 [3]. In the European Union, transport accounted for approximately 28.9% of total greenhouse gas emissions in 2022, of which road transport represented 73.2%, maritime and inland waterway transport 14%, and aviation 11.8%, while rail accounted for only 0.4% [4]. Climate change and the growing environmental burden fundamentally affect both the economy and quality of life in Europe. Transport accounts for approximately 31% of final energy consumption, making it a key sector for decarbonization and for identifying opportunities to improve energy efficiency. Current policy frameworks from the Paris Agreement to the European Green Deal underscore the need for rapid emissions reductions, including in heavy freight transport, which is the most emissions- and energy-intensive part of the system [5].

The importance of this topic is also evident from the modal structure of freight transport in the European Union and in the Czech Republic. In 2024, road transport accounted for 78% of inland freight transport performance in the EU, while rail transport represented 17% and inland waterways 5%. A similar structure can also be observed in the Czech Republic, where road freight transport accounted for 78.0% and rail freight transport for 21.1% of total freight transport performance in the same year [6]. These figures confirm the dominant position of road freight transport and, at the same time, the continued relevance of rail freight transport in the European and Czech freight markets.

Technological progress in road vehicles has led to reductions in specific fuel consumption and local emissions. Estimates of the potential for further improvement by 2030 confirm that fleet modernization can significantly reduce energy use and emissions in long-haul road freight transport. This is driven in particular by advances in powertrains, aerodynamic refinements of both tractor cabs and trailers, and the adoption of low-rolling-resistance tyres [7]. Case studies conducted in the rail sector indicate that actual environmental advantages are determined not only by the transport mode itself, but primarily by the composition and age of the vehicle fleet. Real-world data from Slovakia showed that, where older diesel locomotives account for a large share of operations, rail freight can exhibit higher specific NO_x and PM emissions than modernized road transport. However, rail remains more favourable in terms of greenhouse gas emissions, particularly when electricity is generated with a low emissions intensity [8].

The environmental benefits of an electrified railway system are closely tied to the composition of the national electricity mix. If electricity is generated from fossil fuels, for example coal, the resulting greenhouse gas emissions may be only slightly lower than those of diesel-powered trains. By contrast, in countries with a high share of renewables and low-emission electricity generation, rail transport achieves a substantially lower carbon footprint [9]. Electric rail traction can deliver substantial reductions in greenhouse gas emissions, particularly as electricity generation shifts toward a clean power mix. Electrified rail has low direct emissions; however, its WTW emissions remain strongly dependent on the share of fossil fuels in electricity production [10].

Despite the growing importance of alternative energy sources, transport energy demand is still largely met by petroleum products, primarily gasoline, diesel fuel, and jet

kerosene. This is particularly evident in freight transport, where heavy road vehicles, despite representing a relatively small share of the overall vehicle fleet, account for a substantial share of energy consumption and emissions, as they are virtually entirely dependent on diesel fuel. In contrast, rail transport exhibits markedly lower energy intensity per unit of transport work, especially in countries where electric traction predominates and where the electricity mix enables reductions in overall emissions [11]. Significant differences in the energy intensity of road and rail transport are driven not only by the technical parameters of the vehicles, but also by operational factors, particularly payload, capacity utilization, and route topography [12].

The well-to-wheel methodology is widely used to assess the energy and emissions intensity of transport. It divides the energy life cycle into a well-to-tank stage covering extraction/production, processing, and distribution of fuels or electricity and a tank-to-wheel stage, i.e., the energy consumed by the vehicle during operation. This distinction enables the evaluation of energy use and greenhouse gas emissions across the entire supply chain, rather than considering vehicle operation alone. In the European context, WTW is anchored primarily in a consortium whose Version 5 systematically compares fuel–powertrain combinations and, for the first time, extends the analysis to heavy-duty road vehicles [13].

According to the latest data from the European Environment Agency, transport accounted for 28.9% of total greenhouse gas emissions in 2022, confirming the persistently high contribution of this sector to overall emissions [4]. Beyond greenhouse gas emissions, transport affects quality of life through noise exposure and also contributes to land take and landscape fragmentation due to the expansion of transport infrastructure [14].

In the European Union, the transport sector accounts for approximately 31% of total final energy consumption. Road transport is the largest energy consumer, accounting for 74% of total transport energy use [15]. The transport energy mix in Europe remains strongly dependent on petroleum products, which account for more than 90% of the energy consumed in road transport. Specifically, in 2021, oil and petroleum products supplied 90% of energy demand in the transport sector overall, and 92% in road transport in particular [16]. At the same time, transport is the only major economic sector in the European Union in which greenhouse gas emissions have not been successfully reduced over the long term, whereas other sectors have recorded substantial emission declines since 1990 [4].

In 2022, the largest share of greenhouse gas emissions in the Czech Republic came from the energy sector (35%), followed by industry (21%) and transport (17%). In the most recent reporting year, 2024, total transport-related CO₂e emissions amounted to 22.839 Mt, with road transport accounting for the largest share among all transport modes [17].

Building on the above findings, this study aims to compare the energy intensity and greenhouse gas emissions burden of selected vehicle types in rail and road freight transport. In rail freight, the study compares several generations of electric locomotives, complemented by an upgraded diesel locomotive; in road freight, two heavy road freight vehicle combinations commonly found in the European fleet were selected. The calculation of energy and emissions intensity also includes CO₂e emissions from energy production, enabling a more accurate, real-data-based assessment. The study's conclusions may serve as supporting evidence when selecting the most suitable transport vehicle not only on the corridor examined.

In the scientific literature, transport emissions are often reported either as carbon dioxide (CO₂) emissions or as emissions expressed in carbon dioxide equivalent (CO₂e). While CO₂ constitutes the dominant share of transport-related greenhouse gas emissions, the CO₂e metric also captures other greenhouse gases with different global warming

potentials, most notably nitrous oxide (N₂O) and methane (CH₄), thereby providing a more comprehensive view of the climatic impacts of transport processes. This study therefore evaluates the results using the CO₂e indicator within a WTW framework, which enables a consistent and methodologically robust comparison of the energy and emissions requirements of the assessed transport alternatives.

Although previous research has demonstrated that the energy and emissions performance of freight transport is strongly affected by methodological, technical, operational, and energy-related factors [2,8,12,13], an important empirical gap remains in the assessment of vehicle-level variability. Existing modal comparisons and WTW-based approaches provide a necessary framework for evaluating freight-transport energy use and emissions, but they do not always capture how the results may change when the assessment is applied to specific vehicles. This study therefore addresses the following research questions: (RQ1) What differences in WTW energy intensity and CO₂e emission intensity emerge when freight transport is assessed at the level of specific rail and road vehicles? (RQ2) What variation in energy and emission intensity is observed across vehicles differing in generation, traction type, and transported mass? By answering these questions, the study contributes to a more detailed interpretation of freight-transport energy and emissions performance within the examined case study.

2. State of the Art

Rail transport is among the most energy-efficient and environmentally benign modes of transport. It is associated with low emissions and, compared with road transport, reduces other adverse impacts on the surrounding environment [18]. The energy intensity of freight transport has long confirmed the higher efficiency of rail compared with road transport; according to [19], the average energy consumption of rail freight transport ranged from 0.4 to 0.6 MJ/tkm, whereas road freight transport reached 1.5 to 2.0 MJ/tkm [19]. A recent study by [20] reports that the energy intensity of rail freight transport is approximately 0.2 MJ/tkm [20], whereas the energy intensity of road freight transport is around 1.05 MJ/tkm [21]. Rail freight transport achieves an average energy intensity of approximately 0.22 MJ/tkm, with values around 0.30 MJ/tkm for diesel traction and approximately 0.14 MJ/tkm for electric traction [21]. Rail transport exhibits lower energy and environmental burdens than road and air transport, with the operational phase and the source of the energy used being key determinants of sustainability [22]. Energy consumption in combined transport varies by route and logistical conditions: of nineteen routes examined, eight achieved energy savings of up to 20%, six achieved savings between 20 and 40%, and two exceeded 40% compared with road-only transport; conversely, three routes showed up to 15% higher primary energy consumption due to low load factors or inefficient route connections [23]. Rail transport is the most energy-advantageous, primarily due to the higher efficiency of electric traction, approximately 90%, whereas the efficiency of internal combustion engines in road transport reaches only about 40% [24]. According to a U.S. macroeconomic model, fleet renewal and the introduction of emissions standards gradually reduce transport-related emissions, while climate policy that increases emission charges can encourage a shift in part of freight movements from trucks to rail [25]. A WTW-based study found that, under comparable conditions, rail, particularly when operated with electric traction, exhibits the lowest energy and emissions intensity per tonne-kilometre, whereas road transport shows the highest. The results are strongly influenced by capacity utilization, transshipments, and route profile; therefore, it is necessary to assess real transport options rather than transport modes alone [26]. The EcoTransIT World methodology in a WTW setting provides a harmonized framework for calculating energy use and emissions per tonne-kilometre across modes, incorporating key parameters and distinguishing between

electric and diesel rail, and it enables the conversion of energy consumption into CO₂ using national emission factors [27]. Sassine's study compared phosphate transport by trucks and diesel trains and developed a model for transport using electric traction on a specific route, finding that electric rail is the most energy-efficient and the most advantageous in terms of emissions, and recommending electrification of the corridor despite the high upfront costs [28]. Transport contributes substantially to total greenhouse gas emissions, with freight transport accounting for the predominant share; without additional policies, freight-transport emissions would increase by 2050 from approximately 2.5 to 3.7 Mt CO₂ [29]. The environmental advantage of electric traction strongly depends on how electricity is generated; in countries with a high share of fossil fuels in the energy mix, rail transport has higher emissions than in countries with a higher share of renewable sources [30]. Electric traction supplied with low-emission electricity has a substantially lower indirect carbon footprint than traction in countries with a strong share of fossil fuels in the power mix [31]. An LCA-based assessment of emissions from rail and road freight transport conducted on the route between Kırşehir and Niğde-Ulukışla in Turkey showed that a full shift from highway to rail would reduce total CO₂ emissions from 2092.93 t to 444.66 t, representing a reduction of approximately 79%, and the impact on ecosystem quality would decrease from 100% to 14.6% [32]. Most emission-assessment models focus only on environmental aspects, while economic and social dimensions are often neglected; for a comprehensive sustainability assessment, it is necessary to integrate LCA, LCC, and SLCA methods [22]. A study by IRU and IFEU found that combined transport can reduce CO₂ emissions by 20–50% on seven routes and by more than 50% on six routes compared with road-only transport; however, the efficiency of the rail leg depends on the electricity mix [23]. Rail transport has a substantially lower carbon intensity than road transport, and shifting part of road freight to rail can reduce total sector emissions by 25–35% [28]. The structure of the vehicle fleet has a fundamental influence on the environmental burden of individual transport modes, particularly in terms of vehicle age and the traction technology used. Under certain conditions, modern road vehicles can achieve lower emissions than rail transport, mainly due to faster technological development and more frequent fleet renewal [8]. The use of renewable energy sources, such as wind and solar, or alternative fuels, such as hydrogen and biodiesel, can reduce emissions and increase energy efficiency [33]. An LCA-based comparison of road and rail freight transport shows that the vehicle use phase accounts for approximately 70% of total CO₂ emissions, confirming that tailpipe emissions alone underestimate the true emissions burden because they omit, for example, vehicle manufacturing and end-of-life processes, which represent a substantial share of total emissions [34]. Lee and Stoeltje showed that emissions from food transport depend on transport distance, logistics routing and vehicle operating conditions: their road-network-based model estimated 2,719,898 kt-km and 274 kt CO₂ in Texas, approximately 5.7% more than calculations based on straight-line distance, with emissions concentrated on specific road classes, routes and segments where infrastructure condition, congestion, lower speeds and frequent stops affect vehicle operation [35]. Palamutçuoğlu et al. [36] examined sustainable logistics through the capacity-constrained vehicle routing problem and showed that CO₂-based route optimization can reduce emissions compared with distance-based routing, with the proposed genetic algorithm reducing emissions by up to 4.0%; vehicle load, speed, acceleration, road slope and traffic conditions were identified as key operational factors [37].

3. Methodology

For the purposes of energy balances and internationally comparable statistics, it is necessary to convert all energy data into a common energy unit. The energy balance

therefore has to use a single common energy unit: electricity is converted from kWh to MJ, and liquid fuels are converted from volume to MJ using density and the lower heating value [35]. In energy balances, the commodity balances of individual energy carriers are first compiled in their natural units, and the items are subsequently converted to a common energy basis, in this research to MJ. The conversion of liquid fuels from volumetric or mass units is performed by multiplying by product-specific net calorific values (NCV/LHV), whereas electricity is converted using the standard relationship 1 kWh = 3.6 MJ. This expresses energy flows from different fuels on the same energy basis, enabling consistent comparison and subsequent normalization to the same units [38].

Within the WTW assessment of energy intensity, it is also necessary to account for the energy inputs associated with fuel production, transport, refining, blending, and distribution. For diesel fuel with a biofuel admixture, 1 MJ of final fuel requires approximately 1.25 MJ of primary energy, of which 1 MJ is contained directly in the fuel itself. The additional upstream energy input therefore amounts to approximately 0.25 MJ per 1 MJ of diesel fuel [39]. For electricity, the WTW energy assessment was based on an electricity conversion factor of 2.7 applicable to the Czech Republic, as reported by [40]. According to this approach, 1 MJ of electricity consumed corresponds to approximately 2.7 MJ of primary energy equivalent [40]:

1. For diesel traction: The lower heating value of diesel fuel is 43 MJ/kg, and the density of diesel fuel is $\rho = 0.84 \text{ kg/L}$ [41]. The energy content in joules for 1 L of diesel fuel is $0.84 \times 43 \times 10^6 \times 1.25 = 4.515 \times 10^7 \text{ J} = 45.15 \text{ MJ/L}$.
2. For electric traction: $1 \text{ kWh} = 3.6 \text{ MJ} \times 2.7 = 9.72 \text{ MJ} = 9.72 \times 10^6 \text{ J}$.

3.1. Procedure for Calculating Energy Intensity

To calculate the energy intensity of electric traction, the following equation was used:

$$E_{tkm}^{el} = \frac{E_{in} \times 3.6 \times 2.7}{m \times d}$$

where

- E_{tkm}^{el} is energy intensity of electric traction [MJ/gtkm];
- E_{in} is total traction energy drawn [kWh];
- 3.6 is conversion factor [MJ/kWh];
- 2.7 is electricity conversion factor;
- m is train/consist mass [t];
- d is distance traveled by the train/consist [km].

To calculate the energy intensity of diesel traction, the following equation was used:

$$E_{tkm}^{diesel} = \frac{V \times \rho_{diesel} \times LHV_{diesel} \times 1.25}{m \times d}$$

where

- E_{tkm}^{diesel} is energy intensity of diesel traction [MJ/gtkm];
- V is total volume of diesel fuel consumed [L];
- ρ_{diesel} is density of diesel fuel [kg/L];
- LHV_{diesel} is lower heating value of diesel fuel [MJ/kg];

- 1.25 is WTW correction factor;
- m is train/consist mass [t];
- d is distance traveled by the train/consist [km].

3.2. Procedure for Calculating Greenhouse Gas Emissions Intensity

Greenhouse gas emissions were calculated in accordance with the IPCC methodology for fuel combustion in transport vehicles. This approach applies to all transport equipment using internal combustion engines, i.e., both road vehicles and rail traction. The amount of emissions is directly proportional to fuel consumption and its heating value, as carbon dioxide is formed through the oxidation of carbon contained in the fuel. Under the IPCC methodology, complete oxidation of carbon is assumed for mobile combustion, i.e., an oxidation factor of 1.0, meaning that virtually all carbon is converted to CO₂. This assumption is supported by the fact that, in modern internal combustion engines, incomplete combustion is negligible, typically accounting for less than 1%. CO₂ emissions can therefore be reliably derived from the amount of fuel consumed, its heating value, and the relevant emission factor [42].

To ensure full comparability of diesel traction with electric traction where emissions are commonly assessed on a WTW basis, it is necessary to extend the assessment beyond direct CO₂ emissions from fuel combustion and also account for emissions arising across the entire fuel supply chain, expressed in carbon dioxide equivalent (CO₂e). For diesel traction, similarly to electric traction, reporting typically includes only direct emissions from fuel combustion (tank-to-wheel), not the emissions associated with fuel production (well-to-tank). To enable an objective comparison with electric traction, it was therefore necessary to also consider emissions generated during crude oil extraction, transport, and refining into diesel fuel. According to the JEC Well-to-Wheels v5 study, emissions from diesel production and distribution amount to approximately 18.6–18.9 g CO₂e/MJ, corresponding to roughly 0.67 kg CO₂e per liter of diesel. These must be supplemented by emissions from fuel combustion, which reach approximately 2.6–2.7 kg CO₂e per liter [13]. It was further taken into account in the calculation that diesel fuel commonly distributed in the Czech Republic complies with the EN 590 standard in the B7 class and contains a 7% biofuel component, which reduces the resulting emission factor. The total emission factor for diesel therefore amounts to approximately 3.15 kg CO₂e per liter of diesel consumed [43].

To calculate the CO₂e emissions per tonne-kilometre for diesel traction, the following equation was used:

$$I_{\text{diesel}}^{\text{CO}_2\text{e}/\text{tkm}} = \frac{V \times EF_{\text{WTW}} \times 1000}{m \times d}$$

where

- $I_{\text{diesel}}^{\text{CO}_2\text{e}/\text{tkm}}$ is the CO₂e emissions intensity of diesel traction per tonne-kilometre [g CO₂e/tkm];
- V is total volume of diesel fuel consumed on the assessed section [L];
- EF_{wtw} is the total well-to-wheel emission factor for diesel fuel [kg CO₂e/L];
- 1000 is conversion factor from kilograms to grams [g/kg];
- m is train/consist mass [t];
- d is distance traveled by the train/consist [km].

Electric propulsion is often presented as zero-emission; however, for an objective comparison of powertrains, it was necessary to also include emissions arising not only during energy conversion, but also during energy production, which is captured by an

emission factor. The electricity emission factor expresses the amount of greenhouse gas emissions, in carbon dioxide equivalent (CO₂e), generated during electricity production. In the Czech Republic, the calculation of the emission factor is defined by the methodology of the Ministry of Industry and Trade, which is based on IPCC international standards. Since the origin of the electricity used by electric locomotives is not known and the operator draws electricity from the grid without declared guarantees of origin, the emission factor of the residual electricity mix is used to calculate CO₂e emissions. This approach ensures a realistic representation of emissions associated with electricity consumption of unknown origin. According to the aggregated energy balance of the Czech Republic, the electricity emission factor in 2024 was 0.42 t CO₂e/MWh [44]. ISO 14083:2023 reports a global reference value for electricity of 97 kg CO₂e/GJ, i.e., approximately 0.349 t CO₂e/MWh [39]. In the European Union, the average carbon intensity of electricity generation in 2024 was approximately 0.213 t CO₂/MWh [45].

To calculate the CO₂e emissions per tonne-kilometre for electric traction, the following equation was used:

$$I_{el}^{CO_2e/tkm} = \frac{E_{in} \times EF_{el} \times 1000}{m \times d}$$

where

- $I_{el}^{CO_2e/tkm}$ is the CO₂e emissions intensity of electric traction per tonne-kilometre [g CO₂e/tkm];
- E_{in} is total traction energy drawn on the assessed section [kWh];
- EF_{el} is electricity emission factor [kg CO₂e/kWh];
- 1000 is conversion factor from kilograms to grams [g/kg];
- m is train/consist mass [t];
- d is distance traveled by the train/consist [km].

Because the study assessed vehicles powered by different traction energy sources, namely electricity and diesel in the case of locomotives and diesel only in the case of road haulage, it was necessary to normalize the units. The functional unit for energy intensity is MJ/gtkm, or MJ/ntkm when the assessment is related to the net mass of the payload. For the emissions comparison, the functional unit is g CO₂e/gtkm, or g CO₂e/ntkm. The consist masses used for the calculations are therefore first expressed as the total gross mass of the consist, and the results are subsequently recalculated also per net mass of the transported cargo. This dual perspective is crucial for interpreting differences between rail and road transport, as evaluation per gross tonne-kilometre makes it possible to compare the energy and emissions intensity even for transport systems that differ structurally, expressing the energy and emissions intensity relative to the actually transported mass of the consist in a given trip.

4. Data

For the comparison of energy intensity and greenhouse-gas emission intensity between rail and road transport, the study selected railway line Nos. 251/252 from Brno to Břeclav and the parallel section of the D2 motorway. The rail measurements started at Brno-Maloměřice railway station, at an elevation of 210 m a.s.l. (49.2211656 N, 16.6501800 E), and ended at Břeclav railway station, at an elevation of 160 m a.s.l. (48.7534158 N, 16.8934081 E). The road freight transport measurements started in Brno near the Futurum shopping center, at an elevation of 205 m a.s.l. (49.1574306 N, 16.5989981 E), continued for approximately 2 km along the D1 motorway, and then followed the D2 motorway to the exit near Břeclav,

at an elevation of 165 m a.s.l. (48.7835525 N, 16.9252833 E). The railway route follows a double-track electrified line with a maximum line speed of 160 km/h. The road route follows a motorway with two traffic lanes in each direction and a maximum permitted speed of 130 km/h. To improve the objectivity and comparability of the assessment, the 10 km segment was selected as a supplementary measurement to complement the full-corridor analysis on corresponding sections with a comparable gradient profile, enabling a more detailed comparison over a shorter section. For the segment-level measurement, the Vranovice, at an elevation of 177 m a.s.l. (48.9657478 N, 16.6034397 E), to Šakvice, at an elevation of 187 m a.s.l. (48.9119711 N, 16.7084697 E), section was selected for the railway, and the Blučina, at an elevation of 187 m a.s.l. (49.0610831 N, 16.6675981 E), to Starovice, at an elevation of 198 m a.s.l. (48.9748967 N, 16.7019519 E), section was selected for the motorway.

The entire line is electrified with 25 kV, 50 Hz AC, and along almost the whole section the highest maximum speed permitted for trains in the Czech Republic is allowed, i.e., 160 km/h. The Břeclav–Modřice section is equipped with the most advanced train protection system, ETCS, and is controlled from the central dispatching workplace in Přerov. The entire Břeclav–Brno–Maloměřice section is fitted with automatic block signaling with code transmission to the onboard part of the train protection system installed on the traction vehicles.

The D2 motorway runs from Brno to Lanžhot, where, at the Brodské border crossing between Lanžhot and Kúty, it seamlessly continues into the Slovak section of the D2 motorway. The Slovak D2 then extends for a further 80 km before connecting, at the Čunovo border crossing, to Hungary's M1 motorway. The Czech D2 motorway is 61 km long and has four lanes along its entire length. Running parallel to the motorway is the accompanying regional road II/425. Apart from the terminal interchanges at the start and end of the section, the motorway has only four exits, with the longest spacing between them being 16 km.

For the purposes of the measurements, several generations of locomotives were selected. The first was the Class 193, introduced into service in 2011, followed by the Class 183, in service since 2005. The final electric locomotive included in the measurements was the Class 189 Eurosprinter, in service since 2002. Diesel traction was represented by the Class 753.7; this locomotive was originally manufactured in 1968 and underwent a major retrofit in 2001, including replacement of the engine with a more fuel-efficient and environmentally friendly unit. For the road-transport measurements, two heavy road freight vehicle combinations were chosen, namely a MAN TGX tractor–semitrailer combination (in service since 2015) and a Renault Trucks K rigid truck with trailer (in service since 2014). The selected vehicles are representative of the vehicle types that have been operated on the studied corridor and have been present in significant numbers in freight transport in the Czech Republic over the long term. Table 1 presents the technical parameters of the monitored vehicles relevant to the research.

Table 1. Technical parameters of the monitored vehicles.

Vehicle Type	Year Introduced	Power	Weight	Max. Speed
Electric locomotive 193	2011	6400 kW	89 t	230 km/h
Electric locomotive 183	2005	6400 kW	87 t	230 km/h
Electric locomotive 189	2002	6400 kW	87 t	140 km/h
Diesel locomotive 753.7	2002	1344 kW	72 t	100 km/h
Renault Trucks K	2014	360 kW	11.8 t	85 km/h
MAN TGX	2015	412 kW	9.3 t	90 km/h

For the electric locomotives, traction electricity consumption was read from onboard electricity meters integrated into the vehicles. The Siemens Class 189 and the Class 183 locomotives used the onboard energy meter LEM/EMH EM4TII+, which enables measurement of both drawn and regenerated energy. During the research, however, regenerative braking was not used and was therefore not included in the study's energy balance, because its use could not be ensured consistently across all locomotives and operating situations. The meter operates across both AC and DC traction power systems and stores values in load profiles. The measurement is carried out in accordance with the requirements of EN 50463, and the device complies with railway environmental conditions pursuant to EN 50155 [46]. The Class 193 locomotive was equipped with an onboard electricity meter integrated within the Energy Measurement System EGM-3000/CEGM-3000, which enables measurement of electricity consumption as well as feed-in across all common traction power systems in accordance with the requirements of EN 50463; the system is designed for the operating conditions of rail vehicles pursuant to EN 50155 and, with respect to electromagnetic compatibility, complies with EN 50121-3-2; the measured values are archived in data records and are available for subsequent evaluation of consumption over defined sections of the run [47].

Fuel consumption (diesel) in vehicles equipped with internal combustion engines was measured using fuel flow meters (locomotives) and by reading data from the onboard units of the monitored road freight vehicles. The onboard unit collects data on the quantity of injected (consumed) fuel from the injectors, most commonly in mg or mg per injector stroke, and subsequently converts these values, based on the number of injections, engine speed, and vehicle speed, into l/100 km. Modern control units and sensors operate with an accuracy of 1–3%. The accuracy and suitability of this approach to fuel consumption measurement for the purposes of this article were also verified by the authors in the article Fuel Consumption and Information Systems, published in *Truck&business* [48].

For the Class 753.7 diesel locomotive, fuel consumption was determined based on data from the onboard diagnostic system of the Caterpillar 3512B internal combustion engine. The locomotive is equipped with the Caterpillar Fuel Consumption Monitoring System, which uses a pair of flow sensors installed on the supply and return fuel lines; fuel consumption is calculated as the difference between the delivered and returned fuel quantities and is further processed by the engine control unit. Unlike the electric locomotives, this is not a standalone certified measuring system but an integral part of the onboard internal combustion engine system that provides fuel-consumption data [49].

For the Renault Trucks K and MAN TGX heavy goods vehicles, fuel consumption was read from the onboard computers; these vehicles were not equipped with separate external fuel flow meters installed specifically for consumption measurement, as fuel-consumption determination in these heavy-duty vehicles is implemented directly within the design of the powertrain and its electronic control system. The engine control unit derives fuel consumption by calculation based on fuel-injection control parameters and provides these data as operational and diagnostic variables communicated via the CAN bus [50]. For the purposes of consumption evaluation, standardized signals defined by the FMS/SAE J1939 interface are used in practice, in particular variables such as instantaneous fuel consumption and cumulative fuel consumption, which are intended for analytical and computational purposes within fleet management systems [51].

For the calculation of net mass, the tare weight of the wagons was deducted from the total train mass. These tare-weight values were taken primarily from wagon documentation records. Where such records were not available, the author recorded the tare weight of each wagon individually, summed these values, and subsequently deducted the resulting total from the gross consist mass stated in the official train braking report.

For each vehicle, five runs were performed; for the main quantification, the run whose energy intensity corresponded to the median value was subsequently selected from these five runs. Data collection and the measurements themselves were carried out during 2023–2024. All locomotive measurements were conducted personally by one of the authors, who works as a train driver, while during the truck measurements the same author was present in the driver’s cab. The total number of runs carried out for the purposes of the research was higher than the five runs finally reported for each vehicle; however, only runs that met the predefined acceptance criteria were retained for the evaluation. Runs affected by substantial operational disruptions, such as extraordinary traffic restrictions, accidents, interrupted journeys, or other non-standard events, were excluded and repeated where necessary. The measurements were conducted over a longer period because the author established strict criteria for their acceptance, in particular the requirement for a smooth run without stops or any more substantial operational restrictions. For this reason, a considerable proportion of runs in which the course of the journey was disrupted due to traffic conditions were not included in the evaluation, and these measurements were subsequently repeated. None of the accepted measurement runs was conducted under weather conditions that deviated substantially from ordinary operating conditions; no run affected by extreme or clearly atypical weather was included in the evaluated dataset. At the same time, the measurements were conducted on identical regular transport routes. Within the railway measurements, the monitored services consisted of unit trains with typologically consistent train formations on each transport relation. Differences in the measurements and in the mass parameters of the consists resulted from operational circumstances or technical condition, which could slightly affect the number of wagons included and, consequently, the total train weight. Even where the number of wagons remained unchanged, minor deviations in total mass could occur due to the use of a different but typologically similar wagon. In road transport, the mass of the vehicle combinations did not vary and remained constant because they were loaded to the maximum permissible weight in accordance with their respective weight limits. All measurements were carried out exclusively in the direction from Brno to Břeclav in order to maintain an identical gradient profile of both the railway line and the motorway and thereby achieve the highest possible degree of objectivity.

The distances traveled, the masses of the transported vehicle combinations, and the energy consumption of the investigated vehicles, evaluated both for the entire monitored section and within the segment measurement, are summarized in the following tables, separately for each vehicle.

Table 2 and Figure 1 present the individual measurement runs for locomotive 193.

Table 2. Individual measurement runs for locomotive 193 (own source).

Locomotive 193	Distance Traveled	Electricity Consumption Total	Electricity Consumption Segment	Gross Consist Mass
1. run	66 km	901 kWh	170 kWh	2136 t
2. run	66 km	914 kWh	173 kWh	2209 t
3. run	66 km	886 kWh	166 kWh	2064 t
4. run	66 km	949 kWh	177 kWh	2312 t
5. run	66 km	918 kWh	171 kWh	2196 t

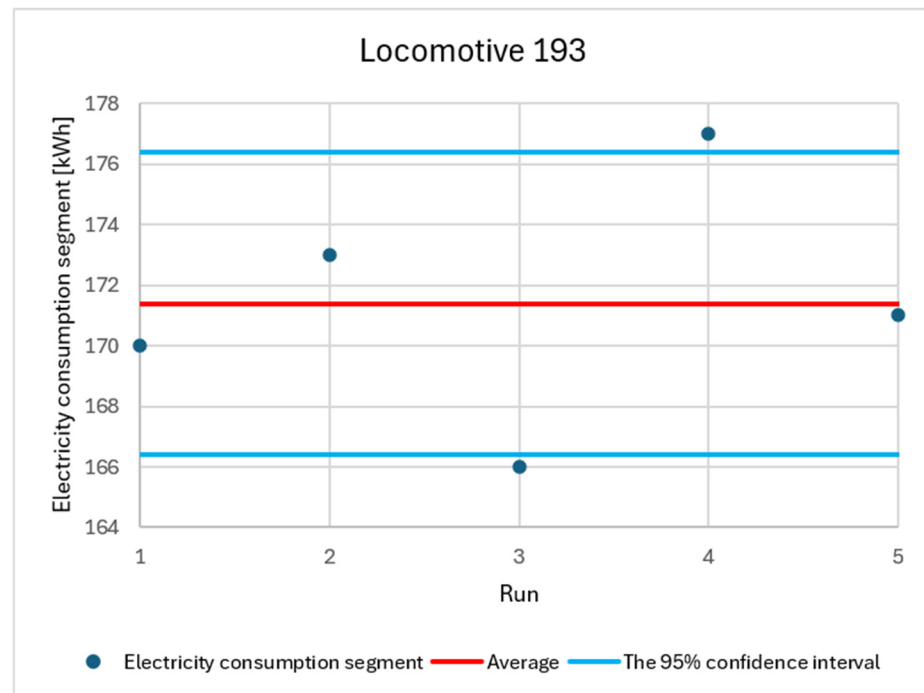


Figure 1. Individual measurement runs for locomotive 193 (own source).

Table 3 and Figure 2 present the individual measurement runs for locomotive 183.

Table 3. Individual measurement runs for locomotive 183 (own source).

Locomotive 183	Distance traveled	Electricity Consumption Total	Electricity Consumption Segment	Gross Consist Mass
1. run	66 km	670 kWh	120 kWh	1116 t
2. run	66 km	706 kWh	126 kWh	1179 t
3. run	66 km	663 kWh	118 kWh	1102 t
4. run	66 km	673 kWh	121 kWh	1119 t
5. run	66 km	666 kWh	119 kWh	1112 t

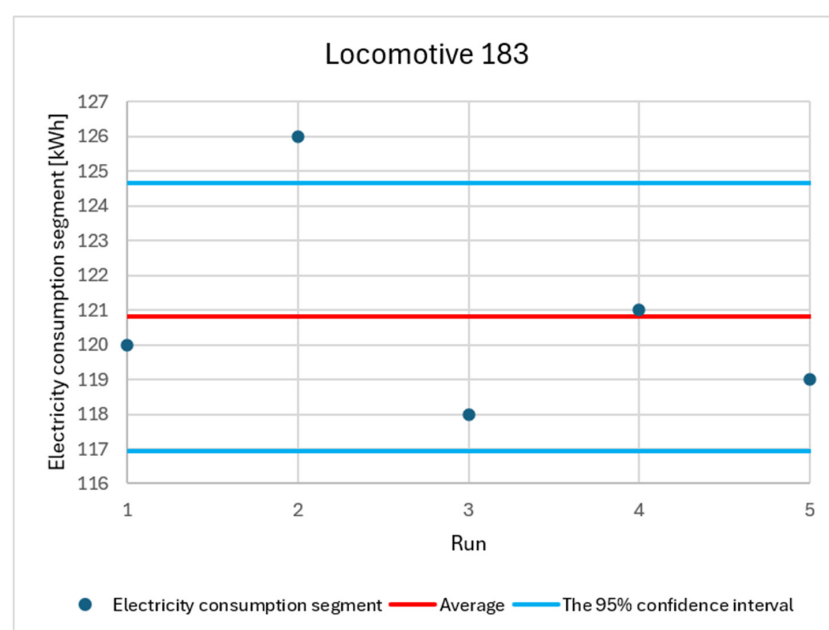


Figure 2. Individual measurement runs for locomotive 183 (own source).

Table 4 and Figure 3 present the individual measurement runs for locomotive 189.

Table 4. Individual measurement runs for locomotive 189 (own source).

Locomotive 189	Distance Traveled	Electricity Consumption Total	Electricity Consumption Segment	Gross Consist Mass
1. run	66 km	1498 kWh	251 kWh	1872 t
2. run	66 km	1463 kWh	246 kWh	1831 t
3. run	66 km	1563 kWh	261 kWh	1935 t
4. run	66 km	1510 kWh	254 kWh	1880 t
5. run	66 km	1558 kWh	263 kWh	1926 t

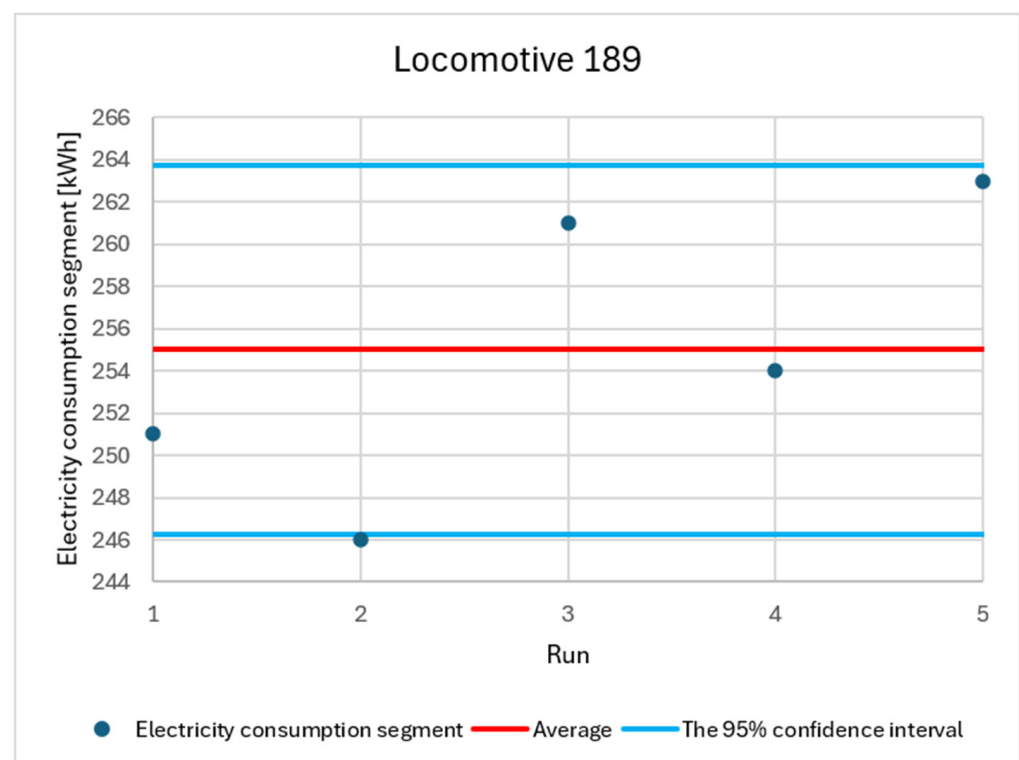


Figure 3. Individual measurement runs for locomotive 189 (own source).

Table 5 and Figure 4 present the individual measurement runs for locomotive 753.7.

Table 5. Individual measurement runs for locomotive 753.7 (own source).

Locomotive 753.7	Distance Traveled	Fuel Consumption Total	Fuel Consumption Segment	Gross Consist Mass
1. run	66 km	290 L	58 L	1257 t
2. run	66 km	288 L	57 L	1254 t
3. run	66 km	304 L	61 L	1301 t
4. run	66 km	289 L	56 L	1255 t
5. run	66 km	291 L	59 L	1259 t

Table 6 and Figure 5 present the individual measurement runs for the MAN TGX truck.

Table 6. Individual measurement runs for the MAN TGX truck (own source).

Truck MAN TGX	Distance Traveled	Fuel Consumption Total	Fuel Consumption Segment	Gross Consist Mass
1. run	51 km	14.7 L	2.6 L	32 t
2. run	51 km	15.4 L	2.8 L	32 t
3. run	51 km	14.9 L	2.6 L	32 t
4. run	51 km	14.5 L	2.5 L	32 t
5. run	51 km	15.2 L	2.7 L	32 t

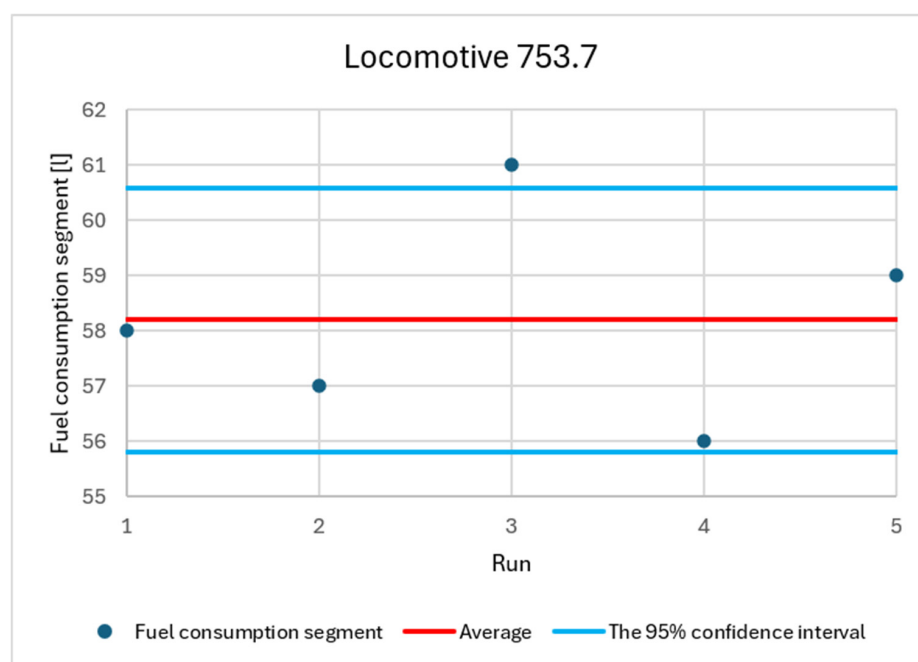
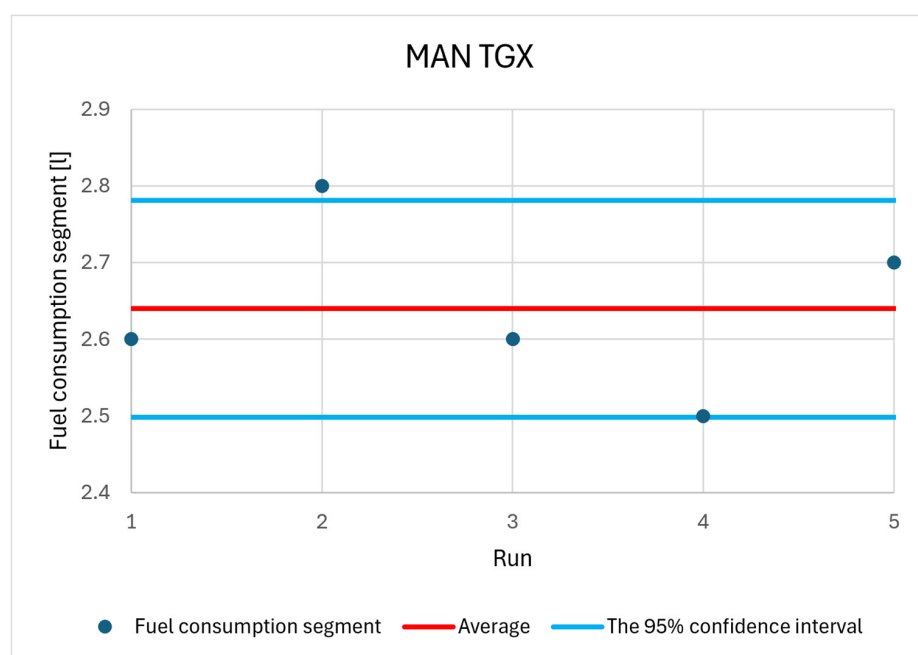
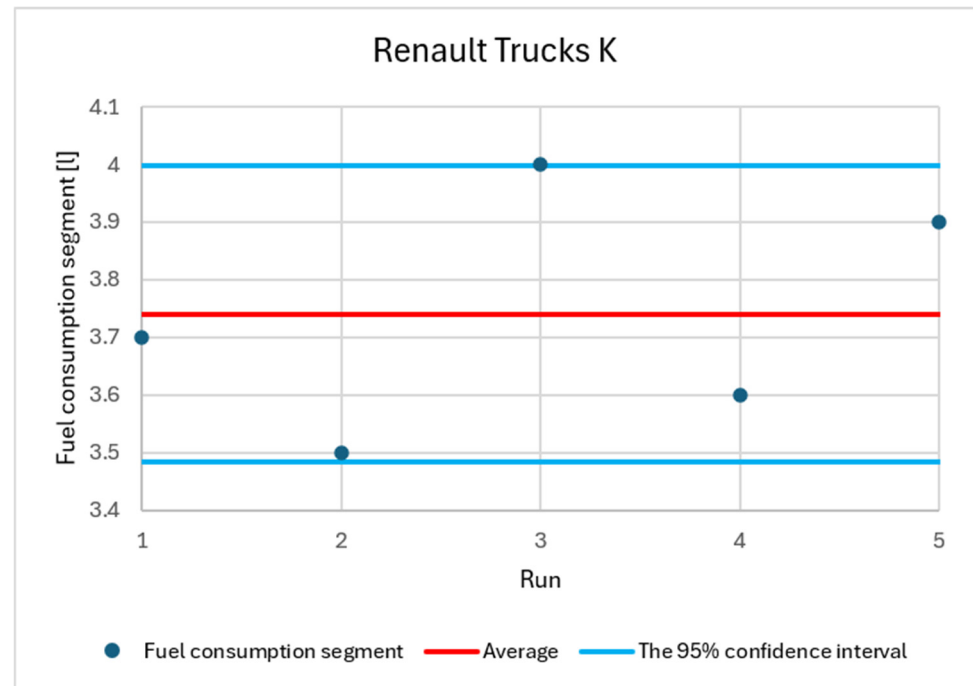
**Figure 4.** Individual measurement runs for locomotive 753.7 (own source).**Figure 5.** Individual measurement runs for the MAN TGX truck (own source).

Table 7 and Figure 6 present the individual measurement runs for the Renault Trucks K truck.

Table 7. Individual measurement runs for the Renault Trucks K truck (own source).

Truck Renault K Trucks	Distance Traveled	Fuel Consumption Total	Fuel Consumption Segment	Gross Consist Mass
1. run	51 km	19.5 L	3.7 L	41 t
2. run	51 km	18.8 L	3.5 L	41 t
3. run	51 km	20.2 L	4.0 L	41 t
4. run	51 km	19.3 L	3.6 L	41 t
5. run	51 km	19.9 L	3.9 L	41 t

**Figure 6.** Individual measurement runs for the Renault Trucks K truck (own source).

The values corresponding to the median run selected for each vehicle are summarized in Table 8.

Table 8. Measured values of the investigated vehicles (own source).

Vehicle	loc. 193	loc. 183	loc. 189	loc. 753.7	MAN TGX	Renault K
Distance traveled	66 km	66 km	66 km	66 km	51 km	51 km
Segment length	10 km	10 km	10 km	10 km	10 km	10 km
Electricity consumption total	918 kWh	670 kWh	1510 kWh	/	/	/
Fuel consumption total	/	/	/	290 L	14.9 L	19.5 L
Electricity consumption segment	171 kWh	120 kWh	254 kWh	/	/	/
Fuel consumption segment	/	/	/	58 L	2.6 L	3.7 L
Gross consist mass	2196 t	1116 t	1880 t	1257 t	32 t	41 t
Net consist mass	1232 t	648 t	998 t	910 t	17 t	23 t

Table 9 summarizes the basic characteristics of the measured electricity and fuel consumption values.

Table 9. Basic characteristics of the measured electricity and fuel consumption values.

Vehicle	Mean	Median	Standard Deviation	Coefficient of Variation	Range
Locomotive 193	171.4 kWh	171 kWh	4.04 kWh	2.36%	11 kWh
Locomotive 183	120.8 kWh	120 kWh	3.11 kWh	2.58%	8 kWh

Table 9. Cont.

Vehicle	Mean	Median	Standard Deviation	Coefficient of Variation	Range
Locomotive 189	255 kWh	254	7.04 kWh	2.76%	17 kWh
Locomotive 753.7	58.2 L	58 L	1.92 L	3.31%	5 L
MAN TGX	2.64 L	2.6 L	0.11 L	4.32%	0.3 L
Renault	3.74 L	3.7 L	0.21 L	5.54%	0.5 L

5. Results

Based on the measured energy consumption, the energy-intensity values were first calculated in units of MJ/gtkm for the entire assessed section as well as for the most gradient-demanding 10 km segment of the route. These values were subsequently recalculated per net tonne-kilometre to assess energy intensity referenced directly to the payload actually transported; the energy data were further used to derive the emission intensity expressed as g CO₂e/gtkm and g CO₂e/ntkm under a WTW approach.

Figure 7 presents the gross- and net-based energy intensity of the three investigated electric locomotives over the full section. The Class 193 locomotive records the lowest energy intensity, approximately 0.062 MJ/gtkm. The Class 183 and Class 189 electric locomotives exhibit higher values, approximately 0.088 and 0.118 MJ/gtkm, respectively. In gross tonne-kilometre terms, the Class 193 locomotive therefore achieves approximately 30% lower energy intensity than the Class 183 locomotive and approximately 47% lower energy intensity than the Class 189 locomotive. The figure shows that electric traction is not internally uniform; even under the same corridor conditions, the selected locomotive type affects the resulting energy intensity.

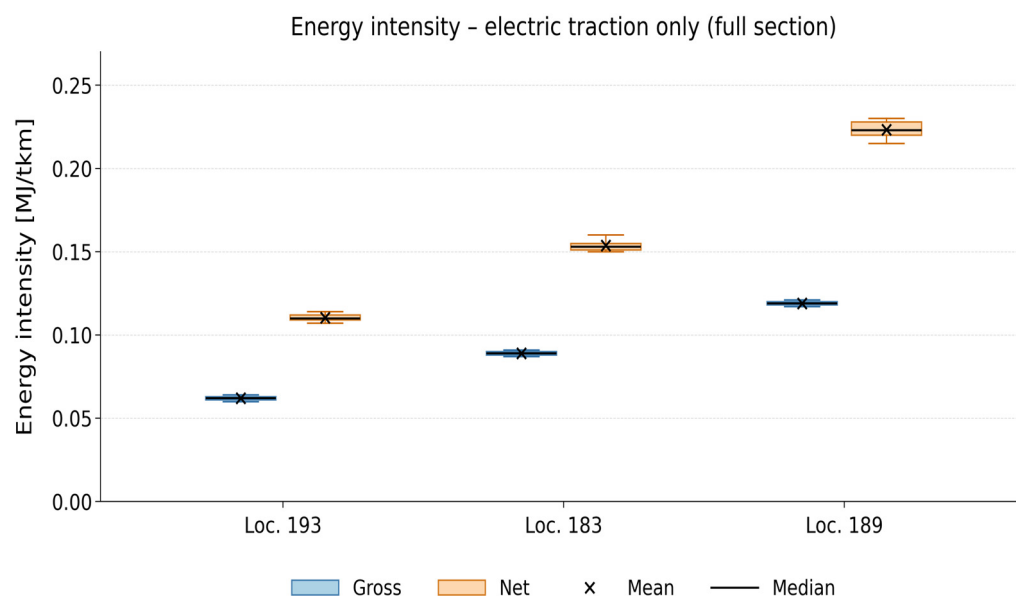


Figure 7. Energy intensity of electric locomotives, full section (own source).

When expressed per net tonne-kilometre, the ranking remains unchanged. The electric locomotives reach approximately 0.110–0.223 MJ/ntkm, with the Class 193 locomotive again achieving the most favourable result and the Class 189 locomotive representing the upper end of the observed range. On a net tonne-kilometre basis, the reduction achieved by the Class 193 locomotive is approximately 28% relative to the Class 183 locomotive and approximately 51% relative to the Class 189 locomotive. The difference between gross and net indicators reflects the effect of payload and train composition: while MJ/gtkm expresses energy intensity in relation to the total transported mass of the consist, MJ/ntkm relates

consumption directly to the useful transported cargo. Because the ranking remains unchanged in both indicators, the observed differences cannot be attributed only to the choice of gross or net tonne-kilometres; they also reflect differences in the energy performance of the individual locomotives.

The practical relevance of Figure 7 lies in its within-rail comparison. It shows that the energy performance of electric rail freight is affected not only by the use of electric traction as such, but also by the specific locomotive. From the perspective of fleet modernization, the result supports the replacement of less efficient electric locomotives where operationally feasible, because such renewal can reduce energy intensity within rail freight transport itself.

The segment measurement provides a supplementary check of this ranking. In the more demanding section, the Class 193 locomotive again recorded the lowest energy intensity, approximately 0.076 MJ/gtkm, followed by the Class 183 and Class 189 locomotives with values of around 0.105 and 0.131 MJ/gtkm, respectively. Although these segment values are not displayed in Figure 7, they support the same ordering observed in the full-section comparison. Thus, the 10 km segment analysis supports the full-section ranking, although it does not replace the full-section assessment.

Building on the within-electric comparison in Figure 7, Figure 8 extends the assessment to the Class 753.7 diesel locomotive and the two heavy road freight vehicle combinations. The aggregated electric-traction category represents the range observed for the three electric locomotives shown in Figure 7. In gross tonne-kilometre terms, electric traction remains the least energy-intensive group, with values ranging from 0.062 to 0.118 MJ/gtkm, while the Class 753.7 diesel locomotive reaches 0.158 MJ/gtkm. Although this value is higher than the electric-traction range, it remains clearly below both road vehicle combinations, represented by MAN TGX and Renault Trucks K with values of 0.413 and 0.422 MJ/gtkm, respectively.

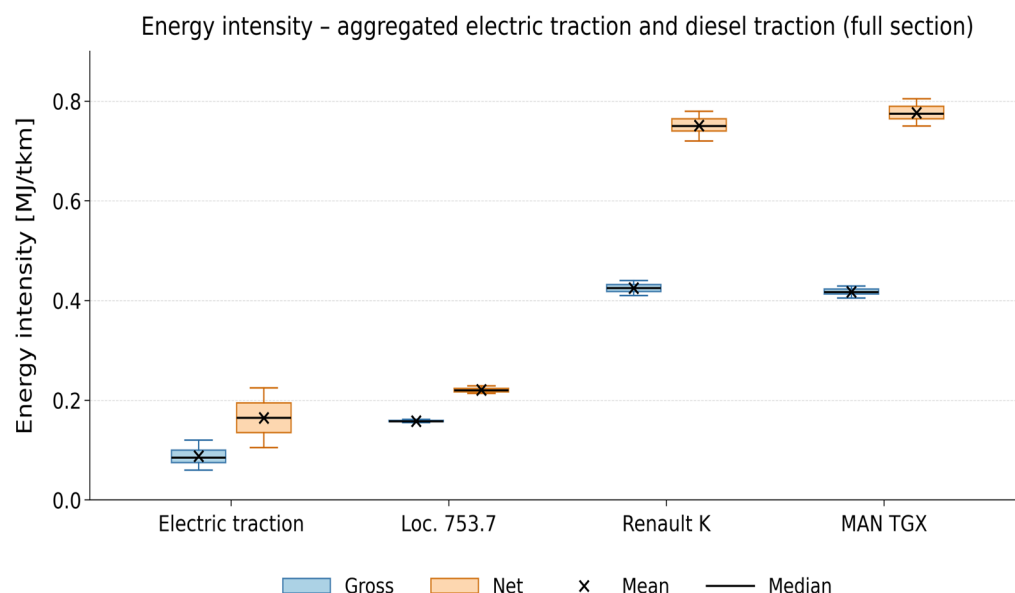


Figure 8. Energy intensity by vehicle group, full section (own source).

In relative terms, electric traction reduces gross energy intensity by 72.0–85.3% compared with Renault K and by 71.4–85.0% compared with MAN TGX. The Class 753.7 diesel locomotive achieves reductions of 62.6% and 61.7%, respectively. This indicates that the main separation in Figure 8 is not only between electric and diesel traction, but especially between rail-based and road-based freight transport.

When expressed per net tonne-kilometre, the same overall ranking is retained. The electric locomotives range from 0.110 to 0.223 MJ/ntkm, while the Class 753.7 diesel

locomotive reaches 0.218 MJ/ntkm and therefore approaches the upper end of the electric-traction range. The road combinations remain clearly above all investigated rail vehicles, reaching 0.752–0.778 MJ/ntkm. On this basis, electric traction is 70.3–85.4% lower than Renault K and 71.3–85.9% lower than MAN TGX, while the corresponding reductions for the diesel locomotive are 71.0% and 72.0%. The comparison between gross and net indicators therefore links the energy advantage of rail freight not only to traction efficiency, but also to the ability of rail transport to concentrate larger cargo volumes into one consist.

The practical implication of Figure 8 differs from that of Figure 7. While Figure 7 highlights the importance of modernization within electric traction, Figure 8 shows that the energy advantage becomes substantially larger when rail vehicles are compared with heavy road freight vehicles. This indicates that the lower energy intensity of rail freight is linked not only to the traction system, but also to the higher transport capacity and utilization potential of railway consists. The supplementary 10 km segment analysis supports the full-section ranking, although it does not replace the full-section assessment; electric traction again recorded the lowest energy intensity, followed by the Class 753.7 diesel locomotive, while the road vehicle combinations remained the most energy-intensive group.

Figure 9 compares the gross- and net-based CO₂e emission intensity of the investigated electric locomotives over the full assessed section. The Class 193 locomotive records the lowest emission intensity, approximately 2.7 g CO₂e/gtkm. The Class 183 and Class 189 locomotives reach higher values, approximately 3.8 and 5.1 g CO₂e/gtkm, respectively. In gross tonne-kilometre terms, the Class 193 locomotive therefore achieves approximately 29% lower CO₂e emission intensity than the Class 183 locomotive and approximately 47% lower CO₂e emission intensity than the Class 189 locomotive. With the same electricity emission factor applied to all three locomotives, these differences arise from vehicle-specific electricity use and the transport performance achieved on the assessed section.

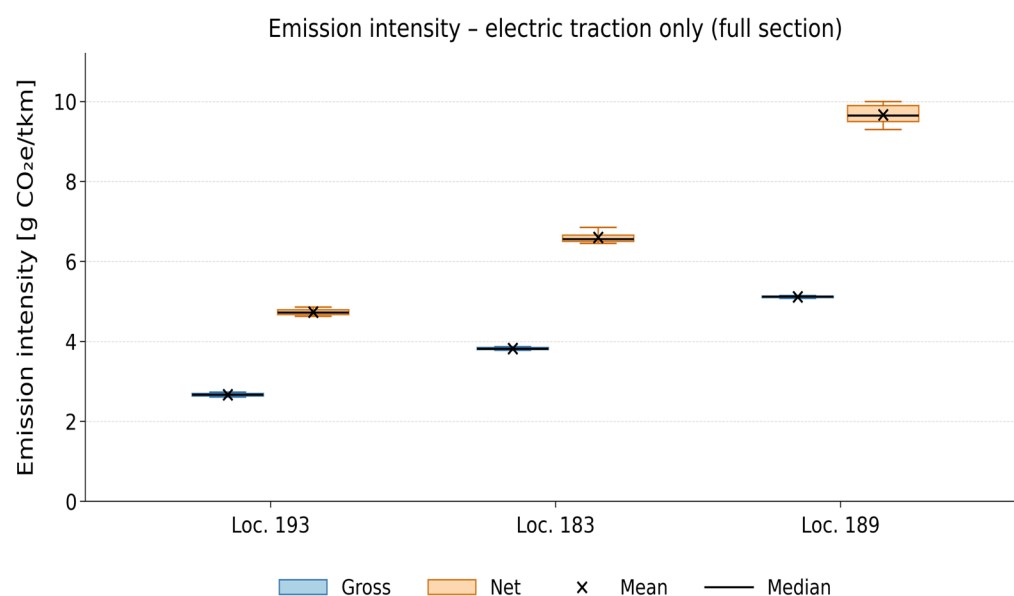


Figure 9. CO₂e emission intensity of electric traction, full section (own source).

When expressed per net tonne-kilometre, this ranking is unchanged. The electric locomotives reach approximately 4.7–9.6 g CO₂e/ntkm, with the Class 193 locomotive showing the lowest value and the Class 189 locomotive representing the upper end of the observed range. On a net tonne-kilometre basis, the reduction achieved by the Class 193 locomotive is approximately 29% relative to the Class 183 locomotive and approximately 51% relative to the Class 189 locomotive. The higher net-based values reflect the fact that emissions are related only to the useful transported cargo rather than to the total consist mass. The

consistent ranking in both gross and net terms indicates that the differences between the locomotives are not an artefact of the selected functional unit.

The practical relevance of Figure 9 lies in its within-electric comparison. It shows that CO₂e emission intensity within electric rail traction is not uniform, even when the same electricity emission factor is used. At the fleet level, replacing less emission-efficient electric locomotives can reduce WTW CO₂e emission intensity within electric rail freight itself.

The 10 km segment provides a supplementary check of the full-section ranking, although it does not replace the full-section assessment. In the more demanding section, the electric locomotives reached approximately 3.3–5.7 g CO₂e/gtkm, and the order of the locomotives remained unchanged. This indicates that the observed differences are also visible under less favourable route-profile conditions.

Figure 10 extends the emission comparison to the Class 753.7 diesel locomotive and the two heavy road vehicle combinations. The aggregated electric-traction category represents the range observed for the three electric locomotives shown in Figure 9. In gross tonne-kilometre terms, electric traction achieves the lowest CO₂e emission intensity, with values of approximately 2.7–5.1 g CO₂e/gtkm. The Class 753.7 diesel locomotive reaches approximately 11.0 g CO₂e/gtkm, which is higher than the electric-traction range but still clearly below the road vehicle combinations. The MAN TGX and Renault Trucks K combinations reach approximately 28.8 and 29.4 g CO₂e/gtkm, respectively. In gross tonne-kilometre terms, electric traction reduces CO₂e emission intensity by 82.7–90.8% relative to Renault K and by 82.3–90.6% relative to MAN TGX. The Class 753.7 diesel locomotive achieves reductions of 62.6% and 61.8%, respectively. The main emission gap is therefore most evident between rail-based and road-based freight transport.

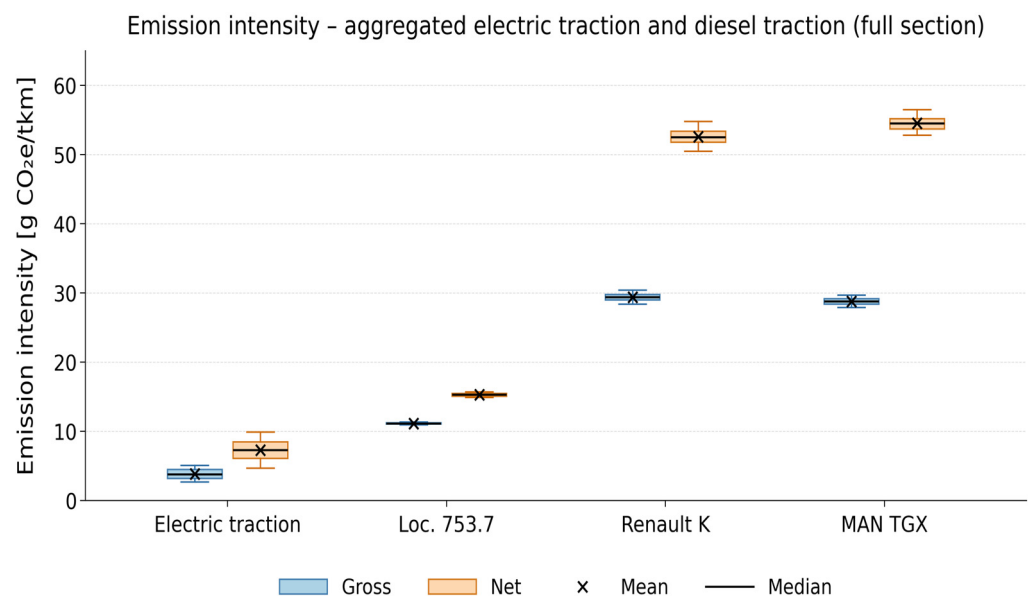


Figure 10. CO₂e emission intensity of rail and road freight, full section (own source).

When assessed per net tonne-kilometre, the same ranking is retained. The electric locomotives reach approximately 4.7–9.6 g CO₂e/ntkm, while the Class 753.7 diesel locomotive reaches approximately 15.2 g CO₂e/ntkm. By contrast, the road combinations reach approximately 52.4–54.1 g CO₂e/ntkm and remain clearly above all investigated rail vehicles. On a net tonne-kilometre basis, electric traction is 81.7–91.0% lower than Renault K and 82.3–91.3% lower than MAN TGX; for the diesel locomotive, the corresponding reductions are 71.0% and 71.9%. This net-based comparison relates emissions directly to the useful transported payload and shows that the rail advantage is preserved even under this stricter functional unit.

The comparison between gross and net values shows that the lower emission intensity of rail transport is not determined solely by the emission factor of the energy carrier or by traction technology. It is also influenced by the ability of rail transport to concentrate larger cargo volumes into one consist. For transport-planning interpretation, this means that emission performance depends not only on vehicle technology, but also on the efficient use of transport capacity. Under the assessed corridor conditions, rail freight therefore retains a clear emission advantage even when diesel rail traction is included.

The 10 km segment provides a supplementary check of the full-section ranking, although it does not replace the full-section assessment. In the selected segment, the electric locomotives reached approximately 3.3–5.7 g CO₂e/gtkm, the Class 753.7 diesel locomotive reached approximately 14.5 g CO₂e/gtkm, and the road vehicles ranged approximately from 25.6 to 28.4 g CO₂e/gtkm. In net tonne-kilometre terms, the road combinations remained clearly above the rail vehicles, reaching approximately 48.2–50.7 g CO₂e/ntkm. Although the absolute values differ from the full-section results due to the specific route profile and operating conditions of the segment, the overall ranking remains unchanged.

For this comparison, final vehicle-level energy intensity is used rather than WTW primary-energy intensity, because the purpose is to verify whether the directly measured operational energy-consumption values fall within internationally reported reference ranges.

6. Discussion

In many published studies, results are based on model assumptions, which limits accuracy when the aim is to assess the efficiency of specific vehicles under a particular operating situation. This led to the need for a methodological approach that is both transparent in its assumptions and grounded in observations from real-world operation.

The methodology of this study was designed to ensure a methodologically consistent and transparent comparison of the assessed alternatives while also enabling an unambiguous interpretation of the results; it is based on operational data from real measurements and on converting the results to transport performance. The results therefore stem from direct measurement; this approach enables a direct comparison of rail and road transport within a unified framework and increases the usefulness of the results for evaluating transport alternatives.

In the part dealing with the greenhouse gas emission intensity, it is essential that the assessment does not consider only emissions caused by the operation itself, but also takes into account emissions associated with energy supply. This is particularly important for electric traction, because the resulting emission intensity depends on the sources from which the electricity was generated. The emission results therefore do not reflect only the vehicle, but also the parameters of the energy system.

Given that the coefficient used to convert electricity into primary energy and the correction factor applied to diesel fuel constitute methodologically fixed input parameters, it was necessary in the discussion section to verify, above all, the credibility and relevance of the measured operational values from which the resulting energy intensity of the individual vehicles is derived. The following section therefore focuses on directly measured final energy consumption at vehicle level, expressed per unit of transport performance, and compares these values with harmonized ranges reported in international reference sources. The purpose of this step is to assess whether the measured values correspond to the typical range of energy intensity reported for individual freight transport modes, thereby establishing a reliable basis for their subsequent broader interpretation.

6.1. Comparison of Final Energy Intensity with Reference Ranges

To verify the plausibility and international comparability of the measured energy-intensity values, the IPCC AR6 report was used as a reference framework [3], which provides harmonized ranges of energy efficiency for individual freight transport modes. The values are not expressed as specific figures but as intervals; these intervals do not represent a single mean value, but are intentionally designed to capture variability driven by differences in technology, train/vehicle size, operating regime, and load factor. They are therefore particularly suitable for discussion as a reference corridor within which realistic results should typically fall.

For heavy-duty road freight transport, the IPCC reports an interval of 0.38–0.93 MJ/tkm at full payload for a diesel vehicle. For freight rail, the reported intervals are 0.11–0.78 MJ/tkm for diesel traction and 0.01–0.12 MJ/tkm for electric traction. Although the IPCC reference values are reported in MJ/tkm, they are based on transported payload and are, therefore, for the purposes of this comparison, methodologically equivalent to values expressed in MJ/ntkm, in which the results of this study are also presented. These ranges indicate that rail energy intensity is, as expected, below that of road transport, but they also show that both modes exhibit substantial internal variability, which is consistent with the claim that energy intensity is sensitive to the specific technology and operating parameters. Table 10 compares the measured net energy-intensity values with the IPCC reference ranges.

Table 10. Comparison of measured net energy-intensity values with the IPCC reference ranges (own source [3]).

Vehicle	IPCC Range	Measured Value
Electric locomotive 193	0.01–0.12 MJ/tkm	0.041 MJ/ntkm
Electric locomotive 183	0.01–0.12 MJ/tkm	0.056 MJ/ntkm
Electric locomotive 189	0.01–0.12 MJ/tkm	0.083 MJ/ntkm
Diesel locomotive 753.7	0.11–0.78 MJ/tkm	0.174 MJ/ntkm
Renault Trucks K	0.38–0.93 MJ/tkm	0.598 MJ/ntkm
MAN TGX	0.38–0.93 MJ/tkm	0.618 MJ/ntkm

The final energy-intensity values presented in Table 10 confirm that all measured values fall within the IPCC reference intervals and can therefore be considered consistent with internationally reported ranges. Under electric traction, the three locomotives examined lie within the 0.01–0.12 MJ/tkm corridor: the Class 193 locomotive achieves the lowest energy intensity and is located in the lower part of the interval, whereas locomotive 189 shifts toward its upper part. This dispersion within a single mode demonstrates that, in addition to the choice of transport mode itself, the selection of a specific vehicle and its technological generation is also decisive for the resulting energy intensity. The diesel locomotive 753.7 lies in the lower part of the interval for diesel rail freight (0.11–0.78 MJ/tkm), which corresponds to efficient operation on the given route. For the road vehicle combinations, the values fall within the interval for heavy-duty diesel vehicles (0.38–0.93 MJ/tkm) and are located approximately in the middle part of this range. Overall, Table 10 supports the conclusion that the measured results correspond to the expected range of energy efficiency reported in the harmonized literature, while also highlighting the importance of within-mode variability, which in practice is driven primarily by technology, load, and operating regime.

In the context of long-term emission reductions in transport, the above ranges imply an important framework: a modal shift, for example, moving a transport route from road to rail primarily reduces the demand for final energy per unit of transport work and thus creates a structural precondition for lower emissions. At the same time, the width of the IPCC intervals indicates that substantial potential also lies in improving energy efficiency within

a mode, i.e., through vehicle fleet renewal, operational optimization, and, in particular, maintaining a high utilization rate of transport capacity. In practice, the achievable emission effect will be strongest when modal shift and technological and operational efficiency improvements are implemented in parallel; in the case of electrification, the final emission benefit will further depend on the carbon intensity of the supplied electricity.

For a more detailed comparison of the energy-intensity results of the vehicles examined in this study, the STREAM Freight Transport 2020 study [52] was selected, as it represents a frequently used reference framework in the scientific literature for standardized cross-modal comparisons of freight transport energy intensity. Methodologically, the study is based on a database approach in which representative technological and operational parameters are defined for selected segments, and indicators per tonne-kilometre are derived accordingly. In this way, the study provides values that are not burdened by the specifics of a single route or a single vehicle combination; instead, it summarises the expected level of energy intensity for a given mode under typical operating conditions.

For road transport, only STREAM motorway values corresponding to heavy road vehicle combinations were selected: 0.8 MJ/tkm for a heavy tractor-semitrailer and 0.9 MJ/tkm for a truck with a gross vehicle weight above 20 t with a trailer. For rail transport, the study reports a markedly lower energy intensity for the same commodity group: under higher load in net mode, approximately 0.065–0.071 MJ/tkm for electric traction, whereas for diesel traction it is 0.176–0.193 MJ/tkm. In the following figure, the reference values are compared with the actual values measured in this research; where database values are reported as ranges, the median values are used. For road transport, both selected motorway reference values are shown separately.

The STREAM study uses tkm as the unit of transport performance. At the same time, the authors define the unit such that a tonne-kilometre represents the transport of one tonne over a distance of one kilometre, i.e., transport performance in terms of both distance and the mass of the delivered cargo. From this definition, it is clear that this is transport performance referenced to the mass of the transported shipment, i.e., net tonne-kilometre. In this study, we therefore consider the MJ/tkm notation used in STREAM to be equivalent to MJ/ntkm, and, to ensure consistency, only our own measured net data are used for the comparison.

Figure 11 shows that the selected STREAM reference values and the results of this study fall within comparable ranges. For electric traction, it is evident that older locomotives are closer to the level represented by the reference framework, whereas the newest locomotive achieves the lowest energy intensity and lies at the more efficient end of the range observed within the mode, highlighting the importance of selecting a specific vehicle and its technological generation. For diesel traction, the measured value lies very close to the STREAM reference range, which suggests that the recorded performance corresponds well to the expected energy intensity of diesel rail freight under comparable operating conditions. This finding is interpretatively important because it suggests that part of the differences attributed in the literature to the mode itself actually arise within the mode as a result of differing efficiency and operating characteristics of the chosen traction vehicle.

For road transport, the values observed in this study are lower than the selected STREAM motorway reference values for heavy road vehicle combinations; as indicated by the reference values, road energy intensity varies substantially with the driving profile and may also be influenced by operational and logistical parameters of the transport. Overall, modal shift is therefore crucial from both an emissions and energy perspective; however, its practical benefit depends on whether it is accompanied by vehicle modernization and operational optimization. These factors largely determine the extent to which the mode's

theoretical advantage translates into realistically achievable energy consumption per unit of transport work.

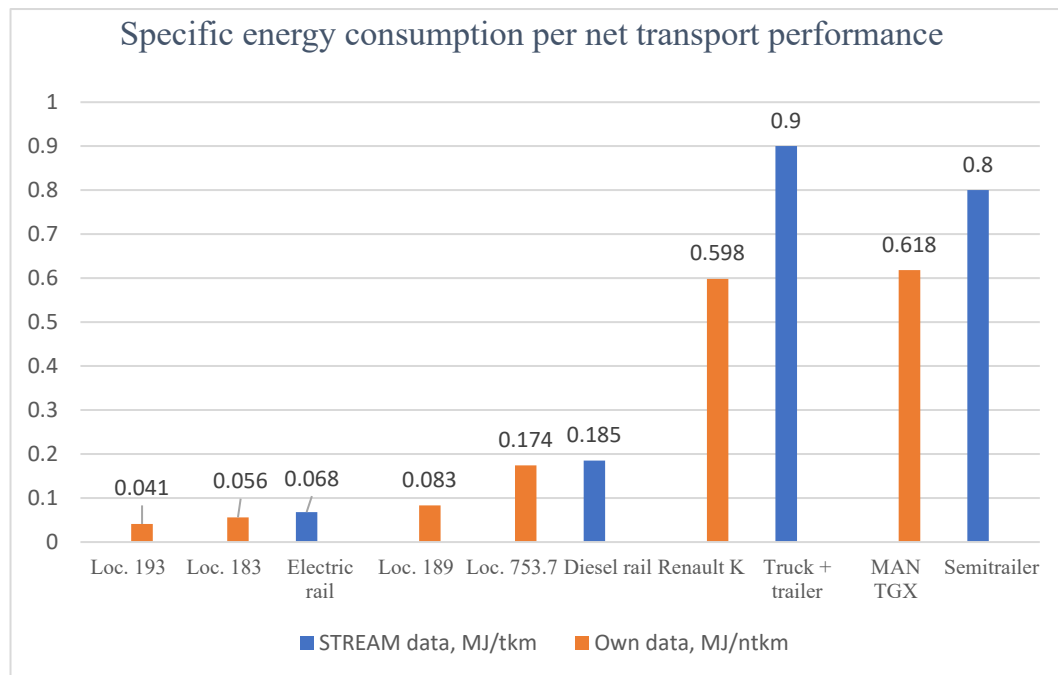


Figure 11. Comparison of measured values with the STREAM study (own source [52]).

From the perspective of transport capacity, a substantial advantage of rail freight transport can be expected when energy intensity is expressed per unit of transport performance. The results of this study make it possible to quantify this expected advantage under real operating conditions and to compare its magnitude with reference values reported in the literature. In the present case, the assessed road vehicle combinations reached 0.598–0.618 MJ/ntkm, whereas the best-performing electric locomotive, Class 193, reached 0.041 MJ/ntkm and the Class 753.7 diesel locomotive reached 0.174 MJ/ntkm. This means that the road vehicle combinations were approximately 14.6–15.1 times more energy-intensive than the best-performing electric locomotive and approximately 3.4–3.6 times more energy-intensive than the diesel locomotive. A comparable order of magnitude is also reported in the STREAM study, where heavy road vehicle combinations reach 0.8–0.9 MJ/tkm, while electric rail freight is reported at approximately 0.065–0.071 MJ/tkm and diesel rail freight at approximately 0.176–0.193 MJ/tkm. These values imply an approximately 11–14-fold difference between road and electric rail freight and an approximately 4–5-fold difference between road and diesel rail freight. The findings of this study are therefore consistent with the expected capacity-related advantage of rail freight transport and with reference values reported in previous research. At the same time, the contribution of the study lies in quantifying this difference for specific vehicles, payloads, and corridor conditions, rather than relying only on aggregated modal averages.

6.2. Comparison of Emission Intensity

The greenhouse gas emission intensity of rail and road transport in this study is based on measured energy consumption and emission factors corresponding to the current energy mix and fuel base in the Czech Republic. Particularly for electric traction, the electricity emission factor plays a crucial role, as it reflects the share of non-renewable fossil fuels and renewable sources in the national power system. In neighboring countries, the structure of the energy mix differs, which leads to different emission-factor values and thus to different

relative advantages of individual transport modes. For diesel fuel, differences in emission factors between countries are generally smaller, because the underlying carbon intensity of the fuel is similar; some variability, however, may arise from differences in crude-oil origin, refining efficiency, and the share of bio-components. The next part of the discussion therefore shows how the overall results would change if the same comparison were carried out under the conditions of the Czech Republic's neighboring countries. According to the aggregated energy balance of the Czech Republic, the electricity emission factor in 2024 was 420 g CO₂e/kWh [44].

The Slovak power sector relies primarily on nuclear energy and has been investing substantially in renewable sources, especially hydropower and solar power plants. At the end of March 2024, the last Slovak coal-fired power plant in Vojany ceased operation. The country has two nuclear power plants, which produce more than half of Slovakia's total electricity generation; in 2023, this share was 63%. Slovakia also makes very effective use of its terrain through the appropriate development of hydropower plants: hydropower ranks second in electricity production in Slovakia and generated a total of 14% of the annual volume of electricity produced [53]. In 2024, the average emission intensity of electricity generation in Slovakia was 93 g CO₂e/kWh. In total, 23% was generated from renewable energy sources, while nuclear power played a dominant role in the energy mix with a share of 61.6% [54].

In recent years, the Polish power sector has remained strongly dependent on coal, which constitutes the dominant share of the generation mix and contributes substantially to the high emission intensity of electricity generation compared with other European countries. Nevertheless, the energy transition indicates a gradual decline in the share of coal, accompanied by an increase in generation from renewable sources, particularly wind and solar power. In 2023, the share of renewables in electricity generation reached approximately 27%, while coal accounted for about 60.5% [55]. In 2024, the average emission intensity of electricity generation in Poland was 652 g CO₂e/kWh. Approximately 29% of electricity was generated from renewable energy sources, while coal remained the dominant source with a share of 57.6% [56].

The Austrian power sector is among the most decarbonized in Europe. Almost 90% of electricity generation comes from renewable sources; Austria has set the goal of achieving a 100% share of renewable electricity in the annual national balance by 2030 and climate neutrality by 2040. In 2023, approximately 87% of electricity generation came from renewable energy sources, and in 2024 the share of renewable electricity reached 89%, with hydropower plants long providing more than half of Austria's electricity generation [57]. In 2024, the average emission intensity of electricity generation in Austria was 69 g CO₂e/kWh. The overall share of generation from renewable sources was 89%, with hydropower as the main source, accounting for 53.8% of total electricity generation [58].

The German power sector is undergoing an intensive transformation towards a low-emission mix, with renewable sources, especially wind and solar energy, assuming a key role. In 2023, renewables reached a share of 59.7% of electricity generation for public supply, while electricity generation from coal declined markedly. At the same time, Germany completed its nuclear phase-out by shutting down its last three nuclear units on 15 April 2023. Strategically, the country is aiming for at least 80% of gross electricity consumption to come from renewable sources by 2030 [59]. In 2024, the average emission intensity of electricity generation in Germany reached 321 g CO₂e/kWh. Renewable sources accounted for 63% of electricity generation, with wind power as the dominant component at 31.2%, while coal accounted for 22.4% of generation [60].

For comparison purposes, the measured greenhouse gas emission intensity of the best-performing class 193 locomotive was recalculated to reflect the conditions of neighboring

countries. For this recalculation, the same operating profile and electricity consumption as observed in the Czech Republic are assumed, while only the electricity emission factor corresponding to the national energy mix of the respective country is changed. The following figure thus shows how the emission intensity of electric traction per unit of transport work would evolve if the identical measurement were carried out in Slovakia, Poland, Austria, and Germany, thereby allowing the influence of technology and operation to be separated from the influence of the carbon intensity of electricity generation.

The results in Figure 12 confirm that the greenhouse gas emission intensity of electric rail transport is highly sensitive to the carbon intensity of the national power system. In the low-emission systems of Austria and Slovakia, it reaches only 0.44–0.59 g CO₂e/gtkm (i.e., 0.78–1.05 g CO₂e/ntkm), whereas in Poland it increases to 4.13 g CO₂e/gtkm (i.e., 7.36 g CO₂e/ntkm). Compared with the Czech scenario, applying the same operating parameters in Austria would reduce emissions by approximately 84%, in Slovakia by 78%, while in Poland emissions would increase by about 55%; Germany represents an intermediate scenario with a reduction of approximately 24%.

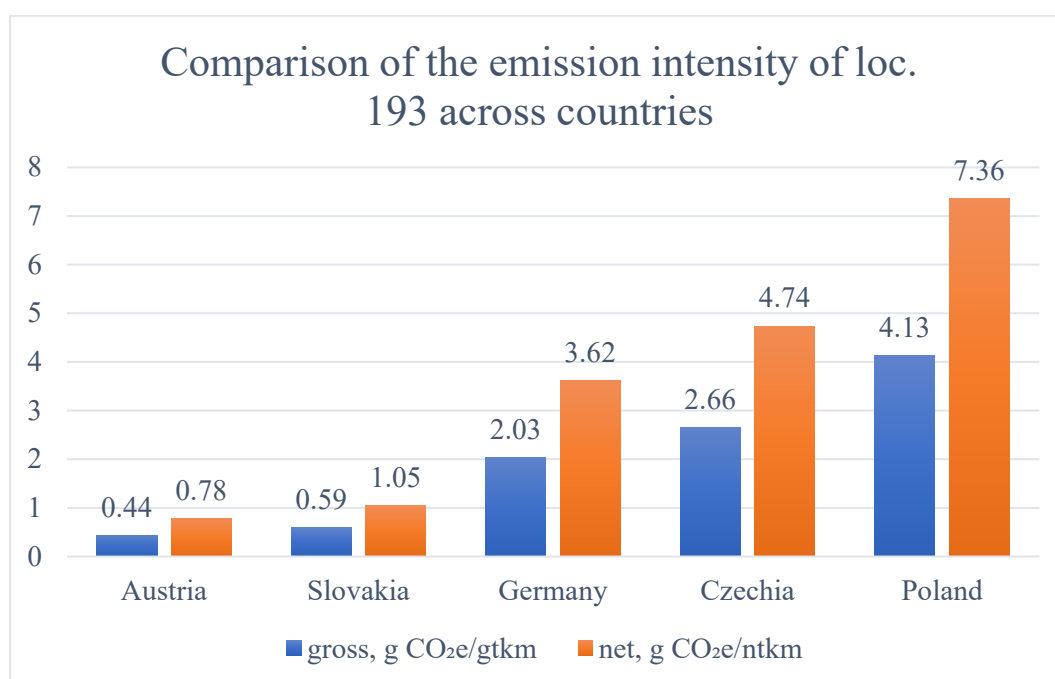


Figure 12. Comparison of the emission intensity of loc. 193 across countries in gross/net terms (own source).

To make differences between national conditions as clear as possible and at the same time as easy to interpret as possible, the measured results for electric traction from the Czech Republic are placed into two contrasting scenarios: Austria as a low-emission counterpart and Poland as a country with highly carbon-intensive electricity generation. In all scenarios, greenhouse gas emissions are derived from the same measured electricity consumption on the given section and differ solely in the electricity emission factor applied for the respective country.

The scenario comparison shows that the emission advantage of electric traction is not constant and is sensitive to the carbon intensity of electricity. Under the Polish scenario, the greenhouse gas emission intensity of electric locomotives increases markedly and, for more energy-intensive configurations, may approach values typical of diesel traction. Conversely, under the Austrian scenario, where the carbon intensity of electricity is low, electric traction emerges as clearly low-emission and differences among individual electric

locomotives are relatively muted in absolute emission terms; operational efficiency becomes the decisive factor. The Czech scenario lies between these poles and serves as a realistic reference level corresponding to Central European conditions. From a system-level perspective, this supports the conclusion that the combination of electrification and power-sector decarbonization represents a consistent pathway to substantial emission reductions in freight transport.

The results for diesel traction are intentionally not included in Figure 13, because this study applies a single WTW emission factor for diesel fuel that is not dependent on the national electricity mix; with the same measured fuel consumption, diesel values would therefore be identical across Austria, Czechia, and Poland.

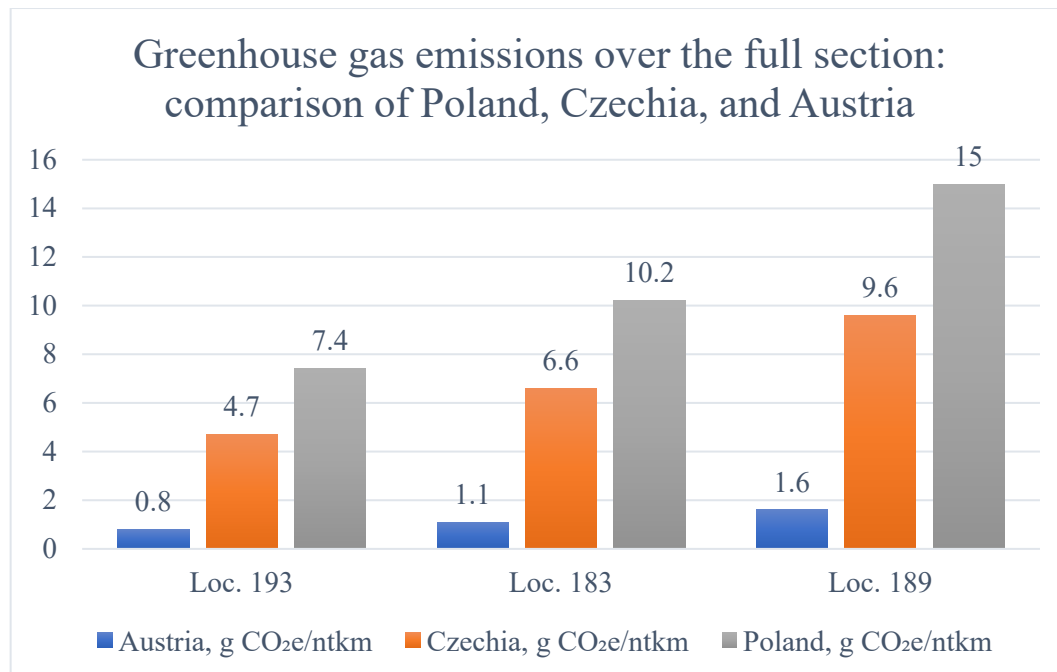


Figure 13. Greenhouse gas emission intensity over the full section (own source).

6.3. Sensitivity Analysis

The sensitivity analysis further underscores the robustness of the environmental advantage held by rail transport. For the Class 753.7 diesel locomotive to achieve lower WTW CO₂e emissions than the electric locomotives, the electricity emission factor would need to increase by at least 1.5 times, representing a 50% increase from the current baseline. In the case of heavy-duty road freight vehicles, this emission factor would require a minimum 5.5-fold increase to offset the advantage of electric rail traction. Similarly, regarding energy intensity, the electricity conversion factor would have to increase at least 3.3 times for road transport to demonstrate superior efficiency compared to electric rail.

The sensitivity analysis confirms that the ecological superiority of rail transport is stable across a wide range of input parameters. Even under a worst-case scenario for electric traction (e.g., utilizing a high-carbon intensity electricity mix similar to the Polish scenario), modern electric locomotives such as the Class 193 maintain a significant emissions advantage over heavy road freight vehicles. However, the analysis also reveals that the margin of this advantage is highly sensitive to the specific carbon intensity of the national power sector, emphasizing that grid decarbonization is essential to maximizing the climate benefits of rail transport.

6.4. Limitations and Future Research

Despite the authors' efforts to ensure the highest possible degree of accuracy and objectivity, several limitations of the study should be acknowledged. The empirical assessment was conducted on one selected corridor, which limits direct generalization to rail and road freight contexts with substantially different route or operating characteristics. The results should therefore be interpreted primarily in relation to railway and motorway corridors of a comparable character.

The rail and road measurements were carried out on broadly parallel routes, although their lengths differed. This approach was chosen because the aim was to compare real transport alternatives within the same corridor rather than artificially constructed routes of identical length. The comparison is therefore methodologically relevant, but it should be interpreted as a corridor-based assessment.

A further limitation concerns the exclusion of regenerative braking from the energy balance of the electric locomotives. This decision was made because its use could not be ensured consistently across all locomotives and measurement conditions, and because regenerative braking cannot be regarded as automatically available under all infrastructure and operating conditions. Its exclusion may therefore have led to a conservative estimate of the energy performance of electric traction, while also maintaining comparable assumptions across the assessed electric locomotives.

Further research should focus on modelling energy and emissions intensity under different operational scenarios, with greater emphasis on generational differences in propulsion technologies. Rather than conducting global assessments at the level of transport modes, it is advisable to systematically compare specific vehicle types and quantify the extent to which energy and emissions intensity changes, for example, as a result of fleet renewal. The results of this study also suggest that conclusions about the environmental performance of freight transport should not be derived solely from broad modal averages, because a substantial part of the observed variability arises within individual modes as a consequence of vehicle technology, operating conditions, and the structure of transport performance itself. Future studies should therefore verify the stability of the observed relationships using a wider set of corridors, vehicle configurations, and operational scenarios, including corridors with different route profiles, traffic conditions, and degrees of rail–road route comparability. They should also examine the influence of regenerative braking where its use can be ensured consistently under the given infrastructure and operating conditions, and should extend the assessment towards operating costs, life-cycle costs, and broader life-cycle assessment.

7. Conclusions

Based on real-world operational measurements conducted on a parallel motorway and railway section, the study shows that the WTW energy intensity and greenhouse gas emissions burden of freight transport are determined not only by the choice of transport mode but are associated with the combined effects of traction type, the technical level, and the age of the vehicle. The results confirm that, even within the same traction category, differences between vehicles of different generations can lead to substantially different energy efficiency and emissions intensity. In particular, the gap between the most efficient electric locomotive, the Class 193, and the least efficient electric locomotive, the Class 189, is approximately twofold, both in WTW energy intensity (0.110–0.223 MJ/ntkm) and in emissions intensity (4.7–9.6 g CO₂e/ntkm). When comparing electric and diesel rail traction, the Class 753.7 diesel locomotive reaches a WTW energy intensity very close to that of the least efficient electric locomotive, but remains approximately two times more energy-intensive than the best-performing Class 193. In emissions terms, however, the

diesel locomotive remains clearly less favourable, reaching up to approximately 3.2 times higher emissions intensity than the most efficient electric locomotive. At the same time, the results indicate that diesel rail traction remains more energy- and emissions-efficient than road transport, by up to $3.6\times$ in both energy consumption and CO_{2e} emissions when assessed per net tonne-kilometre on a WTW basis. These findings can be considered robust for the investigated vehicles, route, and measurement conditions; however, they should not be directly generalized to all rail and road freight transport contexts without broader replication across additional routes, vehicle types, payload levels, and operating conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
CAN	Controller Area Network
DC	Direct current
EEA	European Environment Agency
EN	European standard
ETCS	European Train Control System
EU	European Union
IEA	International Energy Agency
IFEU	Institute for Energy and Environmental Research Heidelberg
IPCC	Intergovernmental Panel on Climate Change
IRU	International Road Transport Union
JEC	Joint Research Centre–EUCAR–CONCAWE consortium
LCA	Life cycle assessment
LCC	Life cycle costing
LHV	Lower heating value
MPO	Ministry of Industry and Trade of the Czech Republic
MŽP	Ministry of the Environment of the Czech Republic
NCV	Net calorific value
SLCA	Social life cycle assessment
UIC	International Union of Railways
WTW	Well-to-wheel

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