

Article

Efficient Deployment of Dual Locomotives in Regional Freight Rail Transport

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Abstract: The present article focuses on the efficient deployment of dual locomotives in regional rail freight transport considering the quantification of traction energy and energy savings. In the first part of the article, a categorization of dual locomotives, according to their power output in electric and alternative traction (and ratio of both power outputs) is proposed. The potential of deployment of chosen dual locomotives in Central European conditions (a sub-network of Czech railway network around mainlines electrified with AC) is verified by calculation of traction energy consumption of the model train (with two examples of dual locomotives). In addition to non-stop running through the entire line, traction energy consumption of stop (and following acceleration) in each intermediate station is calculated, for a particular direction. Then, appropriate freight train paths for passing passenger trains and saving of traction energy are proposed. The results are supplemented by sensitivity analysis in the form of calculation of traction energy consumption with variable numbers of loaded wagons, with the help of iPLAN/FBS timetabling software. The limitations are the maximum length or gross mass of the train. Finally, the conclusions obtained from the computational examples are evaluated and recommendations for appropriate deployment of dual locomotives and planning of targeted improvements of infrastructure are formulated.

Keywords: dual locomotive; freight transport; hybrid locomotive; last-mile; traction energy consumption



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1. Introduction

Thanks to the rapid development of technology, the market with dual rail vehicles has boomed in recent years. These vehicles combine the advantages of both dependent (catenary) and independent (off-catenary) traction. In addition to electric/dual passenger multiple units, dual locomotives are a very important category, designed for a wide range of operational tasks. Railway operators are trying to use these vehicles to save not only traction energy, but also the absolute number of operated vehicles and manpower.

Under these conditions, it is necessary to determine suitable operational deployments and solutions for these locomotives and to classify them. An appropriate classification and performance assignment can assist in improving the efficiency of the use of the vehicles in question and making them easier to classify in the future, as well.

Currently, dual vehicles are still often seen as relatively underused and untested on the European railway network. For this reason, it is necessary to expand their use and prove that they can work very efficiently and with benefits in appropriate operational deployment.

The article is divided into six sections: Introduction, Literature Review, Materials and Methods, Results, Discussion, and Conclusions. The summarized content of the sections are as follows: Literature Review proceeds in a logical order toward the addressed research gap and discusses the appropriate categorization of dual locomotives. Materials and Methods consist of five principal parts that describe materials and boundary conditions for the calculation experiment—definition of the problem, formulation of the method for assessment of energy consumption of a dual locomotive with a given power output (based on gross mass

of the train and stopping in particular stations), introduction of principles of calculation of traction energy consumption in iPLAN/FBS timetabling software [1], introduction of chosen railway lines with three types of terrain and methodological approach for their choice, and, finally, introduction of the model trainset (with two alternative locomotives) and principles of construction of freight train paths. The Results section describes the different values of traction energy consumption of running through chosen lines and optional stop for each intermediate station (and direction) for chosen dual locomotives and model freight trains on different railway lines, as a result of calculation of traction energy consumption in iPLAN/FBS timetabling software [1]. Then, appropriate stations for the stopping of model trains in each direction in terms of energy savings and possible train length, considering the periodic passenger timetable, are proposed. In a subsequent sensitivity analysis, additional loaded wagons are incrementally added to model trains, resulting in the change in stops in favor of stations with longer tracks. In the Discussion section, the results of the timetabling experiment are interpreted in the context of previous research. The final section, Conclusions, summarizes a brief background of the introduced research, its contribution and major findings, followed by recommendations for the appropriate deployment of dual locomotives, for the planning of targeted improvements of infrastructure, and for further research.

This paper was intended as an extended article of the conference paper “Dual locomotives for regional freight trains”, presented at the CETRA 2022 in Pula, Croatia [2]. However, the original timetabling experiment has made this paper a follow-up of the original paper.

2. Literature Review

2.1. Overview of Dual Locomotives

As the field of dual locomotives is still relatively new, small, and rapidly developing, the amount of literature published on the subject is also relatively limited. One of the first general articles is a Swedish paper by Östlund [3]. Then, this topic was further elaborated by Swedish experts [4]. The wide-range treatment of this subject was very well-performed by Vitins [5]. In recent years, the issue of operating diesel locomotives with battery boosters has also been increasingly addressed, for instance, by Bearham [6].

On a general level, a comprehensive analysis of the possibility of the emergence and operation of two-source locomotives in the USA is a rather old but very well-performed treatise. Although the study dates back to 1981, its general ideas and conclusions can be implemented in current conditions after a sensitive review, especially the part devoted to the general problem of conversion of a conventional diesel-electric locomotive to a hybrid or dual locomotive [7]. Moreover, there were very well described methods of propulsion, along with their possible incorporation into existing diesel locomotives, which makes it possible to obtain dual locomotives of good performance parameters cheaper than by manufacturing completely new vehicles.

In terms of operation of dual locomotives, several ideas have already been carried out, including the conversion of a classic diesel-electric locomotive to a battery locomotive and its use on gradient-demanding lines [8]. Another proposal was to design a hybrid drivetrain for a shunting locomotive [9]. Then, the Polish experts discussed energy efficiency and its use in the context of vehicle circulation planning in freight transport [10,11].

In general, it is also advisable to focus on the driving technique and technology to save energy—this was discussed in detail by Bai et al. [12]. Moreover, it is very useful to look at the efficiency of operation and individual operational processes, for example, for shunting locomotives, according to Schaal et al. [13].

Studies on the possibility of charging hybrid locomotives in freight transport have already been carried out using the MATLAB/Simulink calculation tool [14]. Moreover, when planning the operation of these locomotives, it is necessary to consider the general social impact of this transport, which has already been studied by Dolinayova, Kanis, and Loch [15].

Furthermore, the operation of locomotives must be optimized and planned in cooperation with the planning of staff shifts, using the theses published by A. and O. Kotenko in their article [16]. The operation and deployment of locomotives should generally be planned in accordance with the deployment of personnel.

In general, there are also other possibilities to address the efficiency of diesel-electric locomotives on non-electrified lines, for example, as described in the study of Saadat et al. [17]. In France, the possibility of operating the locomotive off the catenary based on ultracapacitors has also been investigated [18].

Finally, when operating a locomotive, it is also very useful to examine the source of the energy used to drive the locomotive. The principles of energy management depending on the energy source have been extensively described in a study from Spain [19].

2.2. Categorization of Dual Locomotives

2.2.1. Role of Power Asymmetry

A dual-source vehicle is generally seen as a railway traction vehicle with two power sources. In a very basic way, dual vehicles can be classified as power symmetric and power asymmetric. This categorization is to observe whether the two power sources are equivalent and can be adequately interchanged.

Most dual locomotives designed and produced today are power asymmetric, as it is usually not possible to fit both power sources of the same power output into the vehicle, especially for space reasons. This indicates that there is one primary and one secondary power source, intended for use only in special operating situations and under specific conditions. Grounds for using a secondary power source can be various, especially operational, technical (for example, absence of overhead catenary) or economic (lower power or lower unit cost of energy, which indicates lower operating costs). With few exceptions, this power asymmetric vehicle cannot operate on both power sources at the same time—it must be clearly time-framed, when the vehicle is powered by one or the other power source.

For this reason, the lower-power secondary power source is intended only for special operational deployment within a limited time frame. The operational range in this case depends on energy consumption and energy reserves—it can be hundreds of meters or even tens of kilometers. The operating time on the secondary power source can also vary considerably, from a few seconds to many minutes. The typical example is a conventional high-power electric locomotive with small auxiliary diesel engine. This engine allows an electric locomotive to run on tracks without a catenary, or on a siding yard, without the help of another vehicle. Locomotives in this category are already offered by several renowned manufacturers, including Siemens, Stadler, etc. Their common denominator is the high power output in an electric traction, allowing for a normal operation (as conventional electric locomotives), and significantly lower power output in diesel traction, which allows for only a very limited, but sufficient range on tracks or lines outside of the catenary [20,21].

However, in recent years, electric locomotives with more powerful motors have also appeared. Although their diesel engine has considerably less power output than a locomotive in electric traction mode itself, it is sufficient to run on sidings at lower speeds (with adequate load). The latest product in this category is the Vectron Dual Mode Light locomotive, which has been ordered by Deutsche Bahn Cargo for the operation of regional freight trains. In electric mode, this locomotive has a power output of 2210 kW, while its diesel engine has a power output of approximately 800 kW. Both power outputs are set to be fully sufficient for the planned operational deployment [20].

Partial (or dual) electric vehicles are generally defined as conventional electric vehicles capable of operating in both modes (dependent and independent traction). In general, these are electric vehicles that can fully operate on sections without a catenary, by diesel engine or batteries. In urban transport, partial trolleybuses equipped with auxiliary batteries are also being extended to serve the end sections of lines without overhead catenary, where it

is not cost-effective to build overhead lines. Two-source electric traction units (BEMUs) are already in operation on the railway, as well.

Under these circumstances, for the purposes of this article, dual locomotives can be divided into the following two basic power categories.

2.2.2. Locomotives of Lower Power Category

As the name suggests, these vehicles have a significantly lower power output in both dependent and independent traction. In general, it can be quantified in the range of approximately 300 to 1500 kW, while it is true that the power output in dependent and independent traction does not need to be (and usually is not) the same.

These locomotives are particularly well suited for the shunting service, where they can combine the advantages of a conventional electric shunting locomotive (low idle power consumption, virtually unlimited range, emission-free, and quiet operation) with the advantages of a diesel shunting locomotive (especially independence from the overhead catenary). However, apart from the shunting service, they are also well suited for the light regional freight service, where they can be used to distribute wagons between marshalling yards (“hubs”) and the end customers in stations in the collection circuit of the marshalling yard, especially in flat areas where this high traction power is not required. A good practical example of this deployment is the Swiss locomotive type Eem 923 (“Butler”), operated by the Swiss national freight carrier SBB Cargo since 2011.

These locomotives are in service at major marshalling yards throughout Switzerland, notably Zurich-Limmattal, Basel, etc. In electric mode, the locomotive achieves up to 1500 kW of power, while its diesel engine has a power of 290 kW, which is fully sufficient to serve sidings and tracks without overhead catenary [2]. The maximum speed in electric mode is 120 km/h, which allows the locomotive to carry a short freight train even on very busy lines, where high speeds are needed for the efficient utilization of infrastructure capacity.

In principle, these types of locomotives do not have to use only the internal combustion engine when moving off the catenary. However, the current state of technology development and the high cost of battery technology have not yet made it possible to introduce locomotives of this power category using a battery rather than an internal combustion engine into regular service. Apart from several prototypes, tested in multiple European countries, the only electric-battery locomotive in regular service at the moment is the Geaf 2/2, ordered by the Rhaetian Railway (*Rhätische Bahn*) in Switzerland in seven units. These locomotives were ordered in 2018 and delivered by Stadler 2 years later. Their hourly power output in electric mode is 500 kW (200 kW on battery), which is fully sufficient, especially for the shunting service and operation of sidings at Chur, Davos Platz, and Samedan stations. However, they are operated (such as all Rhaetian Railway vehicles) on a 1000 mm gauge, which makes them quite different from all conventional vehicles. Therefore, they are mentioned in this paragraph for completeness only [2].

2.2.3. Locomotives of Higher Power Category

The second category of dual locomotives are locomotives of higher power category. This category includes all locomotives whose continuous power in primary mode exceeds 1500 kW. In principle, this includes all locomotives intended for line service and long-distance transport (passenger or freight). They are usually built in a box arrangement, i.e., with two driver’s cabs at both ends of the locomotive frame, between which is the engine room—a space for storing all traction equipment (internal combustion engine, generator, transformer, cooling blocks, ventilators, batteries, etc.).

Most of the currently known and manufactured dual locomotives fall into this category—Siemens Vectron Dual Mode, Stadler Euro Dual, etc. The most efficient use of these locomotives is in mixed operation, i.e., partly on electrified and partly on non-electrified lines, on which they can transport both passenger and freight trains. A more detailed analysis of the operation of these locomotives is the aim of the following parts of the article.

As in the case of the lower power category, the power output in both operating modes (dependent and independent traction) can be dimensioned according to the specific operating application. Locomotives with lower power have a continuous power output of around 2000 kW (e.g., Vectron Dual Mode), but there are also locomotives available on the market with significantly higher power output—Stadler’s Euro Dual has a power output of up to 7000 kW in dependent traction mode (electric mode), mainly due to its frame length of 23 m and six-axle wheelset arrangement. In diesel mode (independent traction), its power output is significantly lower, at around 2500 kW, depending on the customer’s wishes and the planned operating mode [21].

2.2.4. Last-Mile Locomotives

A specific case of dual locomotives are locomotives with the so-called last-mile module. In principle, these are conventional electric locomotives, currently offered by a number of reputable locomotive manufacturers, but supplemented by an auxiliary power unit that allows them to briefly leave the tracks with the overhead catenary. At present, this is usually a small diesel engine, but a battery pack is not ruled out for the future.

The power of this auxiliary propulsion is very low compared to the normal power of a locomotive in dependent traction mode, since it is intended only for the necessary shunting and move, for example, to the factory or other industrial areas, where a train needs to be transported. Therefore, the train operator does not have to use another independent traction locomotive separately for this first and last section of the journey. The auxiliary propulsion is definitely not used to drive the locomotive, or even the whole train during normal running on the line—for this purpose, the locomotive has sufficient power output in electric mode. Nevertheless, the benefit of this independent propulsion is also the possibility of pulling the train off the line if the power supply to the overhead catenary is interrupted.

However, in the following parts of the paper, as well as in the analysis, last-mile locomotives will not be considered further. They are listed here for completeness only.

3. Materials and Methods

3.1. Definition of the Problem

For a more precise assessment of the operating range of dual-mode locomotives, it is necessary to know the typical energy consumption of a stop and following acceleration, and the difference in energy consumption of running uphill and downhill. The main aim of this paper is an evaluation and discussion of the results of a timetabling experiment that was carried out with the help of FBS-iPLAN timetabling software [1] (in which the authors’ faculty have been licensed to use it for academic purposes and to maintain a database of Czech railway infrastructure [22]), for an appropriately chosen locomotive and a model trainset, on three types of Czech secondary mainlines without catenary, in the context of the periodic timetable of passenger trains, and possibly limiting lengths of station tracks. The software estimates the consumption of traction energy on the basis of traction characteristics of the chosen locomotive, rolling, and gradient resistance, as explained in Section 3.3.

3.2. Method for Estimation of Values of Traction Energy Consumption of Stops of the Model Train and Construction of Energy-Saving Freight Train Paths

The first part of the timetabling experiment serves the purpose of an estimation of the traction energy consumption for each possible stop of the model freight train, in each intermediate station of a particular line, for both directions separately. For practical reasons (no necessity for stop), double-track sections of the line 340 (introduced below) were excluded.

For an estimation of traction energy consumption, the calculation of tractive work in FBS/iPLAN timetabling software [1] for the analogous type of the locomotive (Vectron Dual Mode, as well as Stadler Euro Dual) was used as follows. First, the train path for the

model train from the beginning to the end station of a particular line and direction, without any intermediate stop, was constructed. Stops in the beginning and the end stations were designed (for a change in the propulsion and, if needed, for change in the direction of the train), since stations were considered as all of the points on the line, where the passing (crossing) of two trains of opposite directions was practically possible. Intermediate stations with a distance from the beginning of the line are presented in Tables 1–3. For each station in the tables, the length of the longest, practically usable, station track for crossing of the model train is listed, with mostly passenger trains. Practical usability indicates that there are departure signals for both directions and that the stop of a freight train does not hinder boarding and alighting of the passengers in the case of a stop of a passenger train. The main station track (that directly continues from and to the rail line) is always excluded. The length of the longest usable station track is for practical reasons (visibility of the departure signal and reserve for inaccuracy of the stop) shortened by 20 m compared to the distance between departure signals, and listed in the official plans of the stations by Správa železnic [23]. These resulting lengths are listed in Tables 1–3.

For each chosen line, intermediate station and direction, the energy consumption of the stopping of the model train will be calculated as follows:

$$E_{stop,l,AB,X} = E_{line,l,AB,X} - E_{line,l,AB,0} \quad (1)$$

where

- $E_{stop,l,AB,X}$ is calculated as the traction energy consumption necessary for the stop and following acceleration of the model train on the line with number l , in station X in the direction from A to B ;
- $E_{line,l,AB,X}$ is calculated as the traction energy consumption of the journey of the model train on the line with number l , in the direction from A to B , with stops only in A , B , and X ;
- $E_{line,l,AB,0}$ is calculated as the traction energy consumption of the journey of the model train on the line with number l , in the direction from A to B , with stops only in A and B .

After the traction energy consumption of the stop of the model train in each station and direction is calculated, appropriate stations for passing the model freight train and passenger train (with periodic timetable as a rule) can be chosen. If no considered station restricts the length of the train, then a set of stations with the lowest sum of traction energy consumption of the stops that enable a feasible freight train path within a given periodic passenger timetable, is chosen. If one considered station restricts the length of the model train, the neighboring station with comparably low traction energy consumption (for particular direction) is chosen instead. If no replacement of the “short station” with neighboring station enables a feasible freight train path, one or more of the other passing stations are replaced in an analogous way. If no replacement enables a feasible freight train path, the model train has to be shortened in a particular direction in order not to exceed the maximum train length of the most restricting passing station.

Choice of appropriate passing stations for the model freight train with variable (higher) number of wagons is verified by sensitivity analysis in Section 4.3, after the presentation of the results of the timetabling experiment.

3.3. Software Used for Estimation of Values of Traction Energy Consumption

In the FBS-iPLAN timetabling software [1], traction and performance figures of the trains are calculated in the following way. The traction characteristics (speed-force diagram) of each locomotive (or motor unit) must be filled in. At first, the sum of the power outputs of the motors is inserted. Thereafter, the efficiency of the complete traction system is inserted in percent. Then, single points to describe the traction characteristics (in the values in steps of at least 10 km/h) are filled in. Next, the resistance of the locomotive or motor unit is defined. Moreover, wagon resistances are defined for each class. Railway infrastructure

(lines) is defined by longitudinal and speed profiles, including curves and tunnels (due to the additional resistance). Based on the abovementioned data, the software uses common formulas established in the railway sector to calculate the traction dynamic values [24].

The reference values of traction energy consumption, displayed below, were calculated by construction of the train paths for the model trainset, described in Section 3.5, with stops only in the beginning and end station of the particular line. Characteristics of all used locomotives, wagons, and lines have been previously defined in the FBS-iPLAN timetabling software by the software provider iRFP (vehicles) or at the authors' department (infrastructure).

3.4. Rail Lines Chosen for the Experiment

The aim of this part of the paper is to analyze the possibilities of operation of dual locomotives on selected lines, taking into consideration the additional energy consumption caused by running uphill or by the necessary stops and acceleration afterwards.

The authors decided to select three lines on the Czech railway network with different gradient and directional ratios, which are able to illustrate the possibilities of deployment of dual locomotives on a sufficiently differentiated sample. For this purpose, three categories of lines were chosen according to their gradient profiles—hilly line, flat line, and flat line with a significant peak in the middle. From each category, it was decided to select the most suitable line according to the following criteria:

1. Intensity of freight transport and its potential (lines of TEN-T network or lines of national importance according to the categorization of the Czech Railway Infrastructure Administration—Správa železnic). Lines with regular and heavy freight traffic are preferred.
2. Non-electrified line (or not the entire length of the line) linked in at least one end to an electrified mainline (25 kV 50 Hz AC).
3. The line is not ending—it connects at least two other lines.
4. The usable track length in all stations (excluding passenger switches) is at least 400 m (ideally more).
5. The capacity of the line is not significantly used by the intensive suburban passenger traffic.

Based on these criteria, the authors tested the consumption of traction energy on three non-electrified rail lines linked in at least one end to an electrified mainline (25 kV 50 Hz AC). Each rail line can be characterized by different types of longitudinal profile (see Figures 1–3). Each line is numbered according to the official passenger timetable sheets issued by Czech Railway Infrastructure Administration (Správa železnic) [25].

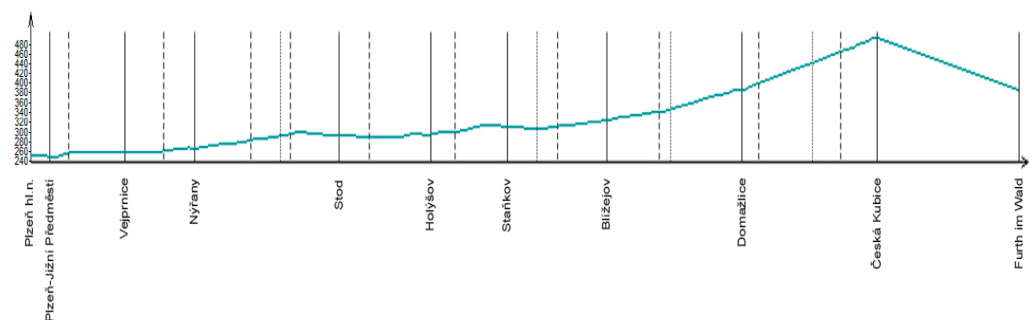
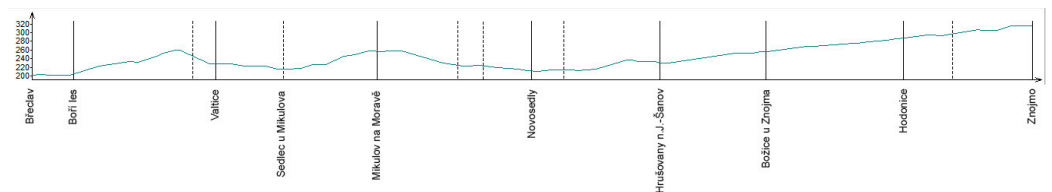


Figure 1. Longitudinal profile of the rail line 180 (data: [1,26]). Source: Authors.

Table 1. Intermediate stations of the single-track line 180 Plzeň–Domažlice–Furth im Wald. (data: [1,23,26]). Source: Authors.

Station	Maximum Train Length [m]	Distance from the Beginning Station [km]
Plzeň hl. n. N. Hospoda ¹	No station track	4.353
Vejprnice	709	7.721
Nýřany	568	13.459
Výh Chotěšov	731	20.526
Stod	560	25.306
Holýšov	637	32.866
Staňkov	527	39.145
Blížejev	803	47.284
Výh Radonice	653	52.536
Domažlice	725	58.392
Česká Kubice	547	69.474

¹ Junction with a change from double- to single-track line.

**Figure 2.** Longitudinal profile of the rail line 246 (data: [1,27]). Source: Authors.**Table 2.** Intermediate stations of the single-track section of the line 246 Břeclav–Znojmo (data: [1,23,27]). Source: Authors.

Station	Maximum Train Length [m]	Distance from the Beginning Station [km]
Boří les	591	2.862
Valtice	584	12.629
Sedlec u Mikulova ¹	180	17.262
Mikulov na Moravě	963	23.686
Novosedly	401	34.287
Hrušovany n. J.-Šanov	411	43.111
Božice u Znojma	502	50.420
Hodonice	609	59.852

¹ This station was built additionally for the periodic passing of passenger trains.

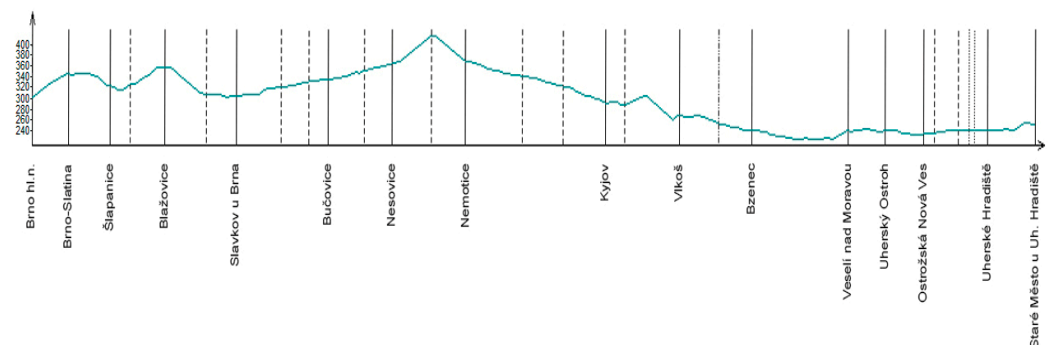
**Figure 3.** Longitudinal profile of the rail line 340 (data: [1,28]). Source: Authors.

Table 3. Intermediate stations of the single-track section of the line 340 Staré Město u U. H.–Brno (data: [1,23,28]). Source: Authors.

Station	Maximum Train Length [m]	Distance from the Beginning Station [km]
Uherské Hradiště ¹	377	5.012
Ostrožská Nová Ves	596	11.734
Uherský Ostroh	568	15.762

¹ This station serves as the beginning/end station for many passenger trains.

The first, single-track, rail line 180 connects Pilsen (located in Berounka valley) and Regensburg (located in Danube valley), both with approximately equal altitude. It overcomes hilly Cham-Furth Depression (Czech: Všerubská vrchovina), located between mountain ranges, and thus there are long uphill and downhill sections that increase the consumption of traction energy. At the other end of the line, there is a connection to the German 15 kV 16.7 Hz AC supply system at Regensburg station. In the paper, the analysis is carried out on the section from the starting station Plzeň to the border station Furth im Wald, located on the Czech-German border, with the highest elevation and the top station (Česká Kubice).

The second, mostly double-track, rail line 340 connects the second largest Czech city Brno and regional centre Uherské Hradiště in south-eastern Moravia. This line is located mostly in flat terrain of southern Moravia, except for the pass between Ždánický les and Chřibý highlands.

The third, single-track, rail line 246 connecting Břeclav and Znojmo, lies in predominantly flat terrain.

For practical reasons (short station tracks due to determination for passenger trains), stations Sedlec u Mikulova (line 240) and Uherské Hradiště (line 340) will be neglected in further calculations (see Tables 2 and 3). However, for freight transport, these stations are of secondary importance.

3.4.1. Hilly Line (180)

This is a typical line in the region of Central Europe, which includes flat but also challenging sections with inclines. The maximum gradient is up to 12 per mille in crucial sections. Therefore, the permissible load limit is significantly limited by these restrictive sections. Gradients are in both directions.

For comparison purposes, the 81.154 km long line section from Plzeň via Domažlice in western Bohemia to the German border station Furth im Wald was selected as a sample line in this category. The whole length of the line is non-electrified, except for a short section in Pilsen (about 2 km), equipped with 25 kV 50 Hz AC power system. However, in the long term, the entire line should be covered by the same power system; the section from the state border to Germany should be covered by a German 15 kV 16.7 Hz AC system.

3.4.2. Flat Line (246)

The representative in this category is the line Břeclav–Znojmo, leading through the flat landscape in the southern part of Czechia, along the state border with Austria. This 68.725 km long line is characterized by a favorable longitudinal profile with minimal gradients. This makes it possible to transport considerably higher load volumes with one locomotive. In most of the length of the line, there are flat sections with a maximum gradient of 5 to 7 per mille. As well as in the case of the first line, the line is currently non-electrified, except for the starting station Břeclav, located under the 25 kV 50 Hz AC power supply system. On the other hand, the second end station Znojmo is equipped with a 15 kV 16.7 Hz AC power system, which is used in neighboring Austria. In this case, there are also plans to electrify the line with 25 kV 50 Hz AC system in the future.

3.4.3. Flat Line with Significant Peak in the Middle (340)

The third category represents lines that run through predominantly flat areas but have one significant peak that limits the maximum permissible train weight. There is a considerable number of these lines in Central Europe.

An example for this last category of lines is the 111.431 km long line Brno–Veselí nad Moravou–Staré Město u Uherského Hradiště, located in the south-eastern part of Czechia. Among the three lines presented, it is specific in that it is electrified in the section between Brno railway junction and Blažovice station (the first 20 km), again with a 25 kV 50 Hz AC power supply system. From Blažovice to the end of the line, the line is non-electrified, but the final station Staré Město u Uherského Hradiště is again on the electrified line, also under the 25 kV 50 Hz system. This line is located mostly in the flat terrain of southern Moravia, except for the pass between Ždánický les and Chřiby highlands. For this reason, the line in question is also very suitable for the deployment of dual vehicles, which can use the overhead catenary in sections where it already exists, and thus reduce diesel consumption. In addition, modern dual locomotives usually allow for switching between dependent and independent traction modes directly while running.

3.5. Model Trainset and Construction of Train Paths

The reference trainset consists of 20 container wagons (type Sgnss-x); for simplicity, the trainset is considered as homogeneous and composed only of these wagons with a unit weight of 78 tons (the average weight of a wagon loaded with two 40-foot containers). Therefore, the total length of the trainset (with the longer of the two considered locomotives) is 419 m, and the hauled (towed) weight is 1420 tons. Two types of dual locomotives—Siemens Vectron Dual Mode (G15 variant) and Stadler Euro Dual (HVLE variant)—transport this set on the reference lines. The technical parameters of the locomotives are as follows.

As can be seen from Table 4, both locomotives have a similar power output in independent (diesel) traction, but their power output in electric traction differs significantly in favor of the Stadler locomotive. The aim is to find how these parameters will affect the journey time (the average speed) on the reference lines, and also how they will affect the energy consumption (and thus the range per full tank of fuel when running off the overhead catenary).

Table 4. Technical parameters of dual locomotives (E: Catenary mode, D: Off-catenary mode) Source: [20,21]. Source: Authors.

Locomotive Type	Siemens Vectron Dual Mode	Stadler Euro Dual
Length	19,975 mm	23,020 mm
No. of axles	4	6
Weight	90 t	120 t
Power output in E mode	2400 kW	6150 kW
Power output in D mode	2000 kW	2800 kW
Maximum speed	160 km/h	120 km/h
Fuel tank	2600 L	3500 L

To calculate the modeled energy consumption and off-catenary range of the dual vehicle, model freight trains pulled by dual locomotives were modeled on all three reference lines, whose data models are already maintained in the iPLAN/FBS timetabling software [1] and owned by the authors' department. The train paths were designed, on the basis of the chosen model trainset, in iPLAN/FBS timetabling software [1] with regard to the regular (periodic) passenger trains operating on these lines in Czech railway timetable (Timetable 2022/23) [29–32]. To demonstrate the comparison of the energy consumption for repeated stops and starts (due to passing oncoming trains), reference train paths during night hours were also constructed, calculating the energy consumption along the whole line without intermediate stops.

4. Results

4.1. Estimation of Values of Traction Energy Consumption of Stops of the Model Train

First, the reference energy consumption $E_{line,lrAB,0}$ was calculated by the construction of the train path of the model freight train without an intermediate stop—for each combination of line, direction and locomotive. The values obtained from the driving dynamics calculation by iPLAN/FBS timetabling software [1] are displayed in Table 5.

Table 5. Traction energy consumption [kWh] for running of the model train without intermediate stops. Source: Authors.

Line and Direction	Siemens Vectron Dual Mode	Stadler Euro Dual
180 Plzeň–Furth im Wald	2296	2470
180 Furth im Wald–Plzeň	1661	1771
246 Břeclav–Znojmo	1963	2130
246 Znojmo–Břeclav	1432	1557
340 Brno–Staré Město u U. H.	2602	2961
340 Staré Město u U. H.–Brno	2825	3222

4.1.1. Hilly Line (180)

For both directions, stops in Nýřany and Blížejev are connected with high traction energy consumption. However, stations with the highest values of traction energy consumption caused by stopping differ according to the direction. For the train running toward Furth im Wald, the stop in Stod should be avoided. For the opposite direction, stops in Radonice, Blížejev, and Holýšov should be avoided. On the other hand, Česká Kubice is, as the peak station, is suitable for the energy-saving stop in both directions. Values of traction energy consumption are displayed in Table 6.

Table 6. Traction energy consumption [kWh] of stops in intermediate stations on the line 180. Source: Authors.

Station	Direction to Furth im Wald		Direction to Plzeň	
	Siemens	Stadler	Siemens	Stadler
Vejprnice	46	55	43	55
Nýřany	61	70	67	86
Výh Chotěšov	52	63	54	66
Stod	81	95	47	67
Holýšov	45	48	66	70
Staňkov	44	46	49	51
Blížejev	52	60	66	80
Výh Radonice	44	53	82	86
Domažlice	27	39	49	54
Česká Kubice ¹	9	14	10	17

¹ Peak of the line.

4.1.2. Flat Line (246)

For both directions, the stop in Valtice is connected with the high energy cost, since the station is located in a valley. Values of traction energy consumption of other stations, except for Boří les, are low due to the comparably flat terrain. Station Novosedly is suitable for the energy-saving stop in both directions, but it restricts the length of the model train—as well as the neighboring station Hrušovany nad Jevišovkou–Šanov. For the direction toward Znojmo, Božice and Hodonice enable energy-saving stops. For the opposite direction, Mikulov is the best possibility after Novosedly. Values of traction energy consumption are displayed in Table 7.

Table 7. Traction energy consumption [kWh] of stops in intermediate stations on the line 246. Source: Authors.

Station	Direction to Znojmo		Direction to Břeclav	
	Siemens	Stadler	Siemens	Stadler
Boří les	34	35	41	45
Valtice	70	77	82	82
Mikulov na Moravě	28	37	21	25
Novosedly	23	24	21	22
Hrušovany n. J.-Šanov	29	29	26	27
Božice u Znojma	22	22	27	28
Hodonice	21	21	28	29

4.1.3. Flat Line with Significant Peak in the Middle (340)

On this line, the comparably short single-track section contains only two (practically usable) intermediate stations. For both locomotives, traction energy consumption of stopping in the direction to Brno is lower for Ostrožská Nová Ves. For the opposite direction, the more energy-saving station is Uherský Ostroh. Values of traction energy consumption are displayed in Table 8.

Table 8. Traction energy consumption [kWh] of stops in intermediate stations on the line 340. Source: Authors.

Station	Direction to Brno		Direction to Staré Město	
	Siemens	Stadler	Siemens	Stadler
Ostrožská Nová Ves	51	43	45	46
Uherský Ostroh	57	63	39	41

4.2. Choice of the Most Suitable Stations for Stop of the Model Train

On the line 180, in the direction to Furth im Wald, the most suitable station that can be reached by the model train from Plzeň, is Výh Chotěšov. The next station with the lowest traction energy consumption, that the model train can run to from Výh Chotěšov without passing, is Staňkov. From Staňkov, the next passing is necessary in Česká Kubice, with the lowest traction energy consumption from the whole line. The resulting train path with three intermediate stops is (for the variant with less powerful Siemens locomotive) displayed in Figure 4. The model train with the Stadler locomotive does not even need to stop in Česká Kubice. The train path in the opposite direction, displayed in Figure 5, differs in the longer stop in Česká Kubice, forced by the longer runtime (uphill) from Furth im Wald. The next difference is passing in Stod rather than Výh Chotěšov for the train hauled by Siemens locomotive, due to the lowest traction energy consumption from the first half of the line in this direction (except for Vejprnice, but it is located very close to the end station Plzeň). However, for the train hauled by Stadler locomotive, the stop in Výh Chotěšov is more energy-saving than in Stod.

On the line 246, the critical section in terms of usable capacity is between stations where passenger trains pass each other—Sedlec u Mikulova and Znojmo. The last station that the model train from Břeclav can reach without passing a passenger train is Mikulov na Moravě, with the lowest traction energy consumption for the stop from the first three intermediate stations (in the direction to Znojmo). Then, two pairs of passing stations for the model freight train are practically usable—Novosedly and Božice or Hrušovany-Šanov and Hodonice. The sum of values of traction energy consumption of the first pair is lower, and thus the first pair was chosen. For the opposite direction, the same pair of passing stations was chosen for the same reason. Furthermore, Mikulov is the station with the most energy-saving stop, from which the model train can proceed to Břeclav without any

other stop. These train paths are equal for the model trains with both locomotives. For the train with the less powerful Siemens locomotive, the train path to Znojmo is displayed in Figure 6. The train path toward Břeclav is displayed in Figure 7.

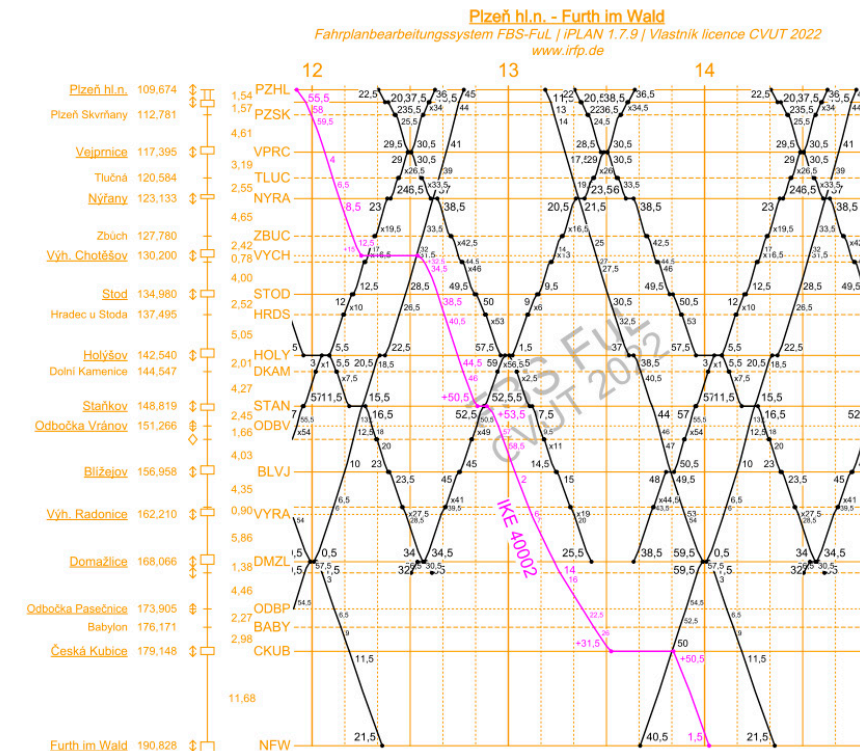


Figure 4. Proposed freight train path on the rail line 180—direction to Furth im Wald (data: [1,26]). Source: Authors.

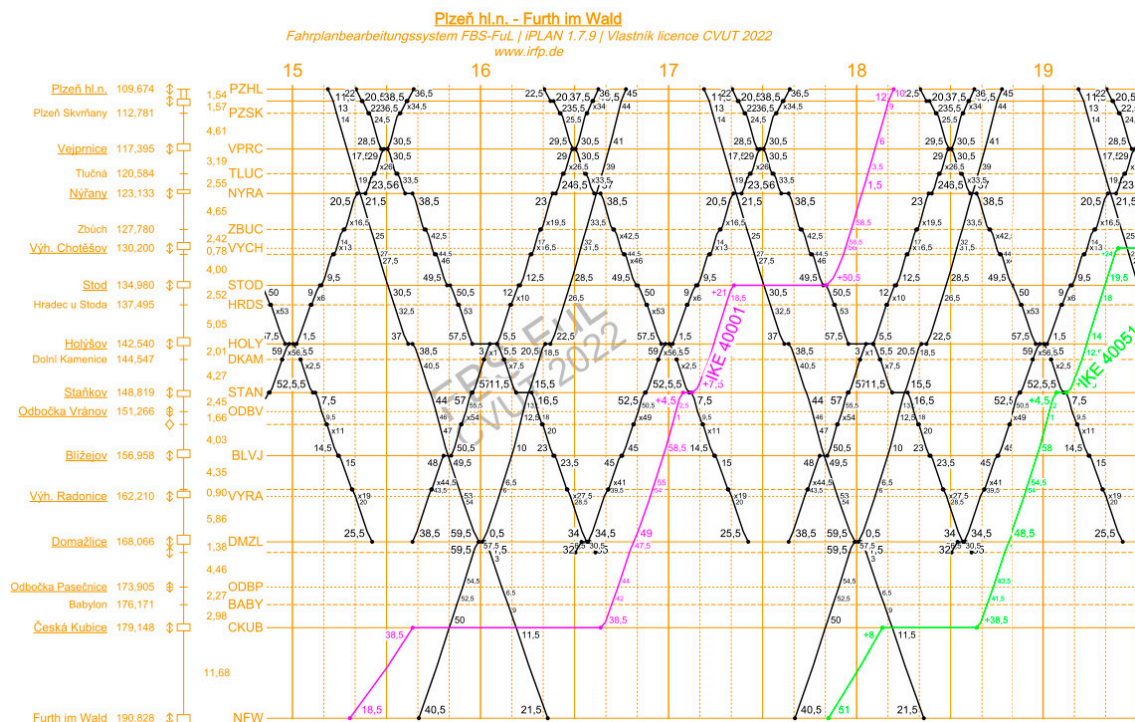


Figure 5. Proposed freight train paths on the rail line 180—direction to Plzeň (data: [1,26]). Source: Authors.

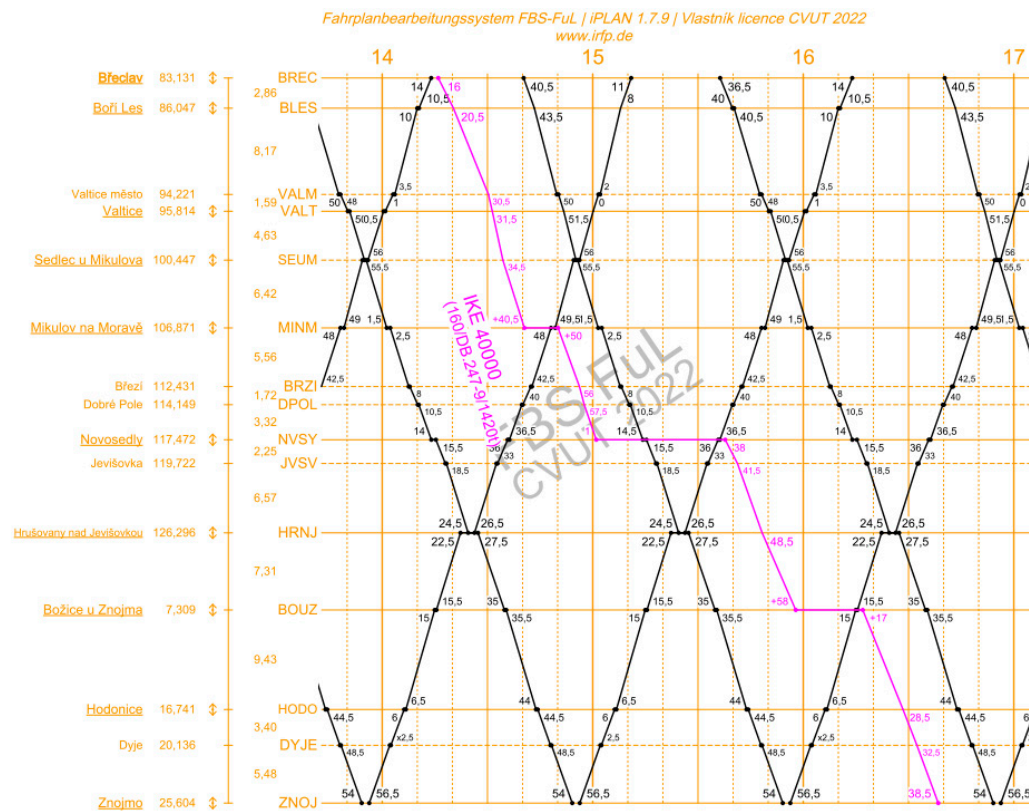


Figure 6. Proposed freight train path on the rail line 246—direction to Znojmo (data: [1,27]).
Source: Authors.

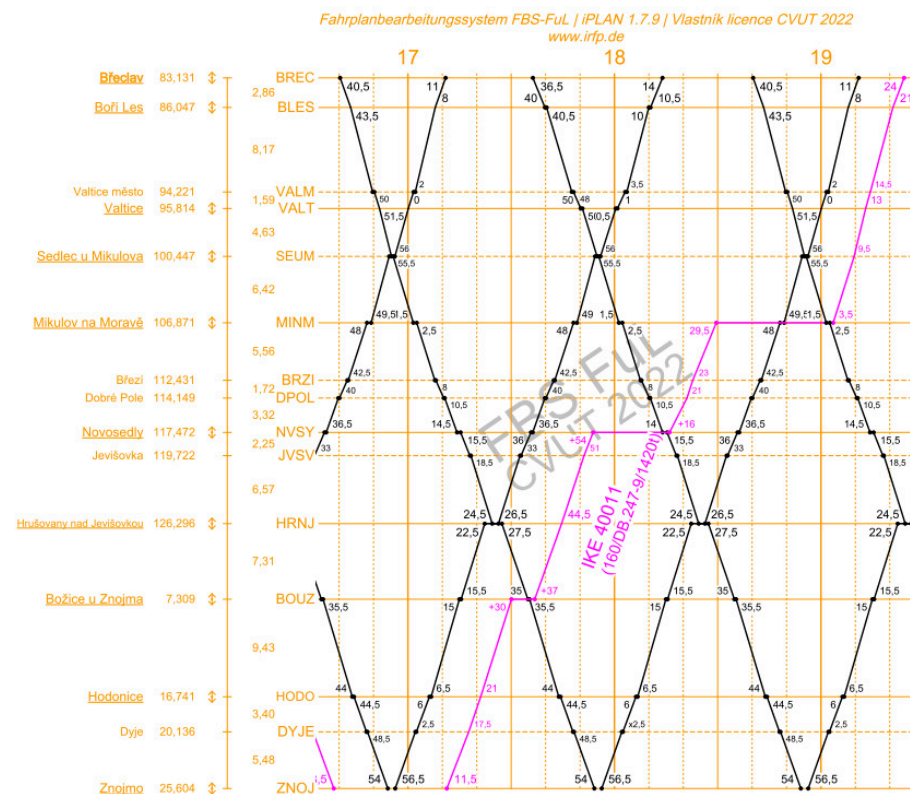


Figure 7. Proposed freight train path on the rail line 246—direction to Břeclav (data: [1,27]).
Source: Authors.

For the single-track section of the line 340, the solution is trivial, as described above (see Section 4.1.3). All freight train paths are displayed in Figure 8, where trains with Siemens locomotive are displayed in pink color and trains with Stadler locomotive in light green color. On some sections of the double-track majority of the line, an additional buffer time had to be added to achieve similar average speeds with the passenger train, to avoid further stops. An alternative solution, applicable on double-track lines with modern interlocking and remote-control systems, could be active overtaking, for instance, as discussed by Janoš and Kříž [33].

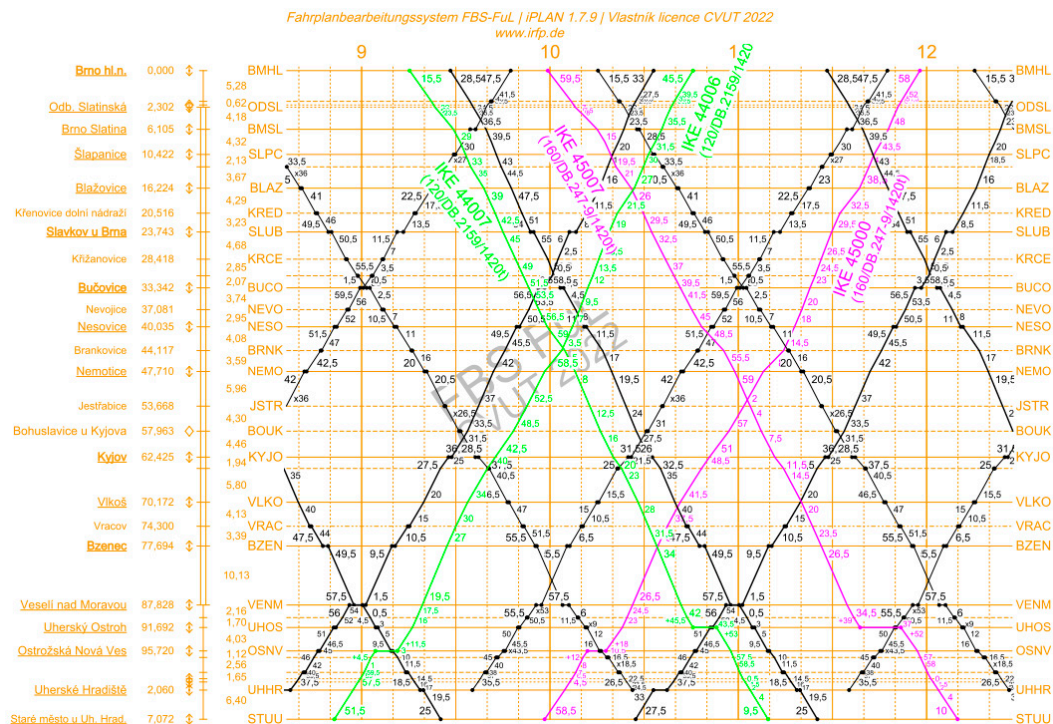


Figure 8. Proposed freight train paths on the rail line 340 (data: [1,28]). Source: Authors.

4.3. Sensitivity Analysis—Variable Mass of the Model Trainset and Numbers of Stops

The results presented above should be verified with the help of sensitivity analysis, whose purpose is changing an input value to see the extent of changes in the output (results). Therefore, it is necessary to choose variable(s) whose input values will be changed.

The most appropriate variable to be changed is the gross mass of the model trainset—the number of (equal) loaded container wagons. This variable directly influences energy consumption. Length of the train, which is proportional to the number of wagons, can lead to the movement of the passing to a longer station, whose traction energy consumption of the stop can be greater. This is a secondary effect on energy consumption. The third factor of energy consumption—not only of running through the line, but for the stops as well—is the growing gross mass of the train that lowers acceleration (and lengthens section runtimes) and can lead to the necessity of an additional stop and corresponding additional traction energy consumption.

If all stations necessary for passing are sufficiently long, the power output of the locomotive can restrict the addition of more loaded wagons due to the critical uphill section of the line. This limitation can be illustrated by a very low minimal speed except for stops (approximately 15 km/h) in a dynamic speed profile simulated by iPLAN/FBS timetabling software [1]. Of course, the exact lowest allowed speed except for stop V_{min} can be influenced by the traction characteristic of the particular locomotive or varying adhesion due to weather, etc. For the sake of simplicity, the authors have chosen that V_{min} must

not be lower than 15 km/h. Therefore, V_{min} has to be observed by the sensitivity analysis, as well.

On the flat line 246, the station Novosedly has proven to be restricting for the length of the model train (19 loaded wagons). Therefore, the consideration of lengthening the model train has no practical sense. As a result, out of the three rail lines, only two remain for the sensitivity analysis.

Results of the sensitivity analysis, including the movement of passing to neighboring longer stations if necessary, and total traction energy consumption for each additional loaded wagon are for the hilly line 180 displayed in Table 9 (Siemens locomotive) and Table 10 (Stadler locomotive). On this line, all variants are limited by the maximum train length in the shortest station, where the stop is necessary—Holýšov as a rule. The only exception is the train hauled by Siemens locomotive toward Furth im Wald, where the passing has to take place in the even shorter station Stod.

Table 9. Sensitivity analysis for the model train with Siemens locomotive on the line 180. Source: Authors.

Direction to Furth im Wald			Direction to Plzeň		
No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]	No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]
20	38	2405	20	40	1800
21	36	2481	21	39	1854
22	34	2555	22	37	1905
23	32	2632	23	36	1953
24	30	2706	24	35	2008
25 ¹	29	2803	25	34	2059
26 ¹	27	2880	26 ²	32	2208
27 ¹	25	2956	27 ²	31	2254
			28 ²	30	2301
			29 ²	29	2349
			30 ²	28	2392
			31 ^{2,3}	27	2444

¹ Passing in Stod rather than Staňkov, due to the train length. ² New set of passing stations due to the train length: Výh Radonice, Holýšov, and Výh Chotěšov. ³ Train with length of 634 m.

Table 10. Sensitivity analysis for the model train with Stadler locomotive on the line 180. Source: Authors.

Direction to Furth im Wald			Direction to Plzeň		
No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]	No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]
20	44	2588	20	46	1939
21	43	2669	21	45	1999
22	41	2745	22	44	2063
23 ¹	39	2839	23 ³	42	2169
24 ¹	37	2910	24 ³	40	2229
25 ¹	35	2990	25 ³	39	2289
26 ²	34	3061	26 ⁴	37	2351
27 ²	33	3138	27 ⁴	36	2404
28 ²	31	3211	28 ⁵	35	2501
29 ²	30	3284	29 ⁵	34	2551
30 ²	29	3361	30 ⁵	33	2598
31 ²	28	3439	31 ⁵	32	2651

¹ Additional passing in Česká Kubice. ² New/additional passing in Holýšov and Blížejev. ³ New set of passing stations due to dynamic properties of the train: Domažlice, Staňkov, Výh Chotěšov. ⁴ New set of passing stations due to the train length: Domažlice, Blížejev, Stod. ⁵ New set of passing stations due to the train length: Výh Radonice, Holýšov, Výh Chotěšov.

Results of the sensitivity analysis for the line 340 with a significant peak in the middle are displayed in Table 11 (Siemens locomotive) and Table 12 (Stadler locomotive). On this line, there are different types of limitations for each locomotive. Siemens locomotive is, due to the lower power output, limited by reaching 15 km/h through the critical section (peak of the line) in both directions. The train hauled by Stadler locomotive is limited in both directions by the maximum allowed length of the train in the longest passing (crossing) station—Ostrožská Nová Ves.

Table 11. Sensitivity analysis for the model train with Siemens locomotive on the line 340. Source: Authors.

Direction to Staré Město u U. H.			Direction to Brno		
No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]	No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]
20	29	2766	20	26	3012
21	26	2847	21	24	3096
22	24	2924	22	20	3183
23	17	3001	23	15	3268
23	17	3001	23	15	3268

Table 12. Sensitivity analysis for the model train with Stadler locomotive on the line 340. Source: Authors.

Direction to Staré Město u U. H.			Direction to Brno		
No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]	No. of Wagons	V_{min} [km/h]	Traction Energy [kWh]
20	33	2866	20	35	3265
21	31	2947	21	34	3358
22	30	3034	22	32	3455
23	29	3113	23	30	3545
24	28	3198	24	26	3638
25	26	3271	25	25	3727
26	25	3349	26	23	3813
27	25	3422	27	22	3904
28 ¹	25	3504	28	20	3988

¹ Passing in Ostrožská Nová Ves rather than Uherský Ostroh, due to the train length.

5. Discussion

5.1. Energy Intensity of Stops

The obtained data have clearly shown that the altitude differences on a particular line had greater influence on traction energy consumption than the stop and further acceleration of the freight train, unless the station was located in a valley (at least in the beginning of) or in a steep uphill section. The ratio of energy consumption when stopping the same train in the same direction at different stations can reach up to 9 (line 180, direction to Furth im Wald, model train hauled by Siemens locomotive, stations Stod and Česká Kubice). On the other hand, the share of one additional stop in the total traction energy consumption for running through the whole line is relatively low—few percentages as a rule. Nevertheless, by the appropriate choice of stations for passing the passenger trains, a freight carrier can save at least tens of kilowatt-hours of energy, whose price, regardless of its source, tends to be volatile and uncertain.

A freight train may have to stop for various operational reasons. On single track lines, the most apparent reason is passing (crossing) with another train. In addition to passing a passenger (or freight) train running on time, a freight train can pass a delayed train as well, at a different station than planned. Another reason for an additional stop can be caused by overtaking by a faster (mostly passenger) train. However, this situation occurs mostly on electrified mainlines with higher allowed speeds (120 to 200 km/h, in Czechia up to

160 km/h only), which are mostly double-track. Furthermore, a freight train may stop for an operational reason on the carrier's side, such as change in drivers. However, this change occurs for practical reasons mostly in large node stations (e.g., Plzeň, Brno, Břeclav). Therefore, for the frequency of few pairs of freight trains per day (common on single-track secondary mainlines), only stops for passing passenger trains have a practical sense to be considered. Nevertheless, circulation planning of dual locomotives must include a sufficient energy (fuel) reserve for additional (not scheduled) stops.

5.2. Daily Variations of Periodic Passenger Timetable

On the one hand, running the freight train in off-peak time (in terms of passenger transport) can save the freight train one or more stop (and the induced traction energy). On the other hand, this approach is sustainable only in short or middle term, since the passengers require a more regular offer of services to ensure all-day mobility without restrictions. Therefore, in the middle to long term, freight carriers have to cope with the all-day hourly passenger service.

5.3. Operating Range of Dual Locomotives

One liter of diesel can give approximately 10 kWh of energy [34]. Therefore, with the inclusion of 30% reserve for unplanned stops or bad adhesion conditions, the locomotives presented in this paper (see Table 1) in off-catenary mode can use 18,200 kWh or 24,500 kWh of energy, predominantly for traction energy. Since the traction energy for running of the model train through a chosen line with up to three intermediate stops mostly did not exceed 3000 kWh, it can be assumed that these locomotives can serve three to four cycles of longer off-catenary journeys without refueling. The number of off-catenary cycles and their length are strongly related to the location of marshalling yards or logistic hubs [35].

Values of specific traction energy consumption per kilometer for the above proposed freight train paths for the model train and particular line, direction and locomotive (absolute energy consumption divided by length of a line) are displayed in Table 13. In addition to the terrain and numbers of intermediate stops, the power output of particular locomotive has a significant impact on the resulting values.

Table 13. Specific traction energy consumption [kWh/km] for the proposed train paths. Source: Authors.

Line and Direction	Absolute Energy Consumption [kWh]		Specific Energy Consumption [kWh/km]	
	Siemens	Stadler	Siemens	Stadler
180 Plzeň–Furth im Wald	2401	2579	29.6	31.8
180 Furth im Wald–Plzeň	1767	1905	21.8	23.5
246 Břeclav–Znojmo	2036	2213	29.6	32.2
246 Znojmo–Břeclav	1501	1632	21.8	23.7
340 Brno–Staré Město u U. H.	2641	3002	23.7	26.9
340 Staré Město u U. H.–Brno	2876	3265	25.8	29.3

Some of the freight train paths proposed above require a considerably longer transport time (or, in other words, lower average speed) due to waiting for a free time slot on a single-track line for the longest possible running without stop (see, for instance, Figure 5). However, real preferences of a particular freight carrier may differ—transport speed can be prioritized over energy efficiency. Nevertheless, freight railway is mostly less sensible to time requirements than (especially long-distance) passenger railway (for example, see Šperka et al. or Dedík et al.) [36,37].

5.4. Infrastructure Requirements for Improvement of Energy Saving

The section Novosedly–Znojmo on the line 246, along with the periodic timetable of passenger trains (unchangeable in the medium term, due to interconnections for passenger

transfers in node stations) have clearly shown that two neighboring stations with short station tracks (Hrušovany nad Jevišovkou-Šanov and Novosedly) can effectively prevent carriers from operating a longer freight train, at least during the daytime passenger operation. Therefore, the targeted improvement (by lengthening) of the stations located in flat terrain or at the top of the line, that enable suitable passing with passenger trains in both directions, is advisable. For sections with steep gradients, the situation is more complicated. As a rule, two stations, each on a different side of the mountain massif, have to be improved. Each one has to be located in order that it enables the freight train to pass the passenger train after passing through the peak.

5.5. Recommendations for Further Research

Possible further research can be directed toward the possible deployment of dual locomotives in passenger transport or on long-distance routes and in international traffic, where these vehicles have to date appeared very rarely, mainly due to the lack of approval in multiple countries and complicated technology. The authors recommend the reflection of infrastructure requirements of freight railway in feasibility studies and cost-benefit analyses of secondary mainlines in a more detailed way, considering not only construction costs, but potential energy savings of freight carriers, as well. The authors further recommend the measurement of real performance of battery-powered passenger vehicles in the longer term, in order to learn lessons for potential deployment of battery-powered locomotives in longer-haul freight transport.

6. Conclusions

This paper has comprehensively examined the possibilities of deployment of dual locomotives, especially in freight transport on non-electrified lines. On the three selected lines, energy-optimal train paths were found with an emphasis on the minimum number of stops to achieve the lowest possible energy consumption, which is an important step toward enhancing the environmental friendliness of rail freight transport. The train paths found are by no means the only possible ones; in some cases, for example, shorter journey times can be achieved, but at the cost of higher energy consumption. In general terms, dual locomotives make it possible to achieve lower energy consumption, especially in combined deployment, i.e., partly on electrified and partly on non-electrified lines, such as the above-mentioned line 340 in Czechia. They can also be effectively used for transport on non-electrified lines connecting two electrified lines (lines 180 and 340). It has been proven that a dual locomotive does not restrict the operation of freight trains as such and can fully replace a conventional diesel locomotive when properly deployed. The great potential of the operation of these locomotives is not only in Central Europe, but can be applied on suitable lines all over the world with a sophisticated deployment. The most limiting factor, according to the authors, is the passenger timetable on a given line, since it restricts a practically feasible choice of stations to the stopping of a freight train for passing the passenger trains. Another limiting factor can be extremely long sections between neighboring stations—in the sense of runtime, not necessarily long, but with low speed or high gradient. Therefore, the authors recommend the deployment of dual locomotives on single-track rail lines with an approximately hourly (or less frequent) passenger service, without a significantly restrictive section in terms of runtime (i.e., low maximum speed or high gradient) or maximum length of a train. Otherwise, a night service can be an option.

A comparable potential of battery powered dual locomotives remains in question. Targeted improvement of infrastructure, especially lengthening of the stations with low traction energy consumption of the stop that are suitable for passing of a freight train with periodic passenger train, is strongly advisable, in order that the potential of dual locomotives of higher power category can be fully exploited (station tracks on electrified mainlines are longer).

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