

Environmental Comparison of Different Transport Modes

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Summary

The paper describes the energy consumption and GHG production comparison of three transport modes – road, rail and waterborne. The calculations are done according to the legislation in force – standard EN 16 258:2012 Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers). The results have high informative value because they take into account energy consumption and emissions from primary and secondary consideration. The calculation is done by real fuel consumption values (road and waterborne) and by simulation of energy consumption (railway). The energy and emission coefficients from the standard EN were used for estimating the results according to the well-to-wheels and tank-to-wheels principles.

KEY WORDS

energy consumption
GHG production
road transport
rail transport
water transport

1. INTRODUCTION

The current economic situation is directly dependent on transport. The follow-up activities leading to the creation of value products and services that meet the needs of the society and the individual could not be implemented without the transport of goods or services to the population [1-3].

During the transportation process the energy moves vehicles which provide the required transfer of goods and people in the area. Therefore, the transport depends on the supply of energy [4-7]. Today transportation is largely dependent on oil, as the vast majority of vehicles are driven by engines which combust petroleum products - hydrocarbon fuels. This particularly refers to the road, air and water transport. Most rail vehicles are now powered by electric traction motors, so they do not depend on oil as much as the above-mentioned modes of transport [8-11]. But the fact is that in most countries the electricity is produced through petroleum products or coal. These are non-renewable natural resources and their stocks have steadily declined.

Given the above, it is an effort to streamline the transport of energy dependence, as suggested by the legislative measures such as the White Book at the EU level or different policies and programs at the national state level [12-15].

Vehicle energy consumption represents the highest energy intensity of each mode of transport.

2. STANDARD EN 16258:2012 AND ITS USING IN CALCULATIONS

This European Standard EN 16258:2012 Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) specifies general methodology for calculation and declaration of energy consumption and greenhouse gas emissions (GHG) in connection with the provided services (cargo, passengers or both). It specifies general principles, definitions, system boundaries, methods of calculation, allocation rules (allocation, assignment) and recommendations on information to support the standardized, accurate, reliable and verifiable declarations regarding energy consumption and greenhouse gas emissions associated with the freight service. It also contains examples of the use of these principles.

The calculation for one given transport service must be performed using the following three main steps:

- step 1: identification of the various sections of the service,
- step 2: calculation of energy consumption and greenhouse gas emissions for each section,
- step 3: sum the results for each section [16].

The standard does not consider only the secondary emissions produced and energy consumed during the fuel combustion (energy conversion from fuel to mechanical energy), as well as

primary, incurred in the extraction, production and distribution.

- e_w - well-to-wheels energetic factor for the defined fuel,
- g_w - well-to-wheels emissions factor for the defined fuel,
- e_t - tank-to-wheels energetic factor for the defined fuel,
- g_t - tank-to-wheels emissions factor for the defined fuel.

Well-to-wheels is “well on wheels”, that also covers primary and secondary emissions and consumption. Somewhere this factor is also called as LCA (life-cycle-analysis).

Tank-to-Wheels factor is thinking only of secondary emission and consumption.

This Standard specifies the general methodology for calculation and the declared value for the energetic factor. The factor in greenhouse gas emissions must be selected in accordance with Annex A [16].

Emission gases are composed of several individual components (gas). Each one has different chemical and physical properties and participates in environmental degradation. In order to compare emissions from different activities, fuels, vehicles, where emissions have different track, and one representative unit must be designed for the purpose of comparison. This is the CO₂ equivalent, which is a measure of the specific emissions impact similar to the impact of CO₂. The label is CO_{2e} (equivalent).

3. ENERGY CONSUMPTION

Energy and emission factor (e_w , g_w) reflects a partial loss of production and distribution of power energy in the chain:

- energy mixture used in the manufacture of electric energy,
- efficiency of various energy sources,
- transfer efficiency (distribution) el. supply to the final consumer.

Due to these facts the effectiveness (efficacy) of the el. energy is directly related to power production technology.

Energy efficiency in electricity production can be calculated as a weighted arithmetic mean of primary resources and efficiency from various energy sources. Weight values represent the proportions of the various sources.

Produced energy gets to consumers through the transmission system. Recent losses in the transmission of produced energy power in locomotive wheels are custom transmission losses from conduction through the collector and control system of the locomotive. The efficiency of this process

is approximately 90 %. So overall energy efficiency supplied power for the rail transport is:

$$\eta_T = \eta_P \cdot \eta_{TL} \cdot \eta_{VS} = (\sum(\eta_{zi} \cdot p_{zi}) / p_z) \cdot \eta_{TL} \cdot \eta_{VS} \quad (1)$$

where:

- η_T - overall energy efficiency (-),
- η_P - efficiency of power. energy (-),
- η_{TL} - power transfer efficiency (-),
- η_{VS} - efficiency of vehicle system (-),
- η_{zi} - effectiveness of a particular primary source (-),
- p_{zi} - share of a given resource in the production of electric power (-),
- p_z - sum of partial fractions of the individual sources (-).

4. PRODUCTION OF EMISSIONS AND ELECTRIC ENERGY

The same procedure can be used to calculate the total energy efficiency for the emissions production. The procedure is the same, based on the share of individual sources and their emissions. The arithmetic mean was used for the results. The so-called emission factor is the easier way. This value is calculated for each country and includes the overall efficiency of electricity in a particular country along with the vehicle efficiency. Therefore, this emission factor should be used to compare the country without a lengthy search of sub efficiency and emissions.

5. CALCULATION OF ENERGY CONSUMPTION AND EMISSION PRODUCTION

5.1. Railway transport

Software Railway dynamics has been used to calculate the energy consumption of the train. This software calculates the power consumption of the train based on the predefined and selected values for the defined route. The software works with maps and elevation profile rail routes. Based on these defaults and selected characteristics (type of locomotive, train weight, train length, axle load, number and location of stops) the power consumption in kWh is calculated [6], [18].

The output consumption data were defined for further calculations and comparisons.

Calculated energy is the mechanical work needed to move the train. After transforming it into units of MJ, it is subsequently converted to the total consumed energy by an overall energy

Table 1 LCA emission factors of EU-27 countries

Country	LCA emission factor (tCO _{2e} /MWh)	Country	LCA emission factor (tCO _{2e} /MWh)
Austria	0.310	Sweden	0.079
Belgium	0.402	Bulgaria	0.906
Germany	0.706	Cyprus	1.019
Denmark	0.760	Czech Republic	0.802
Spain	0.639	Estonia	1.593
Finland	0.418	Hungary	0.678
France	0.146	Lithuania	0.174
UK	0.658	Latvia	0.563
Greece	1.167	Poland	1.185
Ireland	0.870	Romania	1.084
Italy	0.708	Slovenia	0.602
Netherlands	0.716	Slovakia	0.353
Portugal	0.750	EU-27 average value	0.578

Source: [17]

efficiency of equation (1) [18].

$$E_T = (E_{ME} \cdot 3.6) \cdot \eta_{CE} \quad (\text{MJ}) \quad (2)$$

where:

- E_T - total energy consumed electric traction (MJ),
- E_{ME} - mechanical energy consumed by the movement of the train (train dynamics software result) (kWh).

The LCA emission factor (EU-27 average value) was used to calculate the amount of produced emissions (table 1). The train consumed energy (MJ) is computed by dividing the mechanical work and the efficiency of the vehicle [18].

$$G_T = [(E_{ME} / \eta_{VS}) \cdot 1000] \cdot f_{LCA} \quad (\text{tCO}_{2e}) \quad (3)$$

$$G_T = [(E_{ME} / \eta_{VS}) \cdot 3.6] \cdot f_{LCA}^g \quad (\text{gCO}_{2e}) \quad (4)$$

where:

- G_T - total amount of emissions produced by electric traction,
- f_{LCA} - emission factor for electric energy (tCO_{2e}/MWh),
- f_{LCA}^g - emission factor for electric energy (gCO_{2e}/MJ).

5.2. Road transport

To calculate the total energy consumption of road transport, the amount of consumed fuel by road vehicle should be multiplied by energy factor for that fuel from Appendix A of the standard.

$$E_{TV} = [(FC_{km} \cdot L) / 100] \cdot e_W \quad (\text{MJ}) \quad (5)$$

where:

- E_{TV} - total energy consumed by vehicles (MJ),
- FC_{km} - vehicle fuel consumption (l/100km),
- L - driven distance (km),
- e_W - energetic factor „wtw“ for defined fuel (MJ/l).

To calculate the total GHG production, the consumed amount of fuel should be multiplied by an emission factor for that fuel from Appendix A of the standard.

$$G_{TV} = [(FC_{km} \cdot L) / 100] \cdot g_W \quad (\text{gCO}_{2e}) \quad (6)$$

where:

- G_{TV} - total amount of emissions produced by vehicles (gCO_{2e}),
- g_W - emission factor for defined fuel (tCO_{2e}/MJ).

5.3. Water transport

Consumed fuel by water transport was finding by the real measurement on vessel in real operation on river. To calculate the total energy consumption and GHG production of water transport, the amount of consumed fuel by vessel should be multiplied by energy factor and emission factor for that fuel from Appendix A of the standard. These are similar process of calculation to the road transport operation with small diversions – values from water transport operator are in the absolute amount of fuel (total volume of consumed fuel per shipping) and it is not necessary to multiple the FC_{km} and L [19-22].

6. MODEL STUDY

In this case study here is model transportation of 2100 t bulk cargo (compost plant) by freight trains, road vehicles and vessels as a direct transportation between two places with the distance of 260 km.

Compost plant can be stored and transported in open air. Bulk density of compost is 1200 - 1400 kg/m³. It also depends on the humidity of the substrate. The mean value was 1300 kg/m³.

Calculation of the energy consumption of road transport was considered with consumption of 28 l/100 km fuel at long distances. This value rises on shorter distance because the vehicle consumes more energy to start-up and for the standby operating mode [23-27].

Road vehicles are articulated semitrailer sets with dump body made of aluminium. Their less weight is 13 t, the payload 27 t and the body capacity 24 m³. Considering the maximal weight limit (40 t) it is possible to load only 20.8 m³ of cargo (87 % of capacity). Road vehicles have priority to use highways and expressways [28-31].

The train is composed of 43 Faccs wagons and locomotives Skoda E69 and E 479. The locomotives are used according to the track elevation (needed higher pulling power). This train is 620 m long and its gross weight is 3198 t. The payload represents 2100 t [3], [6], [31].

The 3 train stops during transporting. That is the presumed value of operating on the defined route and the distance.

Vessel set consist of TR MOUFLON and two boats DE II.b. Vessel TR MUFLON was built in shipyard Wroclaw under supervision of Polish estate register. The vessel is equipped with two 5-sheet propellers θ 1300 mm set in fixed nozzle. Steering device consists of 2x2 pieces of fins with proportional turning for moving forward [20], [21].

Here are the other power characteristics:

- main motors: 2 x MAN D2842 LE 412 2 x 588 kW at 1800 rev/min,
- mensural diesel consumption at 100 % load: 205 g/kWh,
- subsidiary motors: 2 x Deutz BF4M 2012C,
- mensural diesel consumption at 100 % load: 243 g/kWh,
- real average diesel consumption: 90 – 140 l/h,
- diesel reserve: 16.8 t (20 000 l),
- max. shipping independence: 140 h with netto mass 158 t.

An approximate duration of the navigation is 26 hour downstream of the river and 47 hours upstream based on the standard nautical terms, i.e. on the water and weather conditions permitting safe shipping.

Diesel consumption and shipping time data are related to the load of 190 – 200 cm, which represents 1.000 – 1.100 t for one boat. This means that the set capacity is 2.000 – 2.200 t [20], [21].

Table 2 Vessel set technical parameters

Vessel	Length (m)	Width (m)	Side height (m)	Dive (m)	Power (kW)	Capacity (t)
TR Mouflon	23.1	8.9	2.0	1.2	566/840	-
Boat DE II.b	76.5	11	3.2	2.7	-	1600

Source: authors

Table 3 Vessel diesel consumption

Route	Diesel consumption (l)
Upstream shipping	7618
Downstream shipping	2188

Source: authors

Table 4 Entry parameters values for calculation of mensural emissions

Motor	Unit	Consumption*
2 x MAN D2842 LE 412	kg/h	130.54
2 x Deutz BF4M 2012C	kg/h	25.2

* Precondition of 100 % load during the whole time of operation

Source: authors

7. EVALUATION

This part shows a graphical evaluation of the above mentioned case study. All calculations were done according to the legal standard EN 16 258 on the basis of real measured values or simulated values of fuel and energy consumption.

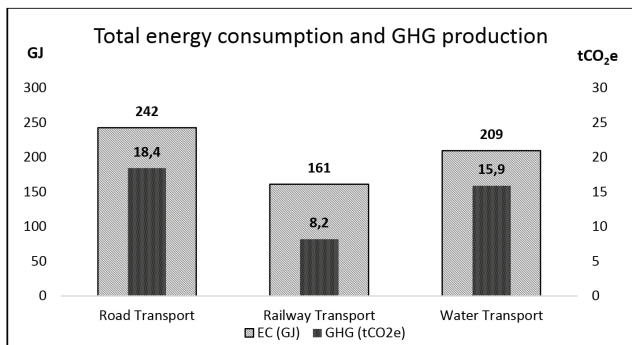


Figure 1 Total energy consumption and GHG production

Source: authors

Fig. 1 represents the absolute values of consumed energy and produced GHG for the solved freight case. The most effective is railway transport. This fact can be proven by lower driving resistances than in road and water transport and also by higher efficiency of the locomotive electric engine. Engines for electric traction reach the efficiency value at about 90 % but the diesel engines (used in road and water transport) only 40 %. This fact affects also the level of GHG production but not proportionally.

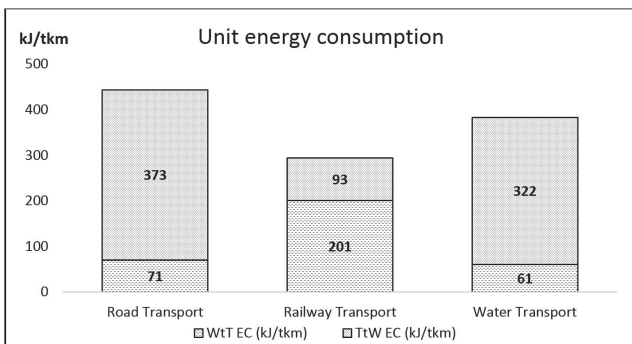


Figure 2 Unit energy consumption

Source: authors

T principle Well-to-Wheels (WtW) was used to estimate the results. This principle considers primary and secondary energy consumption and GHG production together. For higher representative value it is useful to share this principle on two parts – Well-to-Tank (WtT) which represents only secondary effects (production and distribution of the fuel or energy) and Tank-to-Wheels (TtW) which means the final consumption of fuel or energy directly by transport vehicle (f.e. automobile fuel consumption). These two parts represent the global environmental impact WtW.

Fig. 2 describes the diversion in primary and secondary energy consumption of fossil fuels (diesel) and electric power. Vehicle with diesel traction reaches higher values of energy consumption in TtW principle because of lower engines efficiency and high calorific value of diesel. This vehicle reaches lower values of secondary energy consumption (WtT). Production and distribution of diesel is not as intense as the electric power production. Efficiency of electric power production and distribution depends on primary sources but mostly reaches the value of around 35 %.

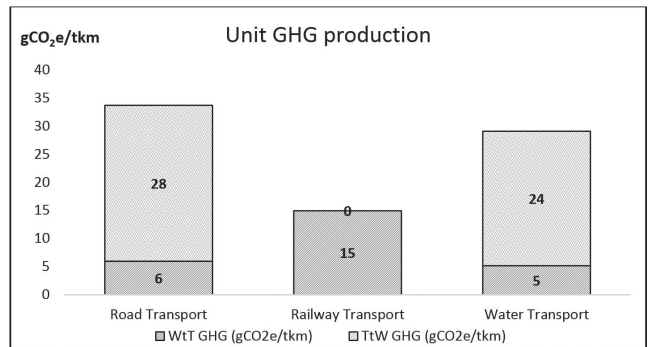


Figure 3 Unit GHG production

Source: authors

Graphical evaluation of unit GHG production describes the effect of “zero emission” electric traction. This fact is not completely true. Zero emission level reaches this traction only by taking into consideration the TtW principle, so the electric powered vehicle produces no emission in its actual location. But globally, the electric traction produces GHG during its production – changing primary sources into electric power. The mixture of these sources affects also the emission level (GHG production intensity). Vehicle which used electric power produced in countries where primary source for production of electricity is mainly coal, it will be never less GHG intense than other diesel powered vehicle. It was calculated with EU average level of electric emission factor (table 1) in this model study. The electric powered railway transport produces less GHG than diesel powered road or water transport vehicles.

8. CONCLUSION

In order to make the transport of goods sustainable, it is important to use the most of the transport modes which in terms of the energy consumption and GHG production are the most environmental friendly. The energy intensity and GHG emissions in transport depend on the available transport infrastructure, the choice of the suitable vehicles, the quantity

and nature of the transported goods and the traction or fuel used. Primary as well as secondary energy consumption must be taken into account in assessing the energy intensity and GHG production. An important factor that is often forgotten is that even electric traction can have a very significant negative impact on the environment if the primary sources for its production are the fossil fuels.

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