U.P.B. Sci. Bull., Series D, Vol. 88, Iss. 1, 2026 ISSN 1454-2358

ASSESSING ENERGY CONSUMPTION OF A TRAIN WITH LIMITED ACCELERATION BASED ON MECHANICAL ENERGY

George ILIE [1], Marius Alin GHEȚI [2, *]

This paper analyses the impact of maximum speed and acceleration on the energy consumption of an Electric Multiple Unit (EMU) operating on the Bucharest–Predeal route. A MATLAB-based simulation model incorporating traction characteristics, resistance forces, and operational constraints was applied to multiple scenarios. Results show that higher acceleration reduces both energy use and travel time by shortening resistive phases, while lower maximum speeds yield up to 12% energy savings with modest time penalties. The findings provide a quantitative basis for eco-driving strategies and driver assistance systems that support sustainable railway operations.

Keywords: railway energy efficiency, traction energy, acceleration limitation, speed profile.

1. Introduction

The global transport sector is a significant consumer of energy, and within this context, rail transport has established itself as one of the most energy-efficient and sustainable modes. Since the year 2000, railways have increased their energy efficiency by an impressive 37%, far surpassing the progress of other transport modes[1]. Rail's carbon emissions per tonne-kilometre for freight are approximately eight times lower than those of road transport, and a single freight train can replace up to 52 trucks [2]. This inherent efficiency and land-use advantage position rail as a cornerstone of sustainable mobility. However, to maintain its competitive edge and address the challenges of global warming and rising energy prices, the rail sector must continue to pursue innovations that further reduce energy consumption. Industrial programs, such as Shift2Rail, have prioritized the development of a "standardised methodology for estimating energy consumption" to accurately assess and demonstrate energy savings, providing a clear justification for targeted research in this area [1].

* Corresponding author

[1] PhD student, Doctoral School of FIMM, POLITEHNICA Bucharest, Romania, e-mail georgeilie27@yahoo.com

[2] Lecturer, Dept. of Railway Vehicles, POLITEHNICA Bucharest, Romania, e-mail marius_alin.gheti@upb.ro

To effectively analyse and optimize the energy consumption of an Electric Multiple Unit (EMU), it is critical to understand its primary energy loads. Traction energy, the power required to propel the train, accounts for the overwhelming majority of total consumption—approximately 80% to 90% for high-speed railways [3,4]. This is the most impactful target for energy-saving research. The factors influencing traction energy consumption can be broadly categorized into three groups: infrastructure effects, transportation organization effects, and external environmental impacts [4]. Among these, operational variables are particularly high-leverage. The relationship between a train's speed and energy use is non-linear, with studies showing that even moderate speed reductions can lead to significant energy savings of 10-25% [5,6,7]. Furthermore, the acceleration phase of a train journey demands the "most amount of energy," making it a critical variable for any optimization strategy [8].

While the literature has extensively explored mathematical and simulation models for train energy consumption, a significant gap remains. Many existing models are often "too idealized" or "too simplified" to fully account for the complex interplay of real-world operational factors [9]. Research has also highlighted that the train operator's driving style and habits are a major source of energy loss, yet there is a continued need for high-fidelity simulations that specifically isolate and quantify the combined effects of key operational variables. This paper addresses this gap by providing a systematic, granular analysis of the relationship between different speed and acceleration profiles and their direct impact on energy consumption. The findings will provide a quantitative basis for the development of more sophisticated and effective driving strategies and driver assistance systems.

This study proposes a simulation-based analysis of the energy consumption of an Electric Multiple Unit (EMU) passenger train by systematically varying two of the most critical operational parameters: maximum speed and maximum acceleration. The core objective is to develop and apply a simulation model to quantify the relationship between these operational profiles and the resulting energy consumption. The paper is structured to detail the mathematical equation who govern the train motion and anergy consumption, methodology, results, and their implications for sustainable railway operations.

2. Train equations of motion and energy consumption calculation

Various forces of different magnitudes and directions act upon a moving train. Analysing these forces is particularly important because their resultant determines both the nature of the train’s motion and the operating mode of the traction vehicle. While running on a line, the train may move uniformly, accelerate, or decelerate, depending on whether the resultant of the acting forces is equal to or greater than zero. Therefore, to establish the type of motion, it is essential to evaluate both the magnitude and the direction of this resultant [10].

The traction characteristic describes how the traction force varies with the vehicle's speed. It is obtained from the intersection between the adhesion-force limit curve (1) and the traction force curve developed by the vehicle's electric motors at constant power F_{Pct} (3).

$$F_a = m_L \cdot g \cdot \psi \text{ [N]} \tag{1}$$

where mL is the adhesive weight of the traction vehicle, g is the gravitational acceleration and ψ is the adhesion coefficient given by the following empirical formula:

$$\psi = 0.161 + \frac{7.5}{44 + v} \tag{2}$$

in which v is the speed given in km/h.

$$F_{Pct} = \frac{P_w}{v} \text{ [N]} \tag{3}$$

The rolling resistance force is given by:

$$R_T = m_{eq} \cdot g \cdot (r + i_c) \text{ [N]} \tag{4}$$

where m_{eq} is the equivalent mass of the train. In this case, considering that the train is a single unit, and the train is not composed of locomotive and waggons, m_{eq} is the train mass itself. In general case, if the train is composed from locomotive and wagons, the rolling resistance formula becomes:

$$R_T = m_{Loc} \cdot g \cdot (r_L + i_c) + m_v \cdot g \cdot (r_v + i_c) \text{ [N]} \tag{5}$$

where m_{Loc} denotes the mass of the locomotive, m_v represents the total mass of the wagons, r_L is the specific rolling resistance of the locomotive, r_v is the specific rolling resistance of the wagons, and i_c refers to the characteristic gradient (declivity).

Some formula for the specific rolling resistance are:

$$r_L = \frac{296 + 7.068 \cdot \left(\frac{v}{10}\right)^2}{120} \text{ [N/kN]} \tag{6}$$

that is used for a six axle locomotive with a mass of 120 tons (this is an empirical relation used for LE 5100 kW Romanian locomotive), and for a full passenger wagon

$$r_c = 2 + \frac{v^2}{2000} \text{ [N/kN]} . \tag{7}$$

The speed for relations (6) and (7) is also in km/h.

While moving along a straight track, on the train acts the following external forces: the traction force F_t and the rolling resistance force R_T. Depending on the values of these two forces, three cases can be identified:

- acceleration $F_t > R_T$;
- moving with constant speed $F_t = R_T$;
- deceleration $F_t < R_T$.

The acceleration of the vehicle at a given moment is obtained from the difference between the traction force and the rolling resistance force, in relation to the total mass of the vehicle:

$$a = \frac{F_t - R_T}{m_{eq}} \ [\text{m/s}^2]\,. \tag{8}$$

To calculate the energy consumption of a traction rail vehicle, the traction force must be at least equal to, and preferably greater than, the total resistance force acting on the train:

$$P = (F_t + R_T) \cdot v \quad [\text{W}]\,. \tag{9}$$

When the traction force developed by the vehicle is kept constant and is at least equal to the total resistance force opposing its motion, the condition for sustained travel is ensured. Under this premise, it becomes possible to determine the minimum power that the traction system must deliver in order for the vehicle to move along the track. This minimum power represents the threshold value necessary to overcome the resistances acting on the train, thereby allowing continuous operation without loss of speed:

$$P_0 = F_t \cdot v = R_T \cdot v \quad [\text{W}]\,. \tag{10}$$

After establishing the minimum power necessary for the vehicle's motion, it becomes possible to estimate the corresponding electricity consumption over a specific section of track. This estimation takes into account both the duration of operation under the given power demand and the characteristics of the route, such as its length, gradient, and resistance conditions. In this way, the calculated value provides a basis for evaluating the energy requirements of the traction system on that section and for further analysis of operational efficiency.

$$E = \int_{t_0}^{t_f} P \cdot \mathrm{d}t \quad [\text{Wh}] \tag{10}$$

This calculation is performed separately for each individual section of the track, taking into account the specific operating conditions that characterize that segment, such as gradient, curvature, rolling resistance, and train load. By analysing the sections independently, a more accurate estimation of the overall energy consumption along the entire route can be obtained.

3. Consumption simulation

The present study is focused on evaluating the energy consumption of a train over a defined hauling section, considering both real operating conditions and idealized scenarios. In each case, the analysis also accounts for the energy demand associated with a maximum acceleration value imposed on the train, thereby enabling a more comprehensive assessment of traction performance and efficiency.

The chosen case study is the Bucharest–Predeal section of Romania's Main Line 300, a route of strategic importance for both passenger and freight traffic. The corresponding speed profile is presented in Figure 1. As can be observed, the maximum operating speed of 140 km/h is sustained mainly along the Bucharest–Ploiești portion of the line, where the track layout permits higher velocities. By contrast, the Câmpina–Predeal segment traverses a mountainous region, characterized by frequent gradients and small-radius curves, which impose operational restrictions and reduce the maximum allowable speed to 100 km/h.

In addition, the altitude variation of the selected route, illustrated in Figure 2, reveals a total elevation difference of approximately 900 meters. This variation was determined by systematically evaluating the gradient of each individual track segment, thus providing a detailed representation of the topographical constraints that directly influence the train's traction requirements and overall energy consumption.

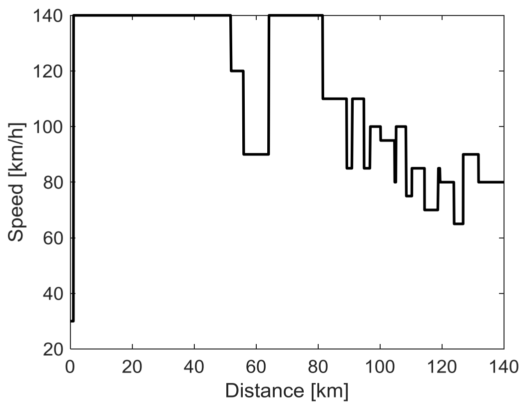

Fig. 1. The real speed profile of the route Bucharest-Predeal

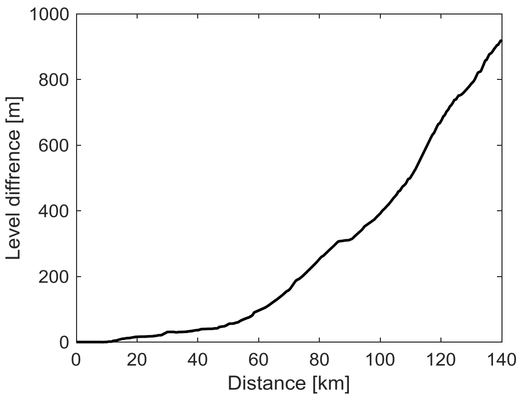

Fig. 2. Variation of the altitude in the simulation

The train model selected for the simulation is the Hyperion electric multiple unit, manufactured by Softronic Craiova. Its main technical characteristics, used to determine the traction characteristic, are: maximum speed v_{max} = 160 km/h, total traction motor power (considered as train traction power) P = 1720 kW, maximum acceleration 0.8 m/s², net weight 134.6 tons, maximum passenger capacity 288, and maximum operating mass 173 tons. The trainset is composed of four articulated cars, with a Bo'2'2'2'Bo' axle arrangement. The theoretical traction characteristic is presented in Figure 3, together with the resistance forces for two cases: zero gradient and the maximum gradient of the considered profile, 23‰. It can be observed that on the maximum gradient, the train reaches a maximum speed of approximately 120 km/h. This does not represent a constraint, since the steepest section lies within a track zone where the maximum line speed is below 100 km/h.

Based on this diagram, the maximum theoretical accelerations of the train can be determined using relation (8), as shown in Figure 4. In general terms, the acceleration curve indicates a maximum value of approximately 1.3 m/s² for level track, whereas on the maximum gradient the acceleration becomes zero at the maximum attainable speed, corresponding to the balance point where the traction force equals the resistance force.

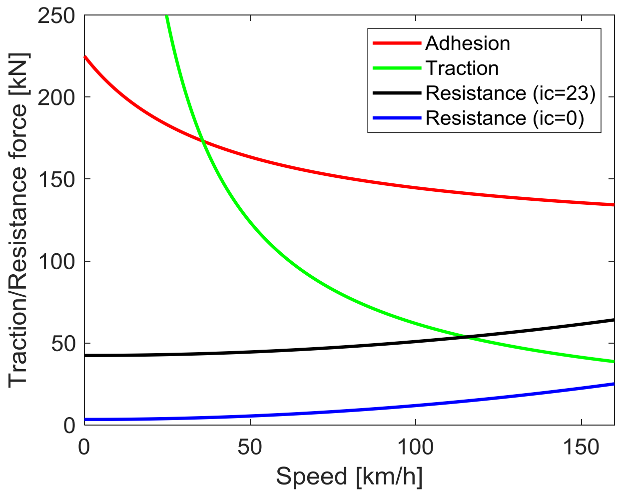

Fig. 3. Hyperion train theoretical traction diagram

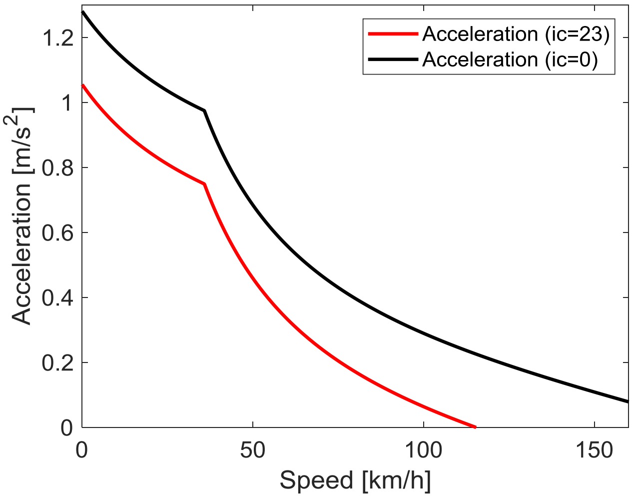

Fig. 4. Maximum acceleration of the train regarding speed and route declivity

Since this paper investigates the influence of acceleration on energy consumption, it is relevant to analyze up to what operating speed a given acceleration threshold can be maintained. Figure 5 illustrates these thresholds, limited by the maximum achievable acceleration under level track conditions and under the maximum gradient of the considered route. It can be observed that an acceleration of 0.1 m/s² can be maintained up to a speed of 150 km/h, while on the maximum gradient the corresponding maximum speed is approximately 90 km/h. At the other end of the range, the maximum acceleration specified by the train manufacturer, 0.8 m/s², can be maintained up to 50 km/h on level track and approximately 40 km/h on the maximum gradient.

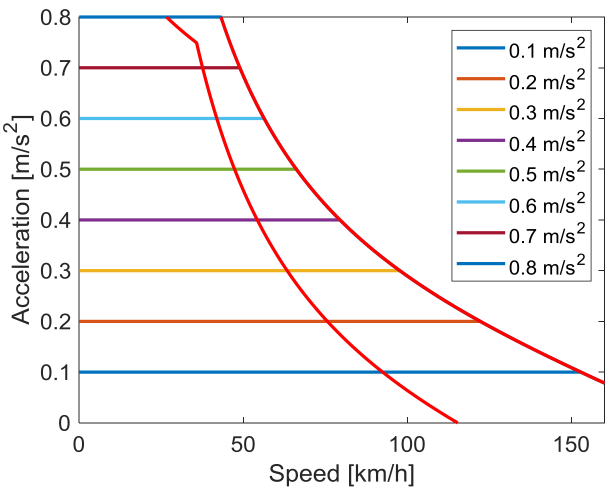

Fig. 5. Acceleration limit and posible speeds.

To obtain results that closely reflect real operating conditions, the train run considered is the Bucharest North – Predeal route, operated as a regional service. The choice of this train category is motivated by its multiple stops, which are relevant for studying the influence of accelerations on energy consumption. In the simulation program, the key input is the kilometer position of these stations. A dwell time of 1 minute is assumed at each intermediate stop, except at the terminus station where a dwell time of 15 minutes is considered. The stations along the route and their kilometer positions are listed in Table 1.

Table 1

Route stations and kilometer points

No.	Station	km
1	București Nord	0
2	Buftea	17
3	Dârza hc	21
4	Periș	30
5	Scroviștea hc	35
6	Crivina	40
7	Prahova	44
8	Brazi	51
9	Ploiești Vest	59
10	Buda	66
11	Florești Prahova	77
12	Câmpina	92
13	Breaza hc	97
14	Nistorești hc	100
15	Breaza Nord	102
16	Comarnic	106
17	Sinaia Sud hc	119
18	Sinaia	121
19	Poiana Țapului hc	126
20	Bușteni	129
21	Azuga	133
22	Predeal	139

The following scenarios are proposed for the analysis of energy consumption: (i) normal operation under real traffic conditions (according to the speed profile in Fig. 1) with a maximum speed of 140 km/h; (ii) operation on the real profile with a maximum speed of 120 km/h; and (iii) operation on the profile with a maximum speed of 100 km/h. Each of these cases is complemented by an additional scenario in which the maximum speed is assumed to be constant (140, 120, or 100 km/h) up to kilometre 80, after which the train continues at a constant speed of 100 km/h. These scenarios highlight the influence of speed variations (including restrictions) on energy consumption. For all cases, the maximum allowable acceleration of the train is varied from 0.1 m/s² up to 0.8 m/s², the latter being the maximum specified by the manufacturer. The six proposed speed profiles are shown in Fig. 6 for clarification.

To determine the energy consumption associated with train operation, a dedicated program developed by the author in MATLAB was employed. This software tool, designed and implemented as an in-house solution, was created to address the specific requirements of traction modelling and to enable detailed analysis of operational parameters. Its modular structure facilitates adaptation to diverse operating scenarios and allows the rapid integration of various input datasets (vehicle characteristics, speed profiles, resistance forces, operational conditions, etc.). The results generated by this tool provide high accuracy and sufficient detail for the research objectives and have been validated against theoretical and experimental data available in the literature.

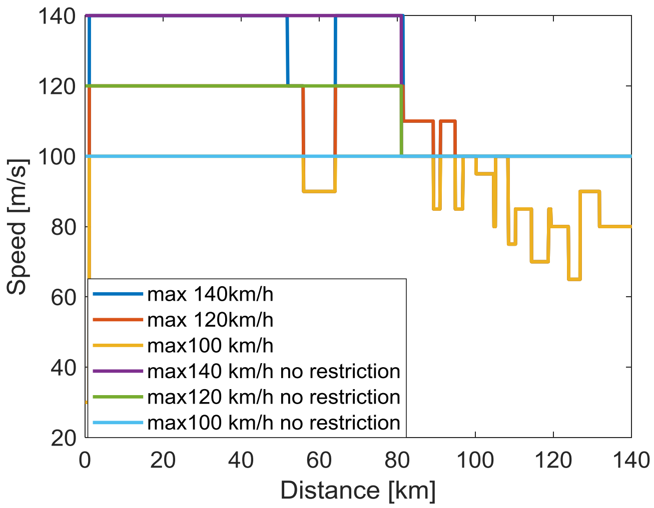

Fig. 6. Max speed of the route profile for all cases.

The energy consumed by the train on the real profiles at maximum speeds of 140, 120, and 100 km/h, as a function of the acceleration limit, is graphically presented in Figures 7, 8, and 9, respectively. For these cases, the total energy consumption and travel times are consolidated in Table II. In all scenarios, it can be observed that lower acceleration limits lead to higher energy consumption. Although counterintuitive, this outcome is explained by the longer time required for acceleration to reach a constant speed—taken in the simulation as the maximum speed of the profile—resulting in extended operation under resistive forces.

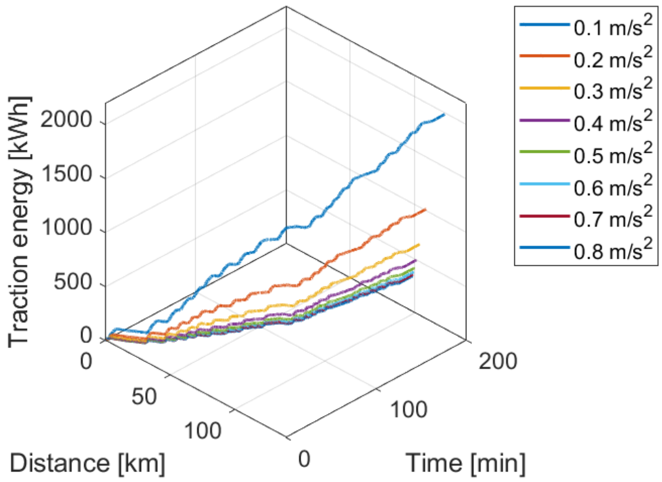

Fig. 7. Energy consumption in distance and time for real profile with max. speed of 140 km/h.

Another factor influencing the results is the time discretization step of the simulation program: a finer step yields more accurate results but requires significantly higher computation time and memory resources. Furthermore, the numerical precision (number of decimal places) with which the program operates must also be sufficiently high; otherwise, rounding errors can occur.

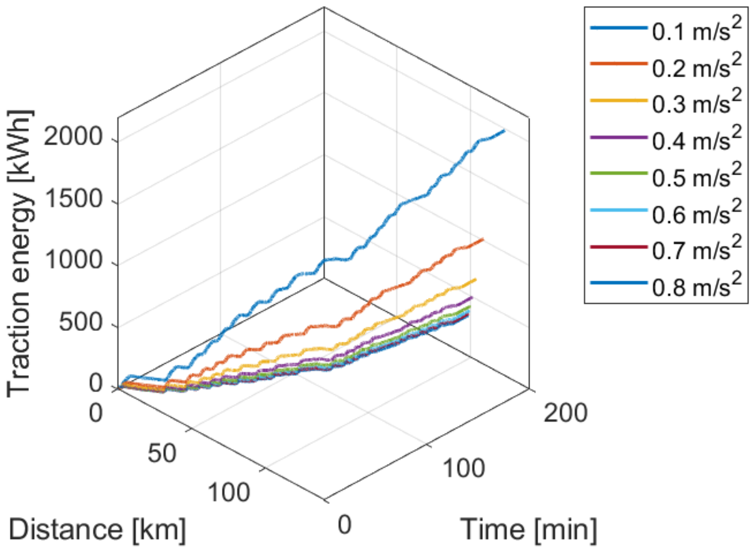

Fig. 8. Energy consumption in distance and time for real profile with max. speed of 120 km/h.

The analysis of the data in Table II highlights the following results: for the same simulation scenario, increasing the acceleration not only reduces travel time but also decreases the total energy consumption. In this study, instantaneous consumption values were not emphasized, although they may become significant at high accelerations and could pose challenges for the train's traction system. On the other hand, the differences resulting from imposing lower maximum speeds are not substantial in terms of travel time. For example, at an acceleration of 0.8 m/s², the journey time increases by only 8 minutes, while the total energy consumption decreases from 1126 kWh to 991 kWh, which is advantageous. These observations remain valid across all imposed acceleration cases analysed.

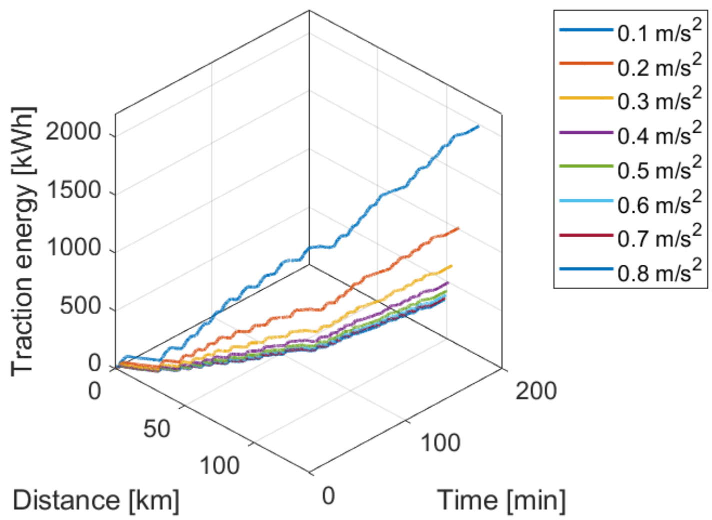

Fig. 9. Energy consumption in distance and time for real profile with max. speed of 100 km/h.

Table 2

Simulation results for the real route profile

Acc m/s^2	max 140 km/h		max 120 km/h		max 100 km/h	
	t [min]	E [kWh]	t [min]	E [kWh]	t [min]	E [kWh]
0.1	172	2367	173	2311	176	2200
0.2	149	1570	151	1515	155	1415
0.3	141	1256	143	1195	148	1122
0.4	137	1126	139	1063	145	991
0.5	135	1063	137	1000	143	928
0.6	133	1029	136	966	142	895
0.7	132	1010	135	947	141	875
0.8	132	999	135	934	141	863

Table III presents the results for simulations on the profile without speed restrictions. The observations made for the restricted profile remain valid. Improvements can be noted in both travel time and energy consumption, which is expected. The reduction in travel time is primarily due to maintaining higher speeds over longer distances, while the decrease in energy consumption is related to shorter acceleration periods. These observations are mainly qualitative, as the quantitative outcome depends on the specific profile, particularly the number of speed restrictions. For the particular case studied, it is shown that operation at constant speed reduces the travel time by an average of 7 minutes; however, from an energy perspective, it may actually lead to an increase. This effect occurs because the train operates at higher speeds for longer durations, and the resistance forces grow with the square of speed.

Table 3

Simulation results for the constant speed route profile

Acc m/s2	max 140 km/h		max 120 km/h		max 100 km/h	
	t [min]	E [kWh]	t [min]	E [kWh]	t [min]	E [kWh]
0.1	167	2450	169	2382	171	2254
0.2	142	1595	145	1527	150	1428
0.3	133	1278	137	1205	142	1133
0.4	129	1151	133	1073	139	1004
0.5	127	1088	131	1011	136	942
0.6	126	1055	129	977	135	907
0.7	125	1035	128	958	134	888
0.8	124	1023	128	945	134	875

Figure 10 illustrates the evolution of energy consumption for the six simulation cases, with the acceleration limit set to 0.8 m/s^2. As expected, the highest energy consumption corresponds to the case with the highest maximum speed (140 km/h), followed by the other two cases. The differences between profiles with and without speed restrictions can also be observed. As previously noted, these differences are relatively small compared to the overall energy consumption; however, a considerable variation is evident when the maximum operating speeds are reduced.

The data analysis highlights that energy consumption reduction is influenced by numerous factors, particularly by the characteristics of the track profile. Simulation results indicate that a significant decrease in energy consumption can be achieved by limiting the maximum operating speed.

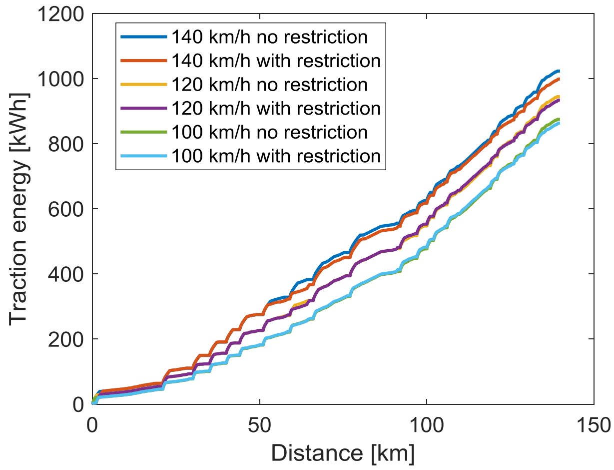

Fig. 10. Energy consumption comparations for acceleration of 0.8 m/s^2

However, this option requires a careful assessment of the trade-off between the benefits of energy savings and the disadvantages associated with increased travel times. Furthermore, reducing the number of sections with speed restrictions relative to the maximum speed has the potential to lower energy consumption by decreasing the number of acceleration phases, while simultaneously contributing to a reduction in the total travel time.

6. Conclusions

This study investigated the influence of maximum speed and maximum acceleration on the energy consumption of an Electric Multiple Unit (EMU) operating on the Bucharest–Predeal route, using a dedicated MATLAB-based simulation framework. The results showed that acceleration has a significant effect on both travel time and energy use. Higher acceleration values consistently reduced overall consumption as well as journey times, despite the potential increase in instantaneous power demand. This counterintuitive outcome is explained by the shorter duration of acceleration phases, which decreases the time spent under resistive forces.

The analysis also revealed that reductions in maximum operating speed can yield notable energy savings, with decreases of up to 12% when comparing operation at 140 km/h and 100 km/h. These benefits, however, come with modest increases in travel time, such as an additional eight minutes for the fastest acceleration case. This highlights the importance of balancing efficiency gains with service quality requirements. Route characteristics also play a decisive role: frequent speed restrictions were found to increase energy use by forcing repeated acceleration phases, whereas maintaining longer stretches of constant speed helped to reduce both journey time and, in some cases, total energy demand, even though higher speeds generally increase resistive losses.

Taken together, the findings confirm the strong potential of operational optimization in reducing the energy footprint of passenger trains. They demonstrate that strategies focusing on controlled acceleration and moderate speed reduction can achieve meaningful savings without significantly compromising travel times. The simulation-based approach presented in this work provides a quantitative basis for the development of advanced eco-driving algorithms and driver assistance systems. In the future, incorporating factors such as passenger load, regenerative braking performance, and real-time traffic interactions will allow for even more comprehensive optimization strategies, supporting the rail sector's continuing role as a cornerstone of sustainable mobility.

Acknowledgement

This work was supported by a grant from the National Program for Research of the National Association of Technical Universities—GNAC ARUT 2023, Grant No. 154/04.12.2023.

R E F E R E N C E S

[1] International Transport Forum. Rail's sustainable chain of mobility. OECD. https://www.itf-oecd.org/rails-sustainable-chain-mobility, (2025, September 1)

[2] VTG. Four good reasons for transporting goods by rail. VTG. https://www.vtg.com/news-and-insights/stories/four-good-reasons-to-transport-goods-by-rail, (2025, September 2).

[3*] Ren, J., Zhang, Q., & Liu, F.*, Analysis of factors affecting traction energy consumption of electric multiple unit trains based on data mining. Journal of Cleaner Production, 262, 121374, 2020.

[4] *Fischer, S., Hermán, B., & Szürke, S. K.*, Possibilities for determining the energy consumption of electric locomotives during acceleration and constant-speed traction. Cognitive Sustainability, 4(2), 2025.

[5] *Lindgreen, E. B. G., & Sorenson, S. C.*, Simulation of energy consumption and emissions from rail traffic. Technical University of Denmark, 2005.

[6] Zhao, H. B., Relationship between energy consumption and speed of the EMU. In 2016 4th International Conference on Electrical & Electronics Engineering and Computer Science (ICEEECS 2016) (pp. 579-583). Atlantis Press, 2016.

[7] *Arsene, S., Sebeşan, I., Certan, A., & Popa, G.*, Influence resistance at advancing on fuel consumption for vehicles that use an internal source of energy. Procedia-Social and Behavioral Sciences, 186, 573-581, 2015.

[8] *Das Gupta, S., Van Parys, B. P., & Tobin, J. K.*, Energy-optimal Timetable Design for Sustainable Metro Railway Networks. arXiv e-prints, arXiv-2309, 2023.

[9] *Lu, G., He, D., & Zhang, J.*, Energy-saving optimization method of urban rail transit based on improved differential evolution algorithm. Sensors, 23(1), 378, 2022.

[10] *Arsene, S., Sebesan, I., & Popa, G.*, The influence of wind on the pantograph placed on the railway electric vehicles bodywork. Procedia-Social and Behavioral Sciences, 186, 1087-1094, 2015.