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ENERGY EFFICIENCY OF RAIL AND ROAD TRANSPORT IN FREIGHT OPERATIONS

Abstract, This study focuses on the energy intensity of rail and road freight transport. The research compares different types of vehicles in both modes of transport with the aim of quantifying the amount of energy required to transport a specific volume of freight over a given distance. Several generations of electric and diesel locomotives were selected for measurement purposes, along with comparable road freight vehicles that are commonly used in operation. Real-world energy consumption measurements were carried out on a section of route where the rail and road routes run parallel, with the aim of determining which mode of transport is more energy-efficient in the context of freight transport, using real operational data.
Keywords: transport, energy efficiency, propulsion systems, freight transport

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Introduction

Energy demand in the transport sector represents one of the most critical challenges in contemporary research, particularly in the context of sustainability targets, the decarbonization of mobility, and the efficient use of primary energy resources. Transport accounts for nearly one-third of final energy consumption in many industrialized countries and remains one of the leading contributors to greenhouse gas emissions, especially carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter. These emissions have not only global climate impacts but also serious local consequences on air quality and public health.

Within this context, the propulsion system alone is no longer sufficient as the primary variable; what matters increasingly is the total energy efficiency of the system, defined as the ratio of usable mechanical energy to the total energy input, including production, transmission, and storage losses. For this reason, it is essential to distinguish between nominal engine efficiency and system-wide energy performance. While traditional combustion engines still dominate road freight transport due to established infrastructure and fueling convenience, their energy-to-motion conversion rates remain significantly lower compared to electric or hybrid systems.

Modern transportation research thus increasingly focuses on a holistic assessment of energy pathways, where factors such as energy source, transmission efficiency, vehicle design, and recovery mechanisms all contribute to determining the true sustainability of a given mode. These evaluations are critical for shaping future infrastructure investments, transportation planning, and legislative frameworks oriented toward long-term environmental responsibility.

Current energy situation within transport

Transport uses a wide range of energy sources, which vary in terms of their properties, availability and environmental impact. Road transport relies primarily on hydrocarbon fuels, while rail transport mainly uses electricity. Despite growing awareness of the need to switch to more sustainable energy sources, the development of alternative fuels such as hydrogen or electricity from renewable sources remains limited. Not only is high fossil fuel consumption a long-term problem, but there is also insufficient infrastructure for alternative energy sources. These shortcomings are slowing down the transition to more energy-efficient and environmentally friendly transport systems. Transport is a sector whose annual final energy consumption accounts for almost a third of total consumption, as shown in the figure below for the last five years:

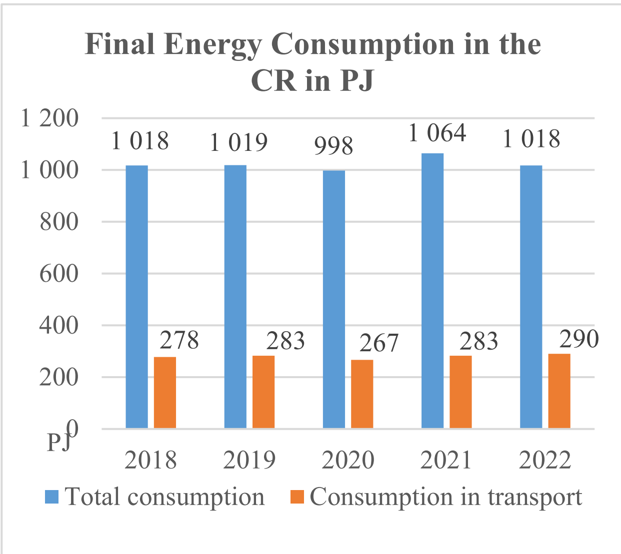

Fig 1. Final energy consumption. (MPO, 2023)

In terms of total energy consumption, transport was the second largest consumer of energy in 2022, behind households. The following figure provides an overview of energy consumption and the position of transport relative to other consumers.

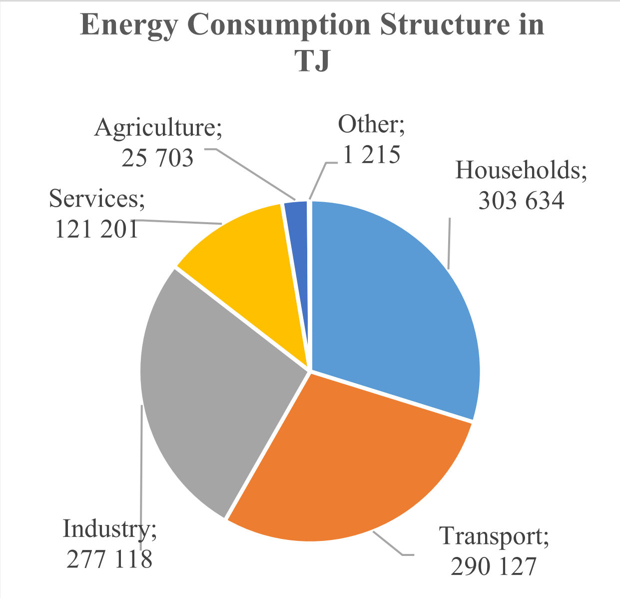

Fig. 2. Energy consumption structure. (MPO, 2023)

Fossil fuels remain the most widely used energy sources, continuing to dominate the transport sector thanks to their high energy density and established infrastructure. Diesel dominates freight and rail transport due to its higher energy efficiency and lower fuel consumption, while petrol is mainly used in private cars. Modern diesel engines can achieve combustion efficiencies of around 40–45%, while petrol engines range from 25–35%. (Yue, 2023)

In 2023, total fuel consumption within transport in Czechia came to 8.384 billion litres, of which 73.47 % (6.160 bn l) was diesel, and 26.53 % (2.224 bn l) was petrol. (ČAPPO, 2024)

However, the combustion of these fuels contributes significantly to emissions of harmful substances such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and particulate matter, which negatively affect air quality and contribute to global warming. Despite the introduction of modern technologies aimed at reducing emissions, diesel and gasoline remain the main sources of environmental pollution in transport.

Diesel and petrol consumption between 2019 and 2023 is shown in the following figure.

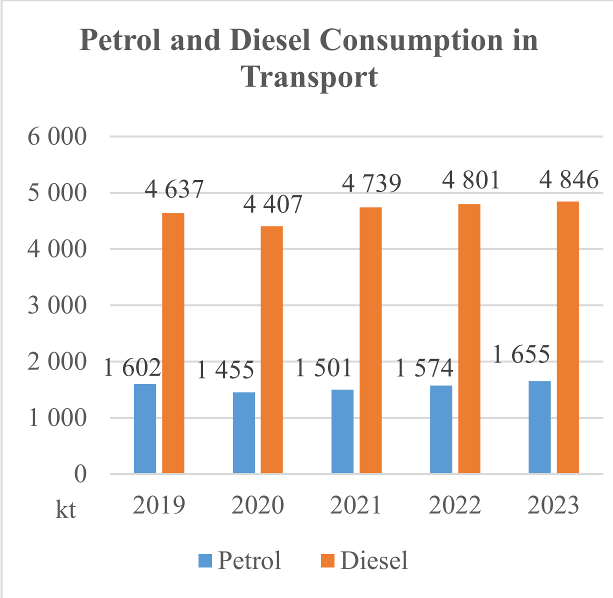

Fig. 3. Petrol and diesel consumption in transport over time. (Sydos, 2023)

In terms of consumption, electricity follows, increasingly used in urban transport and rail operations. Electricity plays a key role in the transformation of transport towards sustainability, and the overall energy efficiency of electric vehicles depends on the source of electricity. Electric vehicles powered by electricity from combined cycle gas power plants achieve an overall efficiency of 13–31 %, while the efficiency of electricity from coal-fired power plants ranges between 13–27 %. When using renewable sources such as wind and solar power plants, the overall efficiency increases to 39–67%. Even higher efficiencies of up to 72 % can be achieved by using rooftop solar systems, which minimize energy transmission losses. Regardless of the origin of the electricity, electric motors themselves have a high energy conversion efficiency of 81–95 %, which significantly exceeds the efficiency of combustion engines, which ranges between 30–45 %. (Albatayneh et al., 2020)

High efficiency is the main advantage of electric power. According to 2019 data, even with minimal consumption, it accounted for almost a quarter of transport performance, as shown in the following figure, which illustrates its efficiency.

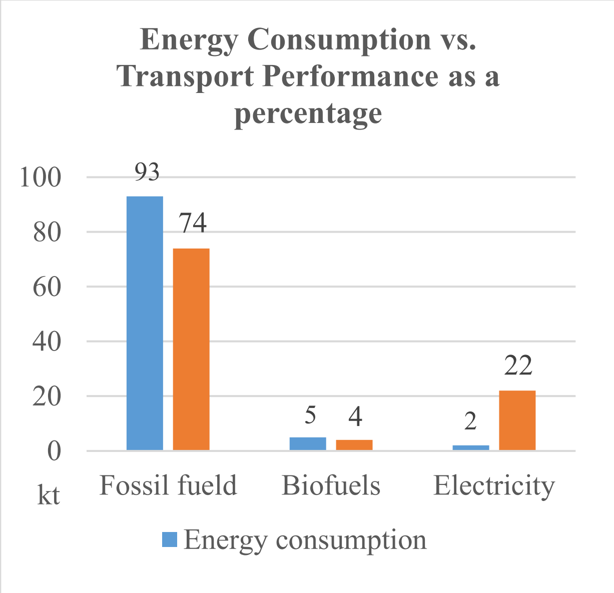

Fig. 4. Structure of electricity consumption vs. transport performance. (Pohl, 2021)

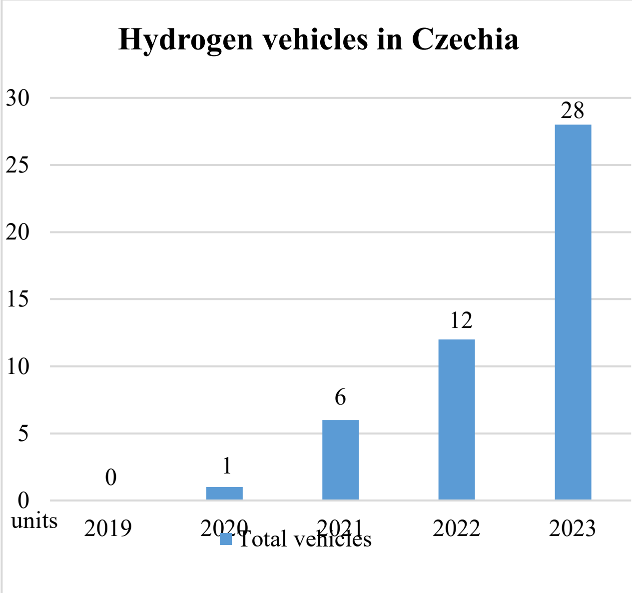

Fig. 5. Number of hydrogen vehicles in Czechia over time. (Sydos, 2023)

Alternative fuels are also becoming increasingly popular, especially hydrogen, which represents one of the key opportunities for transforming the transport sector towards decarbonisation. It is mainly used in fuel cells, which enable the direct conversion of chemical energy into electricity, with water as the only by-product. However, hydrogen has a very low volumetric energy density, which requires it to be compressed to a pressure of 700 bar or liquefied at a temperature of -253 °C. These measures significantly increase the energy intensity of its storage and transport. Hydrogen is currently most commonly produced by steam reforming of natural gas, a technology with relatively high efficiency but generating significant CO_2 emissions, making such hydrogen unsuitable for fuel cells. An alternative is water electrolysis powered by renewable energy sources, which eliminates emissions during the process but achieves lower efficiency, at 50–70 %. For wider use of hydrogen, it is therefore crucial to improve the technological processes of production, storage, and distribution in order to increase its economic competitiveness. (Pohl, 2023)

In the context of transport, hydrogen is a promising solution, especially for segments where battery technologies are reaching their limits, such as heavy goods transport or long-distance buses. For example, hydrogen vehicles have a range of up to 1,000 km and refuelling times comparable to conventional fossil fuels, making them suitable for applications with high operational flexibility requirements. (Pohl, 2023)

Specific data on hydrogen consumption in transport are not available due to the small number of vehicles. In 2024, there will be no hydrogen units in rail transport in the Czech Republic, and the number of hydrogen-powered private cars is increasing only very slowly, as can be seen in the following figure.

Specific efficiency statistics taking into account the entire production system are given in the following table.

Table 1. Differences in propulsion efficiency.

Type of propulsion	Propulsion efficiency
Traction motor and fuel cell (hydrogen)	27 %
Combustion engine (diesel, petrol)	30 %
Traction motor and lithium battery	70 %
Traction motor and overhead traction line	80 %

Source: Pohl, 2021

The continuous evaluation of energy sources used in transport is key to finding the most efficient ways to ensure mobility. Transport is globally responsible for approximately 24 % of CO_2 emissions associated with the energy sector and plays a significant role in dependence on non-renewable energy sources. There is also a significant difference in the prices of electricity, fuel, and hydrogen. The average electric car consumes about 13 kWh of electricity per 100 km, which at current prices (3 June 2025) of 4 CZK per kWh amounts to a total of 52 CZK, while at a petrol price of 34 CZK/litre for a car with an average consumption of 6 l/100 km, the total is 204 CZK. For a hydrogen-powered vehicle that consumes approximately 1 kg of hydrogen per 100 km and at the current price of hydrogen of 500 CZK/kg, the cost per 100 km is CZK 500 (kurzy.cz), (eru.gov.cz), (zpravy.aktualne.cz).

The following table uses accessible information to compare several factors for energy sources used in cars.

Table 2. Comparison of energy

Energy source	Consumption	Price per unit	Cost per 100 km	Emissions in operation. (g CO_2/km)
Electricity	13k Wh/100 km	4 CZK/kWh	52 CZK	0
Petrol	6 l/100 km	34 CZK/l	204 CZK	160–200
Hydrogen	1 kg/100 km	500 CZK/kg	500 CZK	0

Sources: kurzy.cz, eru.gov.cz, zpravy.aktualne.cz, Dell'Aversano, et al., 2024, Guidi, G et al., 2023

Energy comparison of rail and road transport

Rail and road transport account for almost all freight and passenger transport in the Czech Republic. The most widespread transport system in Czechia is the combustion engine car, which, however, has high energy consumption in the form of fossil fuels and is also characterized by low efficiency, as the combustion engine has low efficiency, with approximately 1/3 of the fuel being converted into mechanical work and 2/3 of the fuel being converted into waste heat that is not used in any way. In contrast, an electric motor has an efficiency of up to 90 %. Unlike an electric motor, a combustion engine cannot recover waste heat, which cannot therefore be used. The only mode of transport that currently has a different supply system than hydrocarbon fuels, i.e., "clean" electric energy, is rail transport. In addition, electric vehicles allow energy to be recovered during braking to a standstill or when braking while coasting, which means that part of the energy used is returned to the grid, significantly reducing overall consumption. Depending on requirements, the locomotive can return the energy produced back to the power supply network, store it in a battery, or use it to power its own auxiliary drives. (Pohl, 2014)

Hybrid and battery-powered trains, which are capable of covering part of the route under overhead lines and the final part on battery power, are also currently undergoing significant progress. When travelling under overhead lines, the train recharges its battery cells and is then able to continue on battery power. The development of these trains will make it possible to operate individual connections in different directions without transfers and also to serve adjacent smaller terminal stations where electrification does not appear to be cost-effective. In connection with the launch of hybrid trains, the feasibility of so-called electric islands is being investigated, where only certain sections of the track or railway stations where trains wait for turnaround would be electrified so that they can recharge before the return journey and at the same time do not discharge during downtime.

Compared to rail transport, road transport is less energy-efficient and less environmentally friendly due to the following systemic disadvantages:

- road transport has high aerodynamic resistance, which increases with speed. Compared to rail transport, it is virtually impossible to take advantage of slipstreaming, as apart from trucks and trailers, road transport vehicles are usually alone on the road
- in long-distance freight transport, it is impossible to use fuels other than hydrocarbons, which are associated with low combustion engine efficiency and CO2 emissions: only rail transport uses a different type of energy, i.e. electricity, for its transport
- due to the design of their tyres, which are intended to provide the vehicle with the necessary stability, road vehicles have high rolling resistance. Whereas a wheel running on a rail has a resistance of only 1 ‰, a tyre running on a road has a resistance of 8 ‰
- one of the key energy advantages of rail transport is its ability to create large-capacity long trains, which can transport significantly larger quantities of goods in a single journey than road transport, which is particularly efficient for onward transport (Pohl, 2014).

Energy intensity research

In order to compare the energy intensity of rail and road transport, a section of railway line 251/252 from Brno to Břeclav and the parallel section of the D2 motorway were selected. In addition to measuring total consumption on this section, sectional measurements were also taken over a distance of 10 km, which were carried out during continuous driving without interruption. The starting point for the measurements on the railway was the Brno Maloměřice station and the end point was the Břeclav passenger station. Measurements on the motorway began in Brno at the Avion Shopping Park at the junction of the D1 and D2 motorways, and ended at D2 motorway junction to Břeclav.

Several electric locomotives, one diesel locomotive and two road freight transport vehicles were selected for the measurements. The first of the electric locomotives was a Siemens Vectron, put into service in 2011, followed by a class 183 locomotive, which has been in service since 2005. The last electric locomotive measured was a class 189 locomotive, in service since 2002. Diesel traction was represented by the 753.7 locomotive, which was originally manufactured in 1968 but underwent a major overhaul in 2001, during which the original engine was replaced with a more economical and reliable type. Modern trucks were selected for road transport, specifically the MAN TGX, which entered service in 2015, and the Renault Trucks – K, which has been in service since 2014.

The table below shows distances travelled and the weights of the combinations which were transported by the vehicles investigated.

Table 3. Overview of freight transported

Vehicle	loc. 193	loc. 183	loc. 189	loc 753.7	MAN TGX	Renault
Combination weight	2196 t	1116 t	1880 t	347 t	22,4 t	33 t
Distance travelled	66 km	66 km	66 km	66 km	48 km	51 km

Source: author

Method

The methodology for calculating energy intensity is not entirely straightforward, and the chosen procedure always depends on the type of vehicle being analyzed, the available data, and the purpose of the research. For the purposes of this research, which in the next section examines vehicles powered by different sources of traction energy, i.e., electric power and diesel fuel for locomotives and diesel fuel for truck transport, the total energy consumption of these vehicles was calculated in joules, which allows for a direct comparison of energy efficiency regardless of the type of fuel used. The most energy-efficient vehicle will be the one with the lowest energy consumption per tonne-kilometre transported. The calculation will be performed as follows:

The formula for calculating efficiency per tonne-kilometre is:

$$\text{Energy efficiency (MJ/tkm)} = \frac{Total\ energy\ (MJ)}{Weight\ of\ freight\ (t)\ x\ Distancetravelled\ (km)}$$

For diesel: We shall consider the net calorific value of diesel to be the standard value, e.g. 35.8 MJ/kg, and diesel density to be 0.85 kg/l. Thus, the energy in joules for 1 litre of diesel shall be calculated as $0.85 \times 35.8 \times 10^6$

For electricity: 1 kWh equals $3.6 \times 1063.6 \times 10^6$ joules.

Data collection and evaluation

Measuring energy intensity in the transport sector is a key step in comparing the efficiency of different modes of transport or specific vehicles, as in this study, which involves the collection and analysis of energy consumption data. For electric locomotives, data was obtained from an electricity meter that measures not only the electrical energy consumed, but also the energy recovered and returned to the grid. For diesel locomotives, fuel consumption was measured using an electronic flow meter, which provides accurate data on current consumption. Due to the need for accurate data, older locomotives without fuel flow meters could not be included in the study, as collecting data visually from the fuel gauge could lead to significant inaccuracies, particularly due to the tilt of the locomotive on the rails, for example at bends, where the fuel gauge on each side of the locomotive would show different values.

The energy consumption results for the vehicles investigated are recorded in the figure.

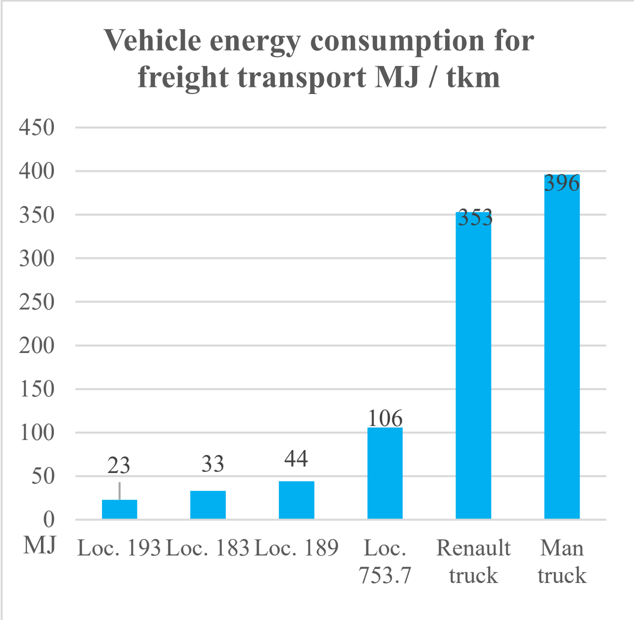

Fig. 6. Vehicle energy consumption for freight transport.

As the research has shown, the latest electric locomotive is, as expected, the most energy-efficient. The diesel locomotive is significantly less efficient than all the electric locomotives compared, but it performs significantly better than the trucks looked at in the research. The results also show that the latest generation of electric locomotives demonstrate progress in reducing energy consumption compared to older, albeit still modern, electric locomotives. This progress underscores the importance of innovation and technological development in rail transport.

Conclusion

The results of this comprehensive analysis clearly indicate that rail transport—especially when powered by modern electric locomotives—delivers significantly higher energy efficiency than road freight transport relying on internal combustion engines. Regenerative braking, low rolling resistance, and the ability to draw electricity from renewable or zero-emission sources make rail an exceptionally promising option in the pursuit of sustainable logistics. The findings also show that even older electric locomotives outperform modern diesel trucks in terms of energy consumption per ton-kilometer, underscoring the resilience and long-term value of electrified railway systems.

However, these advantages are currently constrained by practical and infrastructural limitations that hinder the broader adoption of rail, particularly in last-mile delivery, low-density regions, or areas with fragmented transport networks. In this context, the development of hybrid and battery-electric trainsets, along with the concept of "electrification islands," offers a practical pathway to enhance the operational flexibility of rail.

This study therefore not only validates the superior energy efficiency of rail freight but also highlights the urgency of systemic change and technological investment across the transport sector. It is recommended that infrastructure planning and public policy prioritize electrification, vehicle innovation, and the expansion of energy-efficient logistics corridors. Moreover, continuous real-world data collection remains essential for informed decision-making in both transport planning and environmental strategy.

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