

Horizons of Railway Transport – Determinants of the development of the railway system in the context of the society-wide assessment of investments in railway infrastructure and public passenger transport

The Modelling of Traction Energy Consumption of a Container Train

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Abstract

The authors focus in the paper on the procedure of calculating payments for traction electricity in the conditions of Správa železnic, s.o. (Railway Administration, the national railway infrastructure manager in the Czech Republic). Specific measures to technological factors that cause higher train power consumption are discussed. In the next section, the numerical solution of the train motion and the design of a simulation model for the possibility of computational assessment of the traction energy consumption of the train are described. A simulation model is proposed to numerically solve the train equation of motion. For the purpose of this paper, a specific track section and a specific train are selected. The results are compared with real recorded data obtained from the operation.

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1. Introduction

The railway infrastructure manager Správa železnic concludes contracts with carriers for the operation of rail transport, which in particular provide for matters related to the allocation of railway capacity and the operation of rail transport. Based on the Railways Act (No. 266/1994 Sb.), the Railway Administration is to provide carriers with the

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so-called basic services directly related to the operation of rail transport as well as additional and auxiliary services through service facilities. Additional services within the meaning of the Railways Act also include the supply of traction electricity. In this respect, the Railways Act takes into account the current requirements of European legislation, in particular, Directive 2012/34/EU. The system of itemisation of traction electricity among carriers using dependent traction on the infrastructure of the Railway Administration is implemented using the so-called "hybrid model". This method makes it possible to charge the traction electricity consumed to individual carriers both for electric traction vehicles (or electric units) equipped with an electricity metering system (EMS) and for electric traction vehicles without an EMS. (Huerlimann 2017) The supply service will be monitored and evaluated separately for the DC traction and AC traction systems. The Traction Electricity Supply Contract distinguishes in detail the metered consumption, i.e. the consumption measured by the EMS, which will be increased by the technical loss factor of the traction system. This consumption will be used to calculate the traction electricity charged (Bulíček 2018). The same principle will be used to calculate the traction electricity consumed using the specific consumption coefficients in the cases foreseen (traction vehicles without EMS), which will again be increased by the technical loss coefficient (Schejbal 2020).

2. Factors affecting traction energy consumption

This section focuses on the factors that affect the train's running and that have a major impact on traction energy consumption. These are mainly rotating surface coefficient, running resistances (vehicle and track) and technological factors (track speed limits, energy recovery) (Kendra et al. 2016).

The coefficient of rotating masses takes into account the kinetic energy of the rotational movements of certain vehicle parts (wheelsets, gearbox components, traction motor rotors). It is a certain theoretical increase in the mass of the vehicle which takes account of the fact that, due to the rotating masses, the vehicle has a higher kinetic energy than it would correspond to the purely sliding motion of a body of mass m (Michálek et al. 2017).

The specific value of the coefficient of rotating masses always depends on the parameters of the vehicle (weight, loading condition, drive design). (Černá et al. 2020)

Driving resistances refer to forces that generally act against the movement of the train and are not (unlike braking forces) deliberately induced. These forces are on the right-hand side of the train equation of motion because of the counteracting action. (Gašparík et al. 2017) Depending on the cause of the driving resistance, they are divided into vehicle resistance and track resistance. Resistances depend mainly on the design and technical condition of the rolling stock (train set). The sub-resistances that contribute to the total vehicle resistance include (Michálek et al. 2017) rolling resistance, bearing resistance, buckling resistance, air resistance, charging generator resistance, coasting resistance, etc. Track resistances include increased aerodynamic drag from tunnelling, resistance on inclined tracks, and curve resistance.

One of the most widespread causes of increased traction energy consumption is a local track speed restriction, usually of a relatively short length, where the end of the restriction is followed by the train restarting to the track speed. (Tischer et al. 2020) This is typically the case when slow running is introduced.

From the point of view of train dynamics, the train's passage through a place with a local speed limit (slow run) can be divided into three sections (Šíman 2006):

- reduction of speed (braking, or even coasting before braking),
- actual slow run,
- restart to the original speed.

It is the restart to the original track speed that is the most demanding in terms of energy consumption. If the slow run is on a gradient, then the energy losses are negligible. Of course, the travel time remains negatively affected (Bulková et al. 2022). Significant savings in traction electricity are possible by using energy recovery. However, this aspect is primarily a matter for the haulier and whether it has traction vehicles with regenerative capability.

3. Creating a model to investigate the movement of a train

The choice of the track section was influenced by the availability of data on measured electricity consumption. For these purposes, the Summerau – Praha-Uhřetěves line was used, which is travelled by container trains of the METRANS Rail carrier, which provided the relevant operational data for the purposes of the work. The track section under investigation is approximately 217 km long. The analysis of the available data from the traction unit was based on the coordinates of the departure point at Summerau Station until a stop at Prague-Uhřetěves Station. Approximately 178 km of the route is covered by the AC power system (Summerau – Benešov u Prahy). From the Summerau Station to the Czech state border, the line is fed by AC 15 kV 16.7 Hz. The section from the Austrian state border to approximately Benešov u Prahy is fed by AC 25 kV 50 Hz. The rest of the track section (Benešov u Prahy – Praha-Uhřetěves) is covered by a DC power supply system with a voltage of 3 kV. Fig. 1a shows the reduced slope, which was then used to plot the approximate elevation profile of the track section. The elevation profile of the track can be seen in Fig. 1b.

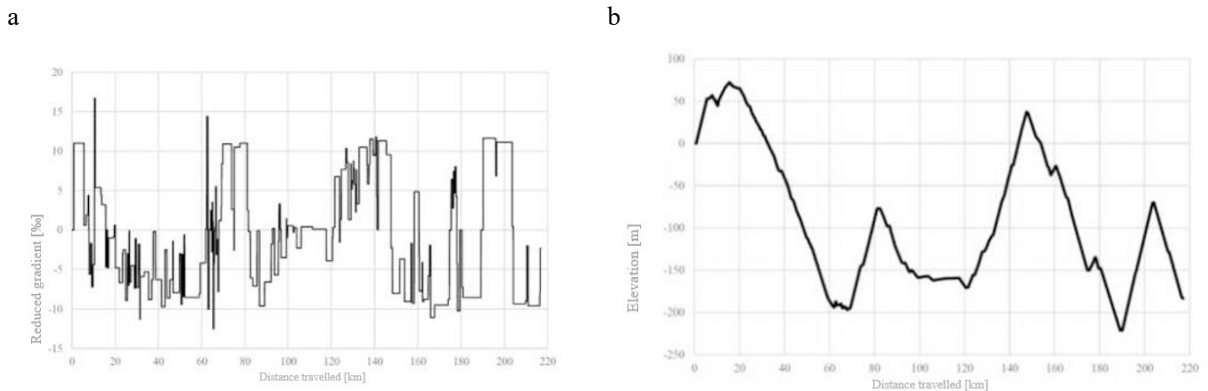


Fig. 1. (a) Course of the reduced gradient (slope) of the track; (b) Elevation profile of the track.

To calculate the travel times and energy consumption (or simulation of the travel) of the selected train in the investigated track section, a calculation model was created, which is based on the numerical solution of the train equation of motion. (Schultz 2018)

The investigation of train travel is carried out under several simplifying assumptions, the aim of which is to obtain the simplest possible mathematical description of the problem, but which will also provide sufficiently accurate results. The following simplifying assumptions are used in train travel modelling (Gašparík et al. 2017):

- the movement of the train is considered as the movement of a mass point with one degree of freedom along the track, thus simplifying its mathematical description to a single second-order differential equation – the so-called train equation of motion,
- when vehicles are moving, only external forces in the direction of travel (tractive and braking forces, driving resistance, gravitational forces) act on them,
- the forces acting on vehicles are usually determined from static characteristics.

If the train is substituted by a single mass point, the forces acting between the individual bodies forming the train, such as the forces in the couplings, cannot be determined by solving the equation of motion of the train. The equation of motion is, therefore, a mathematical description of the motion of a mass point with one degree of freedom along the track (Michálek et al. 2017).

Using Newton's method of constructing equations of motion, the straight-line motion of a mass point can be described by equation (1):

$$m \cdot \ddot{x} = \sum F_x \quad (1)$$

where:

m = weight [kg];

$\ddot{x}$ = acceleration in the x-axis direction [m.s⁻²];

ΣF_x = sum of all forces acting in the x-axis direction [N].

If we break down equation (1) for the train model and at the same time take into account the coefficient of rotating masses, the equation of motion of the train will have the following form (Michálek et al. 2017):

$$m_{vl} \cdot (1 + p_{vl}) \cdot \ddot{x} = F_{ok} - B - O_v - O_t \quad (2)$$

where:

m_{vl} = total mass of all vehicles in the train [kg];

p_{vl} = value of the coefficient of rotational masses of the train [-];

$\dot{x}$ = instantaneous value of the train acceleration in the direction of travel [m·s⁻²];

F_{ok} = total tractive force at the wheel circumference [N];

B = total braking force at the wheel circumference [N];

O_v = total vehicle resistance of all vehicles in the train [N];

O_t = total line resistance of all vehicles in the train [N].

The variability of the forces acting on the train during the travel leads to the fact that the movement of the train can generally be described as unevenly accelerated. The starting point of the numerical solution is that the acceleration at each point on the track (2) can be determined from the train equation of motion (Michálek et al. 2017):

$$\ddot{x} = \frac{F_{ok} - B - O_v - O_t}{m_{vl} \cdot (1 + p_{vl})} \quad [m \cdot s^{-2}] \quad (3)$$

The principle applied in the numerical solution is the division of the track into sub-sections of a given length Δx in the solution of the track tachogram. A constant acceleration value is considered in these individual sub-sections. This makes it possible to convert a non-uniformly accelerated motion into a sequence of successive uniformly accelerated motions. The calculation procedure for solving the train movement depending on the distance travelled can be summarised in the following points (Michálek et al. 2017):

- the investigated line of total length can be divided into n sub-sections of length Δx ,
- for each sub-section, the mean value of the acceleration $\ddot{x}$ can be determined using formula (3),
- formula (3) contains the tractive force on the circumference of the wheels (F_{ok}), whose maximum value at a certain speed can be determined by the formula after exceeding the so-called critical speed:

$$F_{ok} = \frac{P}{v} \quad [kN] \quad (4)$$

where:

P = rated power of the traction unit [kW];

v = train speed [m·s⁻¹].

- if the speed of the train is less than this critical speed, the tractive force is equal to the maximum tractive force that the traction unit is capable of exerting,
- in the case of constant-speed driving, the tractive force is only equal to the sum of the track resistance and vehicle resistance:

$$F_{ok} = O_t + O_v \quad [kN] \quad (5)$$

where:

O_t = track resistance [kN],

O_v = vehicle resistance [kN].

- braking is considered with constant braking deceleration according to ČSD (Czechoslovak State Railways) regulation V7 – 0,2 m·s⁻²; the braking force is derived from the train equation of motion by the relation:

$$B = -m_{red} \cdot \ddot{x} - O_v - O_t \quad [kN] \quad (6)$$

where:

m_{red} = reduced train weight ($m_{vl} \cdot (1 + p_{vl})$);

- by knowing the initial velocity v_i at the beginning of the i -th sub-section, and by knowing the constant acceleration in the sub-sections, the velocity v_{i+1} at the end of the i -th section can be calculated, which is also the initial velocity in the following section:

$$v_{i+1} = \sqrt{v_i^2 + 2 \cdot \ddot{x} \cdot \Delta x} \quad [m \cdot s^{-1}] \quad (7)$$

- the travel time in the i -th sub-section, assuming constant (non-zero) acceleration, is calculated:

$$\Delta t_i = \frac{v_{i+1} - v_i}{\ddot{x}_i} \quad [\text{s}] \quad (8)$$

- the travel time in the i -th sub-section, assuming zero acceleration, is calculated:

$$\Delta t_i = \frac{\Delta x}{v_i} \quad [\text{s}] \quad (9)$$

- the resulting travel time over the whole track section is the sum of the partial travel times:

$$t_c = \sum_{i=1}^n \Delta t_i \quad [\text{s}] \quad (10)$$

Together with the calculation of the travel time, it is also possible to estimate the energy consumption of a given train on a given track section. The traction energy consumption is related to the mechanical work W done by the tractive force F_{ok} on the circumference of the wheels of the traction vehicles on a given track x . The increment of traction work consumption in each i -th sub-section (using the knowledge of the tractive force on the wheel circumference in each i -th sub-section) is calculated by (Bažant et al. 2019):

$$\Delta W_{tr,i} = F_{ok,i} \cdot \Delta x \quad [\text{J}] \quad (11)$$

The total traction energy consumption in the investigated section is expressed as:

$$E_{tr} = \frac{1}{\eta} \cdot \frac{1}{3,6 \cdot 10^6} \cdot \sum_{i=1}^n \Delta W_{tr,i} \quad [\text{kWh}] \quad (12)$$

where:

η – efficiency of the traction unit (ratio of power and input power).

The MS Excel spreadsheet is suitable for the numerical solution of the train equation of motion. Given the assumption of constant acceleration in partial steps, the length of this partial step Δx must be chosen appropriately. This mainly affects the accuracy of the numerical solution. When solving the calculations depending on the distance travelled, it is advantageous for trains composed of the same types of railcarriages to choose a section length equal to the length of each railcarriage. (Brejcha 2015) In addition, this procedure also allows the train length to be taken into account in the calculations by allowing the track resistance to be calculated for each railcarriage separately (they are characterised by their weight and are located at a specific point on the track with a specific gradient) (Potkány 2017).

In Table 1 it is possible to see part of the simulation model for numerical solution of the train equation of motion in MS Excel.

Table 1. Part of the simulation model for the numerical solution of the train movement in MS Excel

Km	S [0/00]	Tr. speed	El. pr.	Tr.R.k	Tr-O- together	VozO [N]	V [km/h]	a [ms ⁻¹]	Fok [kN]	Fbok [kN]	Freq. [kN]	Δt [s]	$\sum t$ [s]	W [kJ]	W _{rek} [kJ]
0,65	0	80	1	80	0	21998,93	0	0,14193	275	0	0	0	0	7150	0
0,676	0	80	1	80	0	22241,71	9,779	0,14179	275	0	0	19,16	19,16	7150	0
0,702	0	80	1	80	0	22484,26	13,827	0,14165	275	0	0	7,937	27,1	7150	0
0,728	0	80	1	80	0	22726,58	16,931	0,14152	275	0	0	6,092	33,19	7150	0
0,754	0	80	1	80	0	22968,66	19,545	0,14138	275	0	0	5,137	38,33	7150	0
0,78	0	80	1	80	0	23210,51	21,847	0,14125	275	0	0	4,527	42,85	7150	0
0,806	0	80	1	80	0	23452,13	23,927	0,14111	275	0	0	4,094	46,95	7150	0
0,832	11	80	1	80	9064,44	23693,52	25,837	1,13589	275	0	0	3,906	50,85	7150	0
0,858	11	80	1	80	17260,2	23925,98	27,553	0,13116	275	0	0	3,633	54,48	7150	0
0,884	11	80	1	80	23909,62	24150,35	29,113	0,12731	275	0	0	3,404	57,59	7150	0
0,91	11	80	1	80	29378,5	24368,13	30,551	0,12412	275	0	0	3,218	61,11	7150	0
0,936	11	80	1	80	35388,01	24580,45	31,89	0,12063	275	0	0	3,085	64,19	7150	0
0,962	11	80	1	80	47612,05	24786,79	33,14	0,11365	275	0	0	3,055	67,25	7150	0
0,988	11	80	1	80	59849,04	24981,21	34,276	0,10668	275	0	0	2,958	70,2	7150	0
1,014	11	80	1	80	64515,07	25163,7	35,309	0,10396	275	0	0	2,761	72,97	7150	0

4. Results of the calculations performed

VARIANT 1 - This variant of modelling train travel is essentially theoretical. It is assumed that the train does not stop during its travel and only takes into account the track speed or the maximum specified speed for freight trains, i.e. 100 km/h. Fig. 2 shows that the train was actually travelling significantly slower than modelled.

- Simulated travel time: 164.5 min. (Real 220 min.)
- Simulated traction energy consumption: 5082 kWh. (Real 4578 kWh.)
- Simulated recovered electricity: 1670 kWh. (Real 871 kWh.)
- The recovered energy is the work done by the braking force of the electrodynamic brake, i.e. 150 kN. This is assumed in all calculation variants.

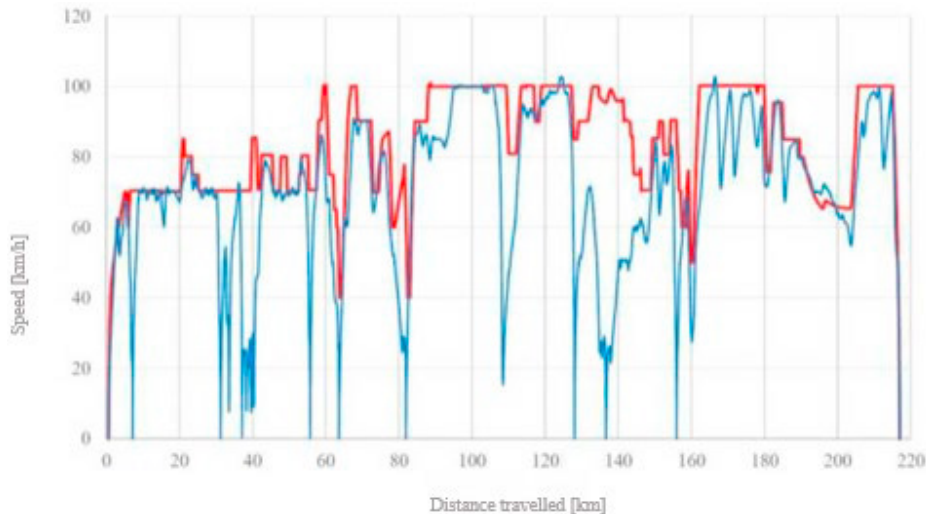


Fig. 2. Track tachogram (Variant 1).

VARIANT 2 - This variant was modelled according to the paperback timetable for the Nex 41500 train. It, therefore, takes into account five scheduled stops. This implies that the travel time has also increased by approximately 13 minutes. The calculated travel time differs quite a bit from the assumption made in the paperback timetable, which may be due to the more conservative consideration of locomotive traction parameters in the calculation for the paperback timetable (e.g. lower achievable tractive effort), as opposed to the traction parameters considered in the modelling of the train run.

- Simulated travel time: 177 min. (Real 220 min., scheduled in the paperback timetable 219 min.)
- Simulated traction energy consumption: 5230 kWh. (Real 4578 kWh.)
- Simulated recovered electricity: 1721 kWh. (Real 871 kWh.)

VARIANT 3 - This option takes into account the biggest deviations from the original Variant 1, i.e. mainly stopping points. It does not take too much account of the speeds actually achieved (e.g. approx. km 33, 40, 90, 130, 150). The track tachogram is much closer to the real track tachogram. As a result of the frequent stops, the traction energy consumption has increased by almost 600 kWh compared to the theoretical Variant 1.

- Simulated travel time: 187.7 min (Real 220 min.)
- Simulated traction energy consumption: 5685 kWh. (Real 4578 kWh.)
- Simulated recovered electricity: 1769 kWh. (Real 871 kWh.)

VARIANT 4 - This variant takes into account as accurately as possible the real speed of the given Nex 41500 train. The track tachogram of this calculation variant can be seen in Figure 20. The simulated and real speeds are very similar. Also, the travel time is very similar to the real travel time. The traction energy consumption has increased by almost 400 kWh compared to the theoretical variant 1.

- Simulated driving time: 207.8 min. (Real 220 min.)
- Simulated traction energy consumption: 5488 kWh. (Real 4578 kWh.)
- Simulated recovered electricity: 1804 kWh. (Real 871 kWh.)

Consumption determined using flat rates - Using flat rates, it was calculated that if the train was not equipped with an EMS meter, its predicted traction energy consumption would be set determined at 5427 kWh. Different values of specific consumption on the AC and DC system are taken into account, with 178 km of track covered by the AC system and 39 km by the DC system. The weight of the train including the locomotive is 1725 t. The result has not been multiplied by the technical loss coefficients or the technological consumption coefficients, as the consumption measured by the EMS is also multiplied by these coefficients. Thus, it does not affect the difference in the results.

5. Comparison of the variants

It is clear from the results and the track tachogram in the figure that calculation Variant 4 gives the most accurate travel time and speed. The travel time has been simulated with a relative deviation of 5.5%. The energy consumption of Calculation Variant 4 is noticeably higher than the real consumption. The relative deviation of energy consumption is 19.8%. This is mainly because the train travel modelling considers the maximum power of the locomotive, which may not always be used in reality. Furthermore, the simulation calculation does not take into account the coasting travel, which reduces the traction energy consumption in real operations. The results also show that the traction energy consumption determined by flat rates is 18.5 % higher than the real consumption measured by EMS. This is the reason why freight rail operators prefer to pay for the actual traction electricity consumed. The consumption simulated using the most accurate Calculation Variant 4 and the consumption determined using the flat rate are almost identical. The relative deviation is 1.1 %, but flat rate payments do not allow for the deduction of recovered electricity. The graphs below in Figures 3 and 4 show the relative accuracy of the results of all calculation variants.

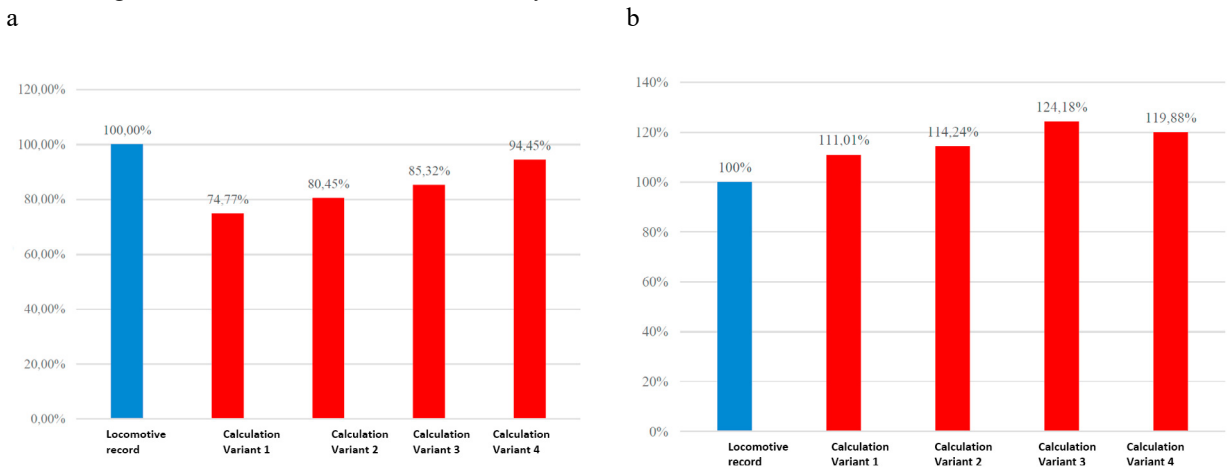


Fig. 3. (a) Relative accuracy of travel time calculations; (b) Relative accuracy of traction electrical energy consumption calculations.

The above results show that the most accurate Calculation Variant 4 gives the most accurate travel time and difference between energy consumed and energy recovered. It is worth noting that when comparing the differences in electrical energy consumed and recovered, the individual calculations (even under the assumptions considered regarding energy efficiency) give results that are very similar to the measured data. Furthermore, it is possible to observe an interesting similarity between the travel time planned in the paperback timetable and the travel time actually recorded, although the train actually stopped more times than planned according to the paperback timetable. This should imply that the actual travel time should be much higher than the scheduled travel time according to the paperback timetable. As already mentioned in the description of Calculation Variant 2, this is probably mainly because more conservative locomotive traction parameters may have been considered in the planning when calculating for the paperback timetable (e.g. lower achievable traction in adverse weather).

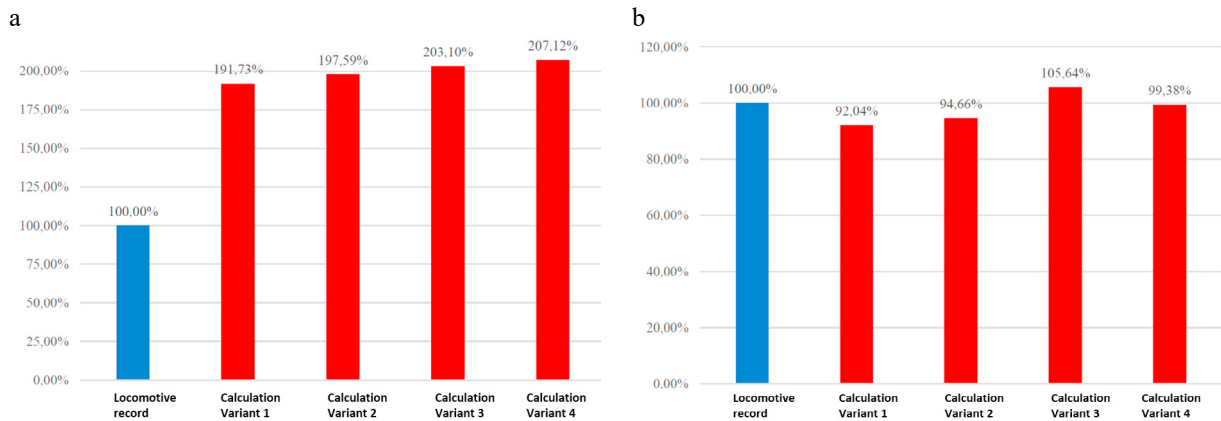


Fig. 4. (a) Relative accuracy of electrical energy recovery calculations; (b) Relative accuracy of calculations of differences between energy consumed and energy recovered.

6. Discussion

The paper aimed to analyse the current hybrid model of payments for traction electricity and to analyse in more detail the factors that enter into the calculation of final consumption for both trains with EMS and trains without EMS. Furthermore, the numerical solution of the train motion equation was described, which allows us to determine the travel time and estimate the traction energy consumption of a specific train in a specific track section. (Nachtigall, 2018) At the same time, a computational model in MS Excel was proposed, which is suitable for this numerical solution. This calculation model was used to simulate four calculation variants of train travel, which were then compared with real recorded data. The result was an evaluation of the results obtained and a demonstration of the accuracy of the calculations. The most important findings are summarised below:

- With the most detailed Calculation Variant 4, the travel time with respect to the real travel time was determined very accurately, with a relative deviation of about 6%.
- It turns out that the travel times quoted for freight trains in paperback timetables appear to be relatively conservative. This was confirmed by the fact that they can be maintained even with more frequent stops.
- The calculated traction energy consumption in Variant 4 compared to the flat rate electricity was very accurate. The relative deviation is 1.1%.
- The results show that, under the given assumptions, the real energy consumption of a freight train can be estimated with an accuracy of 10%-25%, while it was always an overestimation of the actual consumption achieved. This is mainly because the calculation does not take into account the coasting. The differences in consumption and recovery were calculated with a relative deviation of 1 % – 8 % compared to the actual recorded data.
- The results show that the real efficiency of the energy recovery is around 50%.
- By recuperating, saving about 19% of the energy consumed is possible.
- An important finding is that the actual measured traction energy consumption is significantly less than the consumption determined by flat rates. For this reason, rail freight operators prefer to pay for the traction electricity actually consumed, which can reduce one of their cost items.

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