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# DETECTION PROCESS OF ENERGY LOSS IN ELECTRIC RAILWAY VEHICLES

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**Abstract**. *The paper deals with the detection process of energy loss in electric railway hauling vehicles. The importance of efficient energy use in railways and cost-effective rail transport tendency toward regenerative braking energy are considered. In addition, the current situation and improvement opportunities to achieve efficient energy use are examined. Seven measurement series were performed with scheduled Railjet trains between Hegyeshalom and Győr railway stations in Hungary. This railway section is related to the Hungarian State Railways' No. 1 main railway line (between Budapest-Kelenföld and Hegyeshalom state board), which is a part of the international railway line between Budapest and Vienna (capitals of Hungary and Austria, respectively). This double-track, electrified railway line with traditional ballasted superstructures and continuously welded rail tracks is important due to the international passenger and freight transport between Germany, Austria, and Hungary. The value of the regenerative braking energy can be even 20-30% of the total consumed energy. This quite enormous untapped energy can be used for several aims, e.g., for comfort energy demand (air conditioning, heating-cooling, lighting, etc.) or energy-intensive starts. The article also investigates the optimization of regenerative braking energy by seeking the energy-waste locations and the reasons for the significant consumption. The train operator's driving style and habit have been identified as one of the main reasons. Furthermore, train driver assistance systems are recommended to save energy, which is planned for future research.*

**Key words**: *Railway, Electric locomotive, Railjet, Regenerative braking energy, Acceleration-deceleration, Energy optimization*

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## 1. INTRODUCTION

In railway transportation, the electricity consumption [1,2] will be critical due to the so-called worldwide energy crisis and the increased price of energy sources [3]. Therefore, it is a logical decision, and it would be a good attitude, if the railway companies tried to save money by reducing the overconsumption of electricity. It is also an important task and a relevant factor that the world must be cleaner in the future, as well as the countries must use green or "greener" energies instead of fossil ones [4]. In addition, a new type of urbanization also has a positive effect on the green total factor and the energy efficiency [5]. Therefore, people must take care of the planet and try to use as low energy as possible, as well as emit as low green-house and other pollutant gases and materials as they can [6]. For example, Minaminosono et al. [6] reported that train emission in Japan was measured as 22 g $CO_2$/km for 1 km of passenger transport. This value is one-sixth of the carbon dioxide emissions of passenger cars and one-fifth of those of airplanes, suggesting that electric railways have environmental benefits. Furthermore, they gave examples of regenerative energy, reaching the 47% of the running energy on the Yamanote line.

In the case of railway transport, first, the whole consumed energy of a train must be analyzed to reduce it [1,7,8]. The affecting factors regarding energy consumption can be categorized into three main groups: (i) infrastructure effects, (ii) transportation organization effects, and (iii) external environmental impact [9]. The infrastructure effects contain traction and vehicle characteristics and line characteristics. The transportation organization effects are related to speed characteristics, marshaling characteristics, stop plan, utilization ratio of seat capacity, handling characteristics, and signal displays. The external environmental impacts are, e.g., the altitude, climate, barometric pressure, etc. Therefore, the energy consumption of a train is the operational energy consumption (i.e., the sum of the traction energy with a positive sign, as well as the regenerative braking energy with a negative sign), as well as auxiliary energy consumption (i.e., on-board service equipment during train operation including auxiliary equipment, e.g., air conditioner, lighting, and ventilation, etc.).

To minimize and optimize the total consumed energy, one of the main possibilities is the usage of the so-called recuperated (regenerative) electric energy [10-12]. The other significant solution is the optimized planning of the time-table considering all of the horizontal and vertical geometries of the railway tracks (i.e., geometrical characteristics), as well as the planned (and/or the operation) speed of the given railway lines [10,13-15]. It has to be mentioned that the best solution is when the above two methods are combined.

In the case of time-table optimization, the adequate solution is when the optimization procedure is related not only to theoretical calculations but also to real case studies [9,10,16-18]. The most frequently applied methodologies are the several deep learning methods, fully-connected neural networks, recursive neural networks, standard LSTM (long short-term memory), LSTM with convolutional layers, LAG-LSTM (LSTM with lagged information) [17], LP (Linear Programming) [12], MILP (Mixed-Integer Linear Programming) [10,18,19], MINLP (non-linear mixed-integer programming model) [20], Deep-Q-Network and Markov decision process for the application of reinforcement learning (RL) [21], multiple-particle operation model and new methods based on mutated dichotomy and differential evolutionary algorithm (MDDEA) [22], CM-PSO (competition mechanism-based particle swarm optimization) [23], etc.

International research provides examples and connecting solutions for optimization, and they were executed for public railways [1], tramways [24], metro lines [25], as well as Maglev (i.e., magnetic levitation) lines [26].

When examining regenerative braking energy, road vehicles can also be considered. Based on automotive, the quantity of the potentially produced regenerative energy depends on many factors: vehicle, route characteristics, and traffic conditions [11]. Energy recovery systems (ERSs) can be categorized into three main groups: (i) using exhaust gases, (ii) vertical oscillation of the vehicle body, and (iii) application of vehicle inertia. The first group uses thermal energy (e.g., chemical and steam), and the last two items are based on kinetic energy considering chemical and non-chemical types. There are different subtypes, e.g., electric turbo compound (it is below the exhaust gases and kinetic and chemical category), regenerative shock absorber (it is the subtype of vertical oscillation of the vehicle body and kinetic and chemical category), or the flywheel (it is the subtype of vehicle inertia and kinetic and non-chemical category) [11]. The main differences among the possible systems are (a) whether the applied system can provide continuous or non-continuous energy regeneration, (b) the applicability and conformity to hybrid service/operation, (c) the extra weight and space regarding the vehicle body and its dead load, (d) whether it ensures prompt energy storage, (e) contains wearable equipment or not, (f) it is noisy or silent, as well as (g) the additional price compared to the pure, original assembly.

This paper partially investigates the train driver's behavior and recommends localizing the energy-wasting places on railway lines. One of the adequate solutions for storing and using the regenerative braking energy seems to be the on-board battery packs [27-29], supercapacitors [28], and hybrid storage system [30,31]. However, direct charging back to the electric network would be the best solution [32].

Fischer [2] examined the energy needed for acceleration of locomotives and electric multiple units (EMUs). Based on calculations, he concluded that usage of different correction factors is adequate to determine the consumed energy during acceleration. His defined factors are related not only to the passenger trains, but also to freight trains.

International researchers have dealt in a very detailed manner with train driver assistance systems (or in other words, Driver-Advisory Systems, i.e., DASs) [24,33-35]. It seems to be one of the most valuable ways to ensure maximal safety, the lowest consumed energy, and the possibility to guarantee the planned time-table for trains. These systems are also available for train drivers and car, truck, bus, trolley, tram, etc. drivers.

The DASs' type and operation depend on whether the train is "ordinary" (i.e., driven by traditional human drivers) or autonomous [11,16,36].

In the case of train drivers, different driving strategies can be considered: maximum acceleration, cruising (maintaining a certain speed level), coasting (turning off traction), and maximum braking [35]. In the case of the DAS, also four driving strategies were taken into consideration: (i) MTTC (minimum time train control), (ii) MC (maximum coasting), (iii) RMS (reduced maximum speed), as well as (iv) EETC (energy-efficient train control). As a result, the lowest energy consumption was related to EETC and the highest one to the MTTC.

If someone would like to assess the railway system's initial and annual costs, the maintenance costs are the highest part (i.e., considering the whole life-time) [37-39]. On the other hand, the efficiency of the trains and the railway systems are also relevant [40,41]. The life-time costs (LCC) of the railway track depend on a lot of factors, e.g., the condition of the substructure [37,42], the condition of the superstructure [43-47], railway track geometry [48], condition of rolling stock [49], etc. Some researchers have dealt with the projects' risk analysis which is quite significant based on the planning and construction phases of the railway projects [50].

As mentioned earlier, current paper is about the energy loss detection process. The authors' main goal was to give a useful algorithm to localize sections where there are significant energy consumptions. The algorithm applies a dividing process (i.e., dividing into subsections) and searches for the reason for these "steps" and possible peaks. Furthermore, the authors decided to analyze the worst and the best cases (i.e., the lowest and the highest consumption data series or cases) in a more detailed manner. In this way, these cases can be compared, and the differences can be explained in all the divided subsections.

## 2. Methodology of Possibilities for Optimizing Energy Consumption

### 2.1. Methodologies in General

The goal of the examination was to improve the energy efficiency of railroad transportation and investigate the factors generating and influencing the energy loss. The examination of the trains takes into account the routes and the consumed energy. During the test series, the reason for the energy losses is analyzed, and the potential energy recovery opportunities (locations) are examined. Based on the energy consumption optimization, four main categories were defined [9]: (i) condition of the permanent way and connecting infrastructure, as well as the rolling stock, (ii) recovered energy from regenerative braking, (iii) external factors (i.e., environmental factors, temperature, etc.), finally (iv) the human factor. This article neglects the condition of the rolling stock and the external factors – they are planned research.

During the investigation of the condition of the railway permanent way (i), the goal is to identify the locations which cause, or could cause a significant loss of energy and try to explain them. For example, if the railway track geometry is of inadequate quality, a fault can be expected in the railway track (either in superstructure or substructure). Of course, an overhead line problem can be a relevant factor. It is also essential to mention the braking systems of the rolling stock, mainly the engines'.

When using recuperative braking energy (ii), the first aim is the opportunity of its applicability. In this case, the achieving of greater utilization of regenerative energy, locations should be found where the quantity of regenerative braking energy can be further increased.

In the case of external factors (iii), the target is to examine, for example, the temperature dependency of the spent energy and define modification determinants. As mentioned above, as a part of further work, it is planned to investigate how to improve the methodology.

In the case of human factor (iv), it can be noticed that the consumed and recuperated energy significantly relies upon the train operator's driving style. It is essential to mention that the operator is not always the main cause of energy loss. The reasons can often be searched in fault, incorrectly determined and located railway signals (unnecessary or wrong red signals, redundant stopping/braking), which lead to high unnecessary energy consumption – maybe with relatively high values compared to the whole routes of trains.

### 2.2. Analysis and Energy Optimization Process

**1. Data collection:** the analysis of electricity consumption data.

During the beginning stage, the more extensive the accessible database, the more accurately the problem can be recognized. Composition of the data to be tested: acceleration and deceleration data set supplemented by consumed and recuperated energy, accurate time data and speed values. Current research applies data collection (sampling) at the relevant time points. Of course, the best solution would be more frequent data sampling. The higher the data sampling frequency, the better the energy-wasting location(s) can be defined. It has to be noted that more data is required for generalization and, thus, higher computing (computational) power. A possible option is, e.g., to collect more data during larger accelerations and decelerations, as well as constant data sampling during consentaneous progress. The data collection will be more extensive if there is a 5 km/h speed increasing or decreasing (resulting in acceleration or deceleration, respectively). Different evaluation methodology is needed which can be difficult. Alternatively, data are analyzed only in parts if a "fault" is found at a particular location. All in all, the higher frequency data sampling is efficient. Another solution can be connecting a data logger to the telemetry data and analyzing it only when there is a "fault" or only turning it on if there is an assumed or an observed "fault".

**2. Comparative analysis:** based on the balance of the amount of consumed energy in the same section.

It is significant to mention that the direction of the route also has to be considered to determine the exact and accurate longitudinal profile (uphill and downhill slopes). Another significant element to consider is the deviation of external factors (e.g., weather conditions, temperature values, etc.). The correction factors for this must be taken into consideration. The more data were available on a given railway line, the easier it would be to create normative electric energy consumption. Different normative consumption is needed in winter and summer, especially for passenger trains with cooling, heating or combined cooling-heating air conditioners (ACs). The difference is presumably not too big for freight trains, but real measurement data are needed. A weighted ordered averaging (OWA) of many measurement data could be used. Nevertheless, a simple MIN/MAX/AVR (MIN – minimum, MAX – maximum, AVR – average) averaging can also be applied. In addition, calculating the skewness and kurtosis parameters and a statistical distribution calculation and entire statistical analysis with sophisticated up-to-date methods would also be helpful.

**3. Designation of significant deviations:** segregating them into shorter subsections and localizing the positions of energy loss. (Such a resolution can be divided into parts following the chainage/sectioning.) Evaluating the data will show the differences between several tests on the same route. Therefore, it is worth analyzing data from the same subsection of different measurements to set up a better consumption strategy (see Fig. 1).

In Fig. 1, the whole section is divided into smaller subsections to identify energy wastage sites. In Approach A, the whole distance was first split into two parts, then into two other parts (further splitting is also possible), thus providing a detailed analysis of the whole section. In Approach B, in the first case, three different subsections are selected (i.e., #1, #2 and #3, respectively), and only the section with the worst results is split again (they are shown in Fig. 1). This method performs a targeted, iterative fault search, intending to locate energy wasters in as few iterations as possible. The first approach gives more detailed results but it is more computationally demanding. After evaluating and using MIN, MAX and AVR methods, observing the differences between the different sections (or subsections), and defining a transport strategy can be worthwhile.

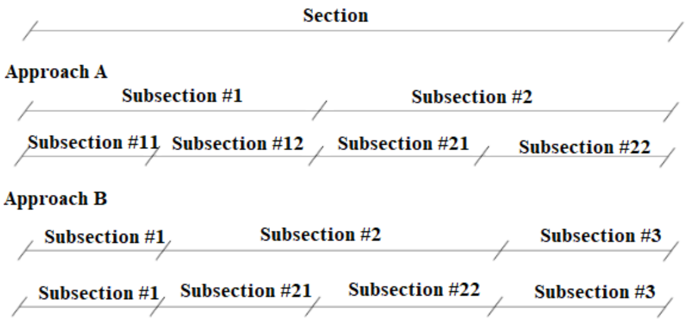


**Fig. 1** Segregating of sections into shorter subsections

**4. Determination of possible error factors:** according to options determined in Section 2.1 (i.e., from points (i) to (iv)).

The condition of the railway track (i) is one of the critical issues in terms of energy loss, as there is an inadequate assessment of the condition of the track, so there is a speed restriction where it is not needed. Vice versa, if a speed restriction is not yet set at the right location where it is needed, it can cause increased degradation of the track geometry and track structure (which is also dangerous and unsafe). However, its determination and evaluation require more complex measurements and analyses, and of course, they cannot be determined by only a few measurements.

The so-called worst case scenario for regenerative braking (ii) is the case that no energy can be recovered or stored. In other cases, battery systems are needed to store energy. With this method, the investment can be returned by covering of the comfort energy as savings. (The so-called best case scenario is when the regenerative braking energy is the maximal, however, the total consumed energy should be considered regarding the recovered part.)

The role of the weather (iii) in the wheel-rail contact (i.e., in this case, mainly adhesional friction) is the main factor to be considered. In rainy, humid, wet weather, adhesional traction is significantly reduced by decreasing adhesional friction. Therefore, it has an effect during acceleration, although not a direct effect. It can be necessary after speed restrictions because the low adhesional friction can increase the length of the re-acceleration phase (due to the decreased adhesional traction force), e.g., it may make the re-acceleration more difficult on steep gradients.

Human error (iv) and possible omittance can be fundamental, as it is an easily avoidable factor with the help of various assistance systems (i.e., with DASs). Thus, it is recommended to aim for the highest possible degree of autonomy of DASs.

**5. Possible solution:** drafting achievable results according to the assessed data. Possible solutions should also be considered according to options from (i) to (iv), determined in Section 2.1.

A repair or renewal strategy should be developed in case of a problem with the condition of railway track (i). It is usually the most expensive solution and may require an accurate CBA (Cost-Benefit Analysis). It determines how long it will take to recover the investment, or, more specifically, when the latest intervention is needed to avoid too much degradation. Unfortunately, the impact of speed restrictions can be felt immediately in costs, but the deterioration of the track does not stop at reduced speeds. On the other hand, there are costs (in terms of person-travel time) associated with slower travel times.

Regarding regenerative braking (ii), it may be worth examining where the most regenerative energy can be used or stored immediately. Also, which braking strategy is better: the more intensive one or the gradually decelerating one.

External temperatures (iii) cannot be influenced, but compensation values (i.e., factors) can be defined, which helps in the planning of energy usage and acceleration-deceleration. Another interesting aspect to investigate is how the operating temperature of traction motors varies with the external temperature and resulted consumption.

In the case of high electricity consumption due to the human factor (iv), it is worth setting up support systems (DASs) to help choose the right driving strategy (ideal choice of acceleration and braking.)

**6. Cost analysis:** formation of alternatives according to price/value among the possible opportunities [50]. First, the optimization aims to obtain minimal energy consumption and/or the time accuracy of the trains according to their time-table. Additionally, it has to be decided which optimization strategy is better, i.e., the speed of the optimization process or the accuracy of the results.

## 3. ENERGY EFFICIENCY ANALYSIS

Regarding the energy efficiency analysis, specific results were examined related to scheduled Railjets between railway stations Hegyeshalom (HH) and Győr (GY) (see Fig.2). During all seven measurement series (MS1 to MS7), the registered energy consumption data are drawn in Fig. 3. The mass of the trains was 479 tons, the length was 206 m.

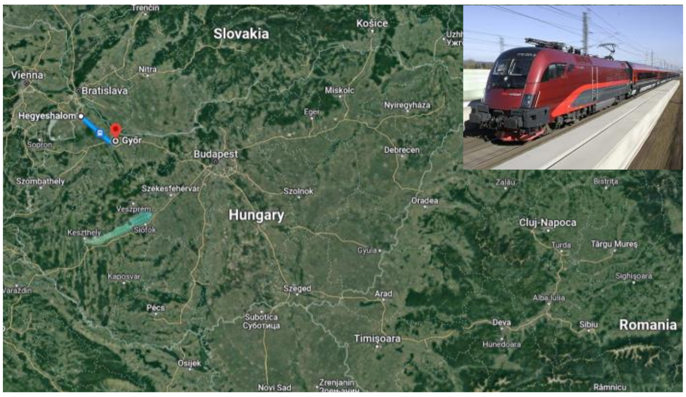


**Fig. 2** Map of the measurement's location and the Railjet train (edited figure based on internet sources)

Fig. 3 illustrates the elapsed time during the measurements (i.e., from zero to approx. 1600 s). The consumed energy values are depicted in the vertical axis (i.e., between zero and approx. 900 kWh). The chart in Fig. 3 demonstrates the executed seven measurement series in unique colors. According to the outcomes, it can be recognized that the character of electric energy consumption was very similar in all cases, but differences can also be noticed. Also, there are more significant differences between the most efficient and the worst cases. Therefore, the following examination stage analyzes the electric energy consumption between the stations along the investigated railway section.

Based on the procedure described in Section 2.2 (part 3), the investigated example section was divided into three parts, i.e., Section #1, #2 and #3, respectively (see Fig. 4). The easiest way to divide it into parts was to consider each station as a breaking point.

There are altogether four railway stations where the Railjet trains regularly stop: Hegyeshalom, Mosonmagyaróvár (MM), Öttevény (OT), and Győr. However, it is relevant to mention that the trains did not stop at MM and OT during MS1 and MS2, i.e., the published results were only approximated (i.e., interpolated) values in these cases.

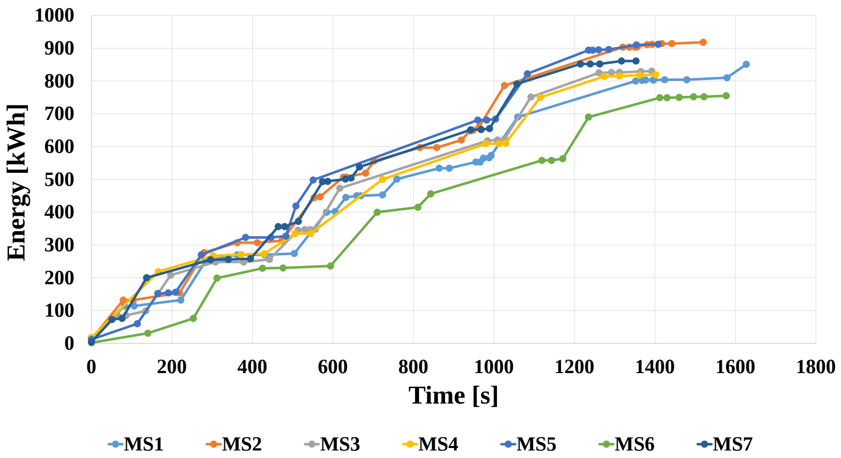


**Fig. 3** Energy consumption during MS1 to MS7

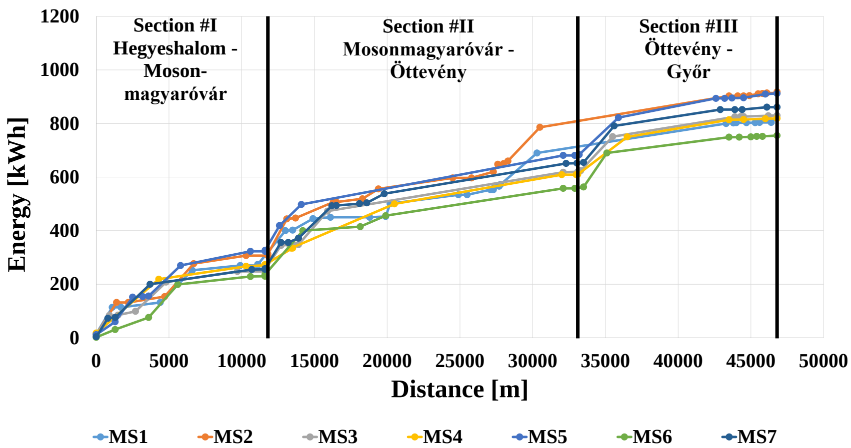


**Fig. 4** Energy consumption between Hegyeshalom and Győr

It has to be mentioned that the longitudinal slope between HH and GY is approximately between zero and seven per mile (‰, i.e., 1/1000), and there are only horizontal curves with relatively high radii. It is why modification was neglected during this investigation.

Tables 1-3 summarize unique measurements regarding stops per railway station.

**Table 1** Energy efficiency analysis #1 (energy consumption data)

| **Railway station** | **HH** | **MM** | **OT** | **GY** |
|---|---|---|---|---|
| **Chainage [km]** | 188.0 | 176.4 | 154.9 | 141.2 |
| **Distance [km]** | 0 | 11.6 | 33.1 | 46.8 |
| **MS #1 [kWh]** | 0 | 270 | 690 | 804 |
| **MS #2 [kWh]** | 0 | 307 | 786 | 914 |
| **MS #3 [kWh]** | 0 | 248 | 620 | 830 |
| **MS #4 [kWh]** | 0 | 273 | 610 | 819 |
| **MS #5 [kWh]** | 0 | 323 | 681 | 912 |
| **MS #6 [kWh]** | 0 | 230 | 558 | 755 |
| **MS #7 [kWh]** | 0 | 256 | 652 | 861 |
| **MIN [kWh]** | 0 | 230 | 558 | 755 |
| **MAX [kWh]** | 0 | 323 | 786 | 914 |
| **AVR [kWh]** | 0 | 272 | 657 | 842 |

**Table 2** Energy efficiency analysis #2 (energy consumption data between stations)

| **Railway station** | **HH** | **MM** | **OT** | **GY** |
|---|---|---|---|---|
| **Chainage [km]** | 188.0 | 176.4 | 154.9 | 141.2 |
| **Distance [km]** | 0 | 11.6 | 33.1 | 46.8 |
| **MS #1 [kWh]** | 0 | 270 | 420 | 114 |
| **MS #2 [kWh]** | 0 | 307 | 479 | 128 |
| **MS #3 [kWh]** | 0 | 248 | 372 | 210 |
| **MS #4 [kWh]** | 0 | 273 | 337 | 209 |
| **MS #5 [kWh]** | 0 | 323 | 358 | 231 |
| **MS #6 [kWh]** | 0 | 230 | 328 | 197 |
| **MS #7 [kWh]** | 0 | 256 | 396 | 209 |
| **MIN [kWh]** | 0 | 230 | 328 | 114 |
| **MAX [kWh]** | 0 | 323 | 479 | 231 |
| **AVR [kWh]** | 0 | 272 | 384 | 185 |

**Table 3** Energy efficiency analysis #3 (consumed energy during measurements)

| **Railway station** | **HH** | **MM** | **OT** | **GY** |
|---|---|---|---|---|
| **Chainage [km]** | 188.0 | 176.4 | 154.9 | 141.2 |
| **Distance [km]** | 0 | 11.6 | 33.1 | 46.8 |
| **MS #1 [kWh/km]** | 0 | 0.41 | 0.36 | 0.12 |
| **MS #2 [kWh/km]** | 0 | 0.43 | 0.43 | 0.13 |
| **MS #3 [kWh/km]** | 0 | 0.36 | 0.29 | 0.26 |
| **MS #4 [kWh/km]** | 0 | 0.39 | 0.26 | 0.25 |
| **MS #5 [kWh/km]** | 0 | 0.46 | 0.28 | 0.28 |
| **MS #6 [kWh/km]** | 0 | 0.33 | 0.26 | 0.24 |
| **MS #7 [kWh/km]** | 0 | 0.37 | 0.31 | 0.25 |
| **MIN [kWh/km]** | 0 | 0.33 | 0.26 | 0.12 |
| **MAX [kWh/km]** | 0 | 0.46 | 0.43 | 0.28 |
| **AVR [kWh/km]** | 0 | 0.39 | 0.31 | 0.22 |

The meaning of the data in the rows of Tables 1-3 is the following: the first rows are related to the several railway stations (HH, MM, OT, and GY), the second rows connect to the chainage (with kilometer sectioning), the third rows are related to the distance in "km" unit from the starting point (i.e., from HH). The following seven rows illustrate the electric energy consumption data. Finally, the last three rows give the MIN, the MAX, and the AVR consumed energy values (see Fig. 5).

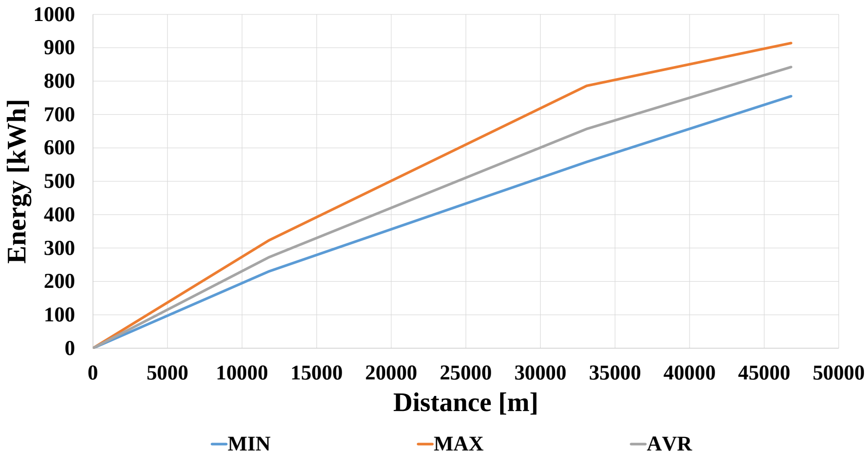


**Fig. 5** Energy consumption between Hegyeshalom and Győr

In Table 1, there are data containing only the hauling and acceleration energy values required to provide the hauling between the two stations. Moreover, recuperated energy values are neglected in this case (Table 1). There is a relevant difference considering the maximal and the minimal cases and it is approximately 159 kWh. Accordingly, the places of the highest deviations were defined, and each stop was examined independently in Table 2. For ascertainability, the consumed energy data were separated into shorter distances (i.e., stations), and the differences between single sections were monitored. For a more unequivocal explanation in Table 3, the consumed electric energy values are shown simultaneously with the traveled length. In this case, a calculated energy need for 1 km can already be observed in accordance with the measurements. Referring to them, the so-called energy-wasting places are able to be effortlessly detected and localized. Based on this approach, the MS5 and MS6 between stations HH and MM, MS2 and MS6 between stations MM and OT, as well as MS1 and MS5 between stations OT and GY, are taken for further detailed analysis. These are the so-called Detailed Analyses #1, #2, and #3 (DA1, DA2, DA3), respectively.

According to DA1, locations with minimal and maximal energy consumption were localized. Fig. 6 illustrates the places with the most relevant deviation in MS5 and MS6.

Fig. 6 presents the section between railway stations HH and MM related to the MS5 (blue lines) and MS6 (red lines). The location is according to the relative "chainage" 0…12 km, based on Table 1. The continuous lines in Fig. 6 present the consumed energy reduced by recuperation, the dashed lines illustrate the speed data, and the dotted lines represent the regenerative braking energy during the measurement series. The relevant difference can be observed in consumed energy around the relative distance of 2000 m, possibly due to the various speeds. During MS6, the considered Railjet accelerated up to

160 km/h and a lot more energy was required compared to MS5. Accordingly, higher recuperated energy can be generated due to the higher speed. However, significantly higher energy is consumed correspondingly. In accordance with it, it can be concluded that unique acceleration and deceleration have a critical influencing factor on the needed energy, and the chauffeur has a significant role in this.

Nevertheless, it is essential to mention that acceleration-deceleration can happen due to traffic issues, i.e., the consumed energy does not expand in all the cases due to the chauffeur's driving habit. (The recuperated energy reached approx. 30% of the utilized energy. It can be seen in Fig. 6, i.e., 54 and 40 kWh values, respectively.)

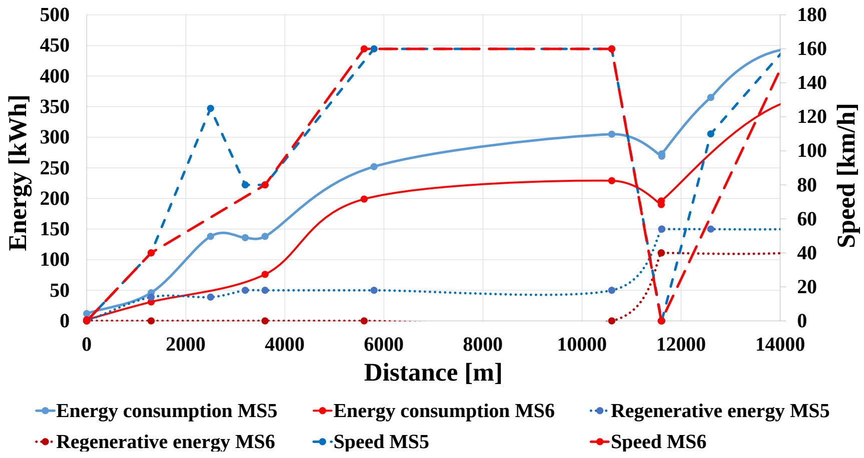


**Fig. 6** Energy consumption during MS5 and MS6

Based on DA2, examining best and worst case scenarios can be seen in Fig. 7. The difference may be due to the train arriving at a higher speed. The braking of MS2 from 160 km/h to 80 km/h generated more regenerative energy of 47 kWh at the location of 26 km, but the subsequent acceleration needed much more energy. As a result, MS2 showed an energy balance (with regenerative subtracted) of approx. 135 kWh, between sections 26.0 km and 33.1 km. During MS1, the energy balance (with the regenerative subtracted) over the same examined subsection is approx. 43 kWh. The difference is, therefore, 92 kWh, so the vast majority of the difference is due to it. The rest is approx. 60 kWh from the initial acceleration, possibly because of the speed restriction. The analysis of the best and worst case scenarios based on the DA3 is shown in Fig. 8.

In DA3, the most considerable difference in consumption was due to acceleration in the 33.1 km and 35.9 km sections. The regenerative energy values were 42 kWh in MS1 and 12 kWh in MS5, respectively. It can be concluded that the application of the braking strategy (see MS1) is recommended.

Results of the best and worst cases are illustrated in Table 4. The values in the last two columns are related to measurement series with the minimal and the maximal energy demand, regarding the several subsections between the considered railway stations.

There is a 361 kWh energy difference value between the sum values, which is significant. Fig. 9 shows the details of the best and the worst cases for the whole examined length. It visualizes the optimal acceleration-deceleration strategy.

The graphs show the relevant energy wasting and energy efficient locations. The relevant differences can be due to the driving style of the chauffeur. It has to be mentioned that some of the differences can be because the speed restrictions were not applied and/or set in the same places during all the measurement series. It can be seen that accelerations and decelerations have a significant impact on energy consumption and determining the optimal train driving speed is a crucial factor. However, it is not always a possibility.

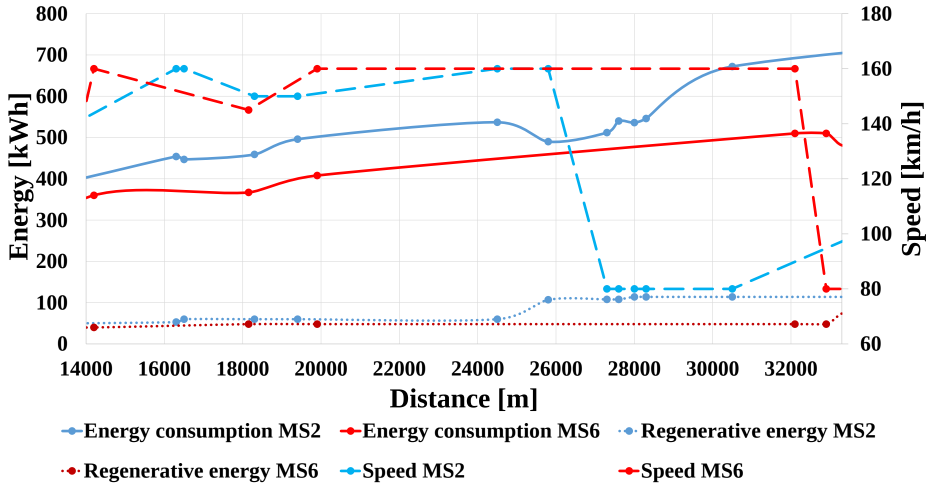


**Fig. 7** Energy consumption between Mosonmagyaróvár (MM) and Öttevény (OT)

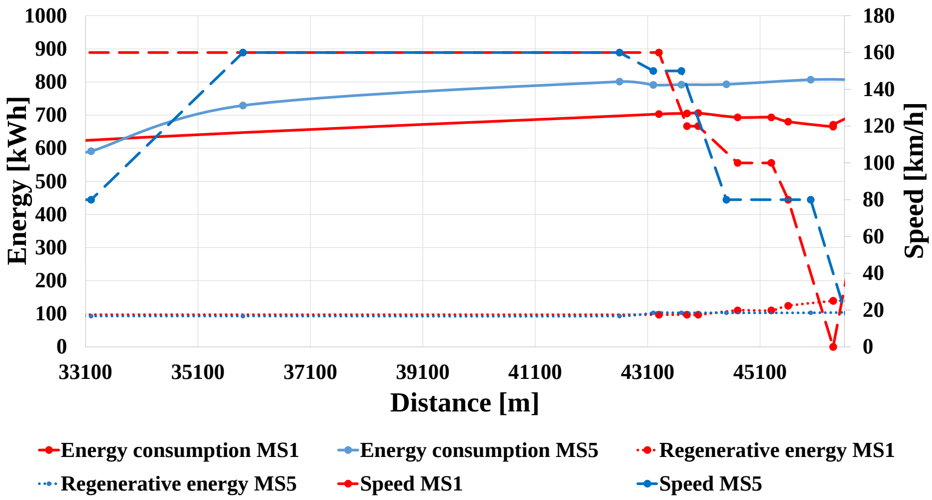


**Fig. 8** Energy consumption between Öttevény (OT) and Győr (GY)

**Table 4** Results of best and worst cases analysis of energy efficiency

| Railway station | Chainage [km] | Distance from the previous railway station [km] | Distance from the Hegyeshalom (HH) railway station [km] | Best Case [kWh] | Worst Case [kWh] |
|---|---|---|---|---|---|
| **HH** | 188.0 | 0 | 0 | 0 | 0 |
| **MO** | 176.4 | 11.6 | 11.6 | 230 | 323 |
| **OT** | 154.9 | 21.5 | 33.1 | 328 | 479 |
| **GY** | 141.2 | 13.7 | 46.8 | 114 | 231 |
| **Sum.** | – | – | **46.8** | **672** | **1033** |

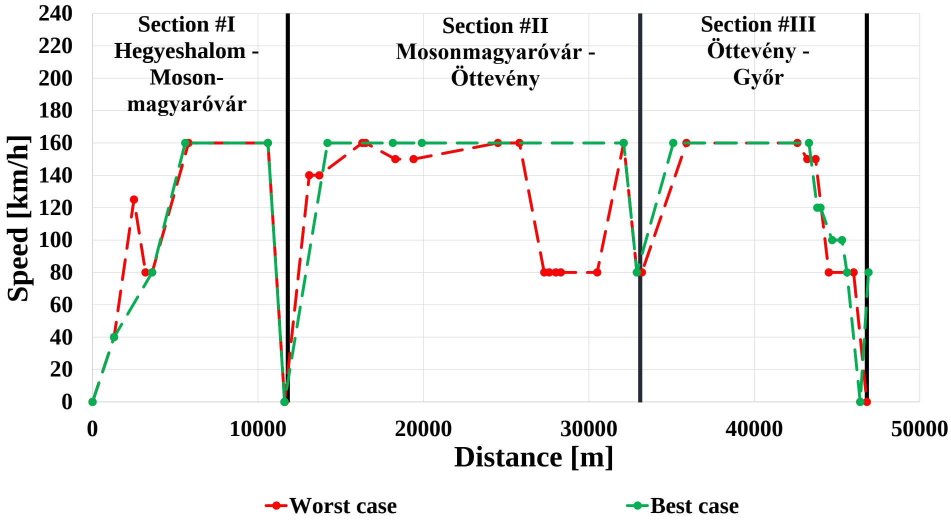


**Fig. 9** Energy consumption between Öttevény (OT) and Győr (GY)

Fig. 10 illustrates the average energy consumption related to smaller subsections. The dots connect the considered subsections' end points. The positive values refer to energy consumption due to acceleration and constant speed hauling. The negative values are related to regenerative braking. Therefore, it can be concluded that the average energy demand is approximately 0.0243 kWh/m.

The advantage of this approach is that it shows the required energy for each distance to be traveled, i.e., how much energy is needed to complete a subsection. However, the approach ignores its relation to the following subsection. For example, once a certain speed has been reached, further acceleration may no longer be required, so the energy demand is reduced. It is therefore recommended to apply a significant sample rate and a small subsection length. It must be noted that several measurement series need to be analyzed separately before the statistical investigation of the whole database.

Furthermore, it can be concluded that it is rather challenging to use the method with rarely/infrequently sampled data. However, short distances and dense data point-sets can greatly help assess a particular section.

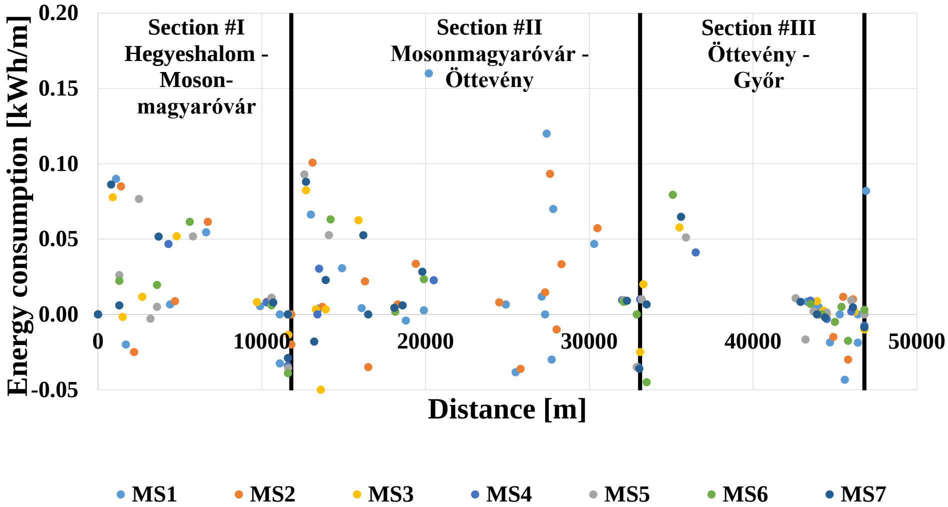


**Fig. 10** Average energy consumption data regarding the several subsections (the indicated dots are related to the considered subsections' end points)

## 4. Utilization of Energy Obtained from Regenerative Braking

The efficient use of the amount of energy recovered is of great importance for increasing efficiency. Fig. 11 illustrates the related measurements.

Fig. 11 shows that braking occured somewhere during MS2 and MS3. The reason was a speed restriction around OT. Relevant differences can also be observed in the quantity of generated regenerative braking energy during all the measurement series, probably due to the chauffeur's driving habit and traffic circumstances. The generated regenerative energy is one relevant factor, and the other is its possible utilization. In the case of optimal conditions, it can be charged into the electric network promptly and directly. Nevertheless, in the considered cases, it was not available, i.e., a substitute application would be needed. One choice could be the generated regenerative energy to supply comfort devices (e.g., lighting, air conditioning). The comfort energy request during all the measurement series is shown in Fig. 12.

The consumed electric energy data are presented in Fig. 12. These values are only approximations and highly dependent on external factors. The aim is to store the regenerative braking energy instead of losing it and ensure part of the comfort energy requests. According to the results, quite large amounts of energy can be stored using battery packs, and a relevant part of the comfort energy need can be covered (c.f., values in Figs. 11 and 12). Fig. 12 illustrates different cases in which the comfort energy consumptions (CECs) are 1.0 kWh during 8, 12, 15 and 18 s (CEC1-CEC4, respectively, see Fig. 12). These consumption values are related to real measurement, however, they are only approximated average values. The more accurate comfort energy consumption data are needed to be considered based on, e.g., on-board measurements. Further investigations are needed to solve this problem.

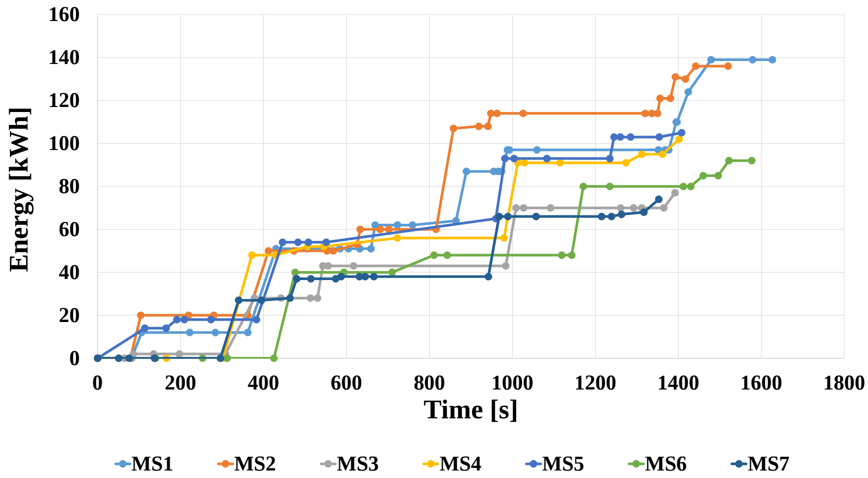


**Fig. 11** Regenerative energy generated between Hegyeshalom (HH) and Győr (GY)

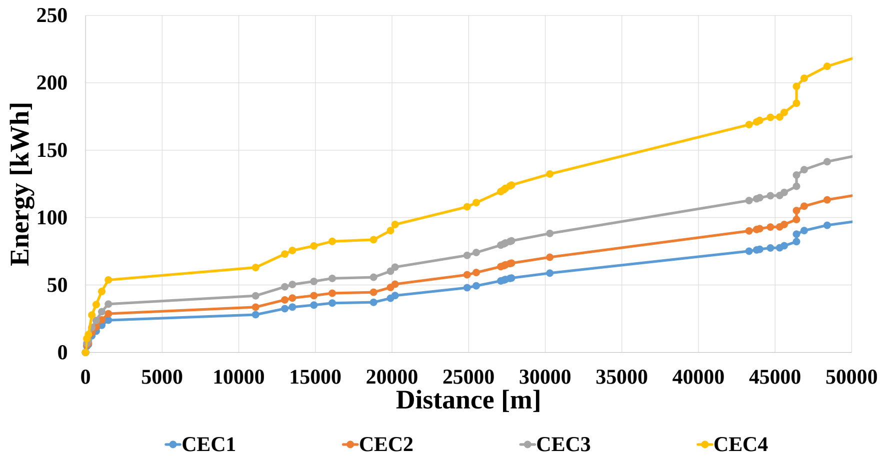


**Fig. 12** Approximated comfort energy consumption between Hegyeshalom (HH) and Győr (GY) considering four different trends

## 5. Conclusions

The paper deals with energy loss and fault location detection. The research is based on seven measurement series (i.e., from MS1 to MS7) performed by Railjet trains in Hungary.

The considered section was between Hegyeshalom (HH) and Győr (GY) railway stations. During the measurements, specific parameters were registered to define the accurate hauling and regenerative braking energy.

The article investigates the reasons for the high energy consumption and optimization of regenerative braking energy. Generally, two major influencing factors were determined:

the speed restrictions (quantities and places) and the chauffeur's driving habit. Therefore, the solutions can contain keeping the rolling stock and the related infrastructure in sufficiently acceptable condition or introducing speed restrictions and/or application of DASs. These systems aid with optimal acceleration and deceleration (i.e., with optimal energy consumption), considering the real permanent way's parameters and characteristics.

This paper also dealt with the energy loss detection process – as a part of energy optimization. The authors' main goal was to provide a useful algorithm to localize places and/or sections where there are significant energy consumptions. The algorithm applies a dividing process (dividing into sections) and searches for the reason for these steps and possible peaks. Furthermore, the authors decided to analyze in a more detailed manner the worst and the best cases (i.e., the data series with the lowest and highest energy consumption). In this way, they can be compared, and the differences can be explained in all the divided subsections.

The analyses also present an ideal acceleration and deceleration strategy to help decide when major energy losses are observed. Of course, these strategies cannot be taken into account in all traffic situations, but it is an excellent approach to designing and implementing an assistance system in the future.

The article also presents the consumed energy per traveled distance strategy, which is found to be inefficient to use on small data volumes (i.e., with low/rare data sampling).

Therefore, the authors propose investigating the initial fault detection using smaller sampling and more measurements. (It would avoid the initial large data set.) Furthermore, after locating the critical section, it must be investigated with a larger data sampling. In this way, the exact amount of energy loss for that subsection can be determined very accurately, and the fault can be more easily detected.

The value of the regenerative braking energy can be up to 30% of the total consumed energy. This relevant unused energy can be utilized for multiple goals: comfort energy requests (lighting, air conditioning) or energy-intensive starts. The accurate comfort energy consumption must be determined by (field, or on-board) measurements to be able to take into consideration in the future for optimization, as well as design related battery packs.

The authors would like to mention that the official price of electric energy for railway hauling is not available nowadays. It is the so-called "secret" between the provider (here, the MVM Group) and the consumer (here, the Hungarian State Railways Ltd., i.e., MÁV Ltd.). Therefore, the authors did not want to calculate approximated costs without accurate energy price values. However, an approx. electric energy price can be found on the internet (e.g., on the stock markets' webpages), and an elementary multiplication can be executed based on the published energy consumption data in kWh unit. It must be noted that the prices on the stock markets can significantly differ from the prices in mentioned contracts.

The authors clearly know that the time-table is one of the most critical aspects of railway transport. However, in the calculations, the optimization of the time-table was not considered. Only the energy consumption of the trains was considered. Railjet trains have the highest significance on railway mainline No. 1, so the authors think that the minimized energy is the most relevant related to Railjets. The time-table can be adjusted to this aim. The time-table optimization is, therefore, a suitable research direction, and it is planned for the future.

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