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ECOLOGICAL SOLUTIONS FOR FREIGHT TRAINS

Martin Chýle*, Michal Drábek

Czech Technical University in Prague, Faculty of Transportation Sciences, Deparment of Logistics and Management of Transport, Horská 2040/3, 128 00 Prague, Czech Republic

* corresponding author: chylemar@cvut.cz

Abstract. The article presents the potential of freight railway transport in terms of saving of emissions and maximizing the efficiency of operation. Attention is paid to the transport of freight trains on electrified lines with higher gradients (up to 25 ‰), alternatively with the possibility of a trip to non-electrified lines and sidings, which generate significant extra costs in the operation of trains and are often a reason for the carrier to deploy a locomotive of independent traction (diesel-electric) even in electrified line sections, even at the cost of increased operating costs and increased emissions. There are many such lines and possibilities of use within the Central European region and the Czech Republic.

In the first part of the article, the basic categorisation of dual-mode freight locomotives and their suitability for individual operating programmes is presented. This part also describes current situation on the rolling stock market in general and directions of development taken by various locomotive manufacturers.

Case studies of deployment of real freight locomotives on chosen Czech railway lines are used in the next part to present the possibilities for energy and cost savings when replacing a vehicle with independent traction by an electric or dual-mode locomotive, at least in sections equipped with overhead catenary. The pros and cons of using several possible solutions are described in detail. Further considerable savings can be achieved by, among other things, using regenerative braking and returning the generated electricity back to the catenary system when driving downhill. In this respect, however, it is also necessary to cooperate with the infrastructure manager, who must also adapt the railway lines to the operation of these vehicles.

Finally, general rules for operational deployments on which the replacement of a conventional vehicle by a dual or pure electric vehicle can be considered are formulated.

Keywords: Energetic mix, freight transport, hybrid locomotive, dual locomotive, last mile.

1. Introduction

Since the beginnings of the railway transport, in was common that all railway traction vehicles had only one mode of propulsion, which was available at the time. First of them was steam engine, followed by electric and diesel engine. Their development allowed to start the thinking about their possible combination with aim to reduce emissions and energy consumption.

Current situation in energetic industry and rising energy costs led everyone in the transport sector to the idea of saving energy and changing the energy mix used to power trains. These topics are going to be more and more serious in the future, and every new solution could be beneficial in the effort to make transport more efficient, environmentally friendly and effective.

2. Energetic mix and power sources

First, it is useful to look at the current situation in European energy industry and present power sources, which are used to power the trains. The energy sources vary widely across European countries.

According to the current data from Eurostat, the energy mix for the whole European Union is very diverse. Mountainous countries can benefit from hydroelectric power plants, as well as other renewable energy source; countries with flat landscape use more nuclear energy, or petroleum and fossil fuels. In European Union in general, 34.5 % of energy comes from total petroleum products, 23.7 % from natural gas, 17.4 % from renewable energy sources, 12.7 % from nuclear energy, and 11.5 % is still produced from solid fossil fuels. It's clear that these numbers have a huge variability, depending on local country conditions and political forces [1].

As can be seen from Table 1, in Czechia is the share of solid fossil fuels much higher than European average – 31.5 %. This is the third worst number in the EU (worse are only Poland and Estonia) and serious topic to address; according to Czech strategic energy plan, this percentage is planned to rapidly decrease in the next few years. On the other hand, the share of nuclear energy is higher than in many European countries (18.6 %), mainly thanks to two big nuclear power plants in Dukovany and Temelín.

By contrast, in Germany, for example, the share of nuclear power is just under 6 percent, and petroleum products account for over 35 percent of energy sources.

Country	Fossil fuels [%]	Nuclear energy [%]	Renewable sources [%]	Petroleum products [%]
Czechia	31.2	18.6	12.7	21.4
Germany	17.1	5.8	16.4	35.2
Austria	9.7	0.0	32.6	34.5
Slovakia	15.4	24.6	13.1	21.9
Poland	40.7	0.0	12.5	28.8

TABLE 1. Countries and shares of their energy sources.

This means that the electricity, used for power supply of rail transport in this country, has higher carbon footprint than in other countries. However, northern parts of Germany benefit from renewable sources like solar and wind power plants, which are located on the sea surface.

Austria has no nuclear power plants; this makes this source here irrelevant. In contrast it has significantly higher share of renewable power sources, thanks to mountainous landscape with wild rivers, where several hydropower plants have been built. The share of petroleum products in Austria is also higher than European average, like in Germany.

One of Europe's pioneers in the field of nuclear energy is Slovakia. This relatively small country has two big nuclear power plants (Jaslovské Bohunice and Mochovce), where ¼ of whole energy amount is produced. This number is the third biggest in the EU; better are only France and Sweden. However, the share of fossil fuels is still also high here (15.4 %). Nevertheless, Slovakian officials have repeatedly declared the closure of coal-fired power plants by 2030.

Poland has long been known for its operation of many coal-fired power plants. They produce more than 40 % of energy, which generates the second worst situation in Europe (after Estonia). The most important reason for this situation is the abundance of high-quality coal in the country, which can be excavated relatively cheaply and used for combustion in power plants. Connected with a lack of nuclear power plants and flat landscape, preventing the expansion of hydroelectric and wind power plants, energetic situation in Poland can be considered as the worst from all countries neighbouring with Czechia.

Conditions and status presented in last paragraphs show that the energy mix used to produce electricity can vary considerably across countries. It certainly cannot be said that the energy used for rail transport is equally clean in all countries. Especially countries with flatter landscape and low share of nuclear and renewable power sources have yet to take a major step towards reducing its carbon footprint [1].

3. Comparison of hybrid, electric and diesel locomotive

To demonstrate the possibility of energy savings, in this chapter the comparison of various locomotive types will be done.

FIGURE 1. Siemens Vectron AC locomotive, which is equipped with last-mile module (small diesel engine), pulling a freight train outside of the electrified track.

A dual-source vehicle can generally be considered as a traction vehicle having more than one power sources. Usually there is one primary and one secondary power source, which is used only in specific operating situations and under specific conditions. The reasons for using a secondary energy source are various, i.e., operational, technical (absence of overhead contact line, third rail, etc.) or economic (lower power and/or lower unit cost of energy, and thus lower operating costs).

These vehicles be designed as power-symmetrical (this means they have the same traction characteristics on electrified and non-electrified lines, but on electrified lines they take advantage of the linear electric power supply), or as power-asymmetrical (on non-electrified lines the power is lower than on electrified lines, the diesel engine or battery is a supplementary power source). A typical example is Siemens Vectron locomotive with last-mile diesel module, as shown in Figure 1. Such a traction vehicle cannot be operated on both energy sources at the same time – it must be time-framed when the vehicle is powered by primary or the secondary energy source.

The aim is to compare conventional diesel-electric locomotive with electric locomotive, as well as hybrid and dual locomotive, in the same operational modus – regional freight train on electrified line. In order to properly understand the context and explain the current situation, the following should be mentioned.

Parameter	Mark	Value	Unit
Calorific value of diesel	H	10	$kWh \cdot l^{-1}$
Efficiency of primary traction source	ν_p	97	%
Efficiency of electric traction in dependent traction	ν_e	85	%
Efficiency of electric traction in independent traction (battery)	ν_a	74	%

Table 2. Defined efficiency values.

Diesel-electric locomotives are still deployed on a significant number of trains running on electrified lines throughout the route (or most of it). In 2019, on the Czech railway network:

- 95.5 % of freight trains were operating on electrified lines,
- 86.8 % of transport capacity of freight railway transport were operated by electric locomotives.

From the numbers we can dedicate, that diesel locomotives are used almost twice much on electrified lines (8.7 %) than on non-electrified lines (4.5 %) [2].

The aim of this part of the text is, based on comparative calculations, to quantify the energy consumption and the resulting savings when running a train with a two-source locomotive, in different variants (both with auxiliary diesel generator and traction batteries) [3].

In the examples, the comparison of traction energy consumption and costs for four variants is addressed, where a) and b) are comparative variants:

a) Conventional diesel-electric locomotive with power output 800 kW (called class 742).

b) Conventional electric locomotive with power output 800 kW, used under an assumption, that all tracks are electrified (called class 210).

c) Hybrid locomotive with auxiliary diesel engine (called class 218).

d) Dual locomotive with traction battery (called class 219).

The main aim is to calculate the energy consumption. For this purpose, a simple model, working with the methodology of physical resistances of the environment, is used.

The most important such components are:

- Specific traction resistivity.
- Mean specific curve resistivity.
- Mean acceleration resistivity.

The sum of all these resistivities we can call the **mean specific traction resistivity**. To determine the values of these resistivities, we need to know a number of physical quantities and values, which depend not only on the specific type and parameters of the vehicle, but also on the parameters of the track and the surrounding environment. All resistivities are treated as dimensionless quantities with the unit N or kN. Detailed calculation is based on the model, originally coming from Mr. Jiří Pohl's model [4].

After the calculation of the mean specific traction resistivity, the traction work can be calculated. This value is the basis for determining the specific work and the resulting specific energy consumption for the given transport performance.

The last of the preparatory calculations is the calculation of specific energy consumption. The already calculated specific traction work and the efficiency of the energy source are used to determine it. This is defined by constants in Table 2.

The result is therefore the specific traction energy consumption according to the formula:

$$q_D = \frac{w_t}{H} \left[\frac{\text{liter}}{1000\ \text{tkm}}\right], \quad (1)$$

for diesel traction and:

$$q_E = \frac{w_t}{\nu} \left[\frac{\text{kWh}}{1000\ \text{tkm}}\right], \quad (2)$$

for electric traction, where w_t is specific traction work, H calorific value of diesel and ν efficiency. The value of specific traction energy, which we'll obtain, can be used in the calculation of the total energy consumption at every power output.

3.1. Example

As a suitable example for the demonstration of possible use a two-source locomotive was chosen the local freight train from Karlovy Vary to Stráž nad Ohří in North-western Bohemia. This train runs along the entire route on a double-track electrified line with a 25 kV/50 Hz AC power supply system; its locomotive runs off the catenary only when serving the secondary tracks and sidings at the siding stations. Currently, the train is pulled by a conventional diesel locomotive class 742 with power output 800 kW.

To simplify all the calculations, we used a model of uniform freight wagons. All wagons on the train are uniform: the weight of each empty wagon is 25 tonnes, while the loaded wagon is 75 tonnes heavy. Tables 3 and 4 give us an example of typical composition of this train in both directions.

Total length of the line is 16 km; on the line are significant gradients (in some parts up to 15 ‰) and sharp arcs. The locomotives run on electric power in the intermediate sections (and diesel loco on diesel power); for shunting and operations with wagons, they used their primary power source (742, 210), or a secondary power source (218 – diesel engine, 219 – a battery).

Track section	Composition of the train (wagons)	Total weight
Karlovy Vary – Ostrov nad Ohří	6 empty	150 t
Ostrov nad Ohří – Stráž nad Ohří	3 empty	75 t

Table 3. Train weight in direction Karlovy Vary – Stráž nad Ohří.

Track section	Composition of the train (wagons)	Total weight
Stráž nad Ohří – Ostrov nad Ohří	3 loaded	225 t
Ostrov nad Ohří – Karlovy Vary	6 loaded	450 t

Table 4. Train weight in direction Stráž nad Ohří – Karlovy Vary.

Track section	Composition of the train (wagons)	Total weight
Jihlava – Jihlava město	20 empty + 4 loaded	800 t
Jihlava město – Batelov	18 empty + 2 loaded	600 t
Batelov – Horní Cerekev	16 empty	400 t
Horní Cerekev – Jihlávka	8 empty	200 t

Table 5. Train weight in direction Jihlava – Jihlávka.

Track section	Composition of the train (wagons)	Total weight
Jihlávka – Horní Cerekev	3 loaded	225 t
Horní Cerekev – Batelov	1 empty + 5 loaded	400 t
Batelov – Jihlava město	5 empty + 5 loaded	500 t
Jihlava město – Jihlava	7 empty + 7 loaded	700 t

Table 6. Train weight in direction Jihlávka – Jihlava.

The same model was applied also at line Jihlava – Jihlávka, which is located in the central part of Czechia (Table 5 and 6).

This line is 37 km long and the maximum gradient is 15 ‰. The height difference between both terminal stations is approximately 160 meters. The assumption of the operating model is the same as in the first example.

3.2. Results

For the equivalent comparison of the energy consumption of all types of locomotives, the weighted sum method was chosen, where the total traction energy consists of:

- for a diesel loco only the diesel consumption, converted by the calorific value of diesel,
- for an electric loco only the consumption of electricity,
- for a hybrid loco with auxiliary diesel engine the consumption of electricity, added up with a diesel consumption of the auxiliary diesel engine and converted by the calorific value of diesel,
- for a dual loco with traction battery the consumption of electricity, added up with a consumption of electricity when running on battery power.

Total amount of consumed energy Q is based on the following formula:

$$Q = q_D + q_E + q_A \text{ [kWh]} , \qquad (3)$$

q_D, q_E and q_A are specific traction energy consumption for every traction mode (diesel, electric, battery).

Energy consumption of the locomotive types are illustrated by Tables 7 and 8.

As can be seen from the tables, using a locomotive with mainly electric power is saving approximately 75 percent of energy consumption. The significant difference is caused mostly by considerably lower energy consumption when staying in the station, as well as during the running with no traction effort. Second reason is using the recuperation, allowing the return of kinetic energy in the form of electrical energy back to the overhead catenary line. It is worth to note that the way in which the locomotive is powered off the overhead contact line (electric, diesel, battery) has no significant effect on the total cost. It is essential that diesel engine is not used on the electrified lines, as the most energy is consumed when running between stations [5].

4. Selected other options for deployment of hybrid and dual locomotives

The comparative examples, presented above, can't cover all aspects of the operation of railway traction

Class	Loco type	Total (day) E [kWh]	Total (year) E [kWh]
742	Diesel	2,617	392,619
210	Electric	978	146,659
218	Hybrid	920	137,981
219	Dual	892	133,772

TABLE 7. Energy consumption of all types of locomotives on the line Karlovy Vary – Stráž nad Ohří.

Class	Loco type	Total (day) E [kWh]	Total (year) E [kWh]
742	Diesel	4,969	1,242,132
210	Electric	1,932	483,106
218	Hybrid	1,913	478,352
219	Dual	1,830	457,555

TABLE 8. Energy consumption of all types of locomotives on the line Jihlava – Jihlávka.

vehicles. However, it's clearly visible, that in freight traffic can electric locomotive, or locomotive with auxiliary power source, bring significant energy savings, connected with appropriate cost savings.

Hybrid and dual locomotives can be used also in passenger transport. Nevertheless, their possible deployment here is much narrower. It is possible to consider their deployment on routes, where part of the train route is on electrified lines and part on non-electrified lines. Typical example is the EuroCity train from Prague to Munich, where the parts Prague – Plzeň and Schwandorf – Munich are electrified, while the middle section between Plzeň and Schwandorf not. The present situation is to change a locomotive twice, but dual locomotive (with a driving wagon) allows to pull the train on whole route and shorten the total travel time. Similar examples can be found all around Europe [6].

In freight transport, the spectrum of possible deployment is even wider. Locomotive with energy-clever power can be deployed for operation similar to mentioned above in passenger transport. For example, electric locomotives with auxiliary diesel engine are suitable for deployment on trains where the origin/destination station is not far from the electrified line and the track conditions do not require high power outside the catenary. Such a locomotive can also pull a train from a marshalling yard or similar location, for example car factories, coal mines etc., instead of a diesel locomotive.

Many operators are trying to reduce operating costs on the shunting operation as well. Modern shunting locomotives with enough power (i.e., from batteries) can then replace conventional diesel locomotives at shunting yards and local freight trains, like the examples mentioned above. One of practical examples is the locomotive of class Eem 923 (built by Stadler), which is already being successfully used in Switzerland for such applications [7]. The main benefit of using these high-performance dual locos is shortening travel times, as well as reduction of emissions. The travel time is directly proportional to the vehicle's output (class Eem 923: 1 500 kW in electric mode, conventional diesel locomotive: ca. 700–800 kW) [8, 9].

5. Evaluation

Because of current situation in energetics, as well as in railway industry, the need for environmentally friendly solutions for rail transport is becoming more and more acute. Principles and comparisons, mentioned in this paper, are considered as one of the possible solutions to the problem. The main objective is the substitution of conventional diesel locomotives on all spectre of traffic, where the conditions allow to use locomotives with lower emissions (mainly electric or battery powered). Electric locomotives with an internal combustion engine could also save operators the costs affected by having a second (diesel) locomotive to cover short sections of the train route (so-called "last mile").

The second important topic is to reflect on the origin of the energy used to power the trains. Currently, the situation across European countries is widely variable and the differences between the countries are meaningful. The strategy is to increase the share low-emission sources, like nuclear power, or renewable sources, while the share of fossil fuels and oil products will have to be as less as possible.

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