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SUSTAINABLE RAILWAYS – INVESTIGATION OF THE ENERGY EFFICIENCY OF ELECTRIC RAIL VEHICLES

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Abstract – *This paper investigates the energy efficiency of electric rail vehicles, focusing on factors that promote more sustainable railway systems. Using real-time data from Siemens Ventus trains operating between Vienna-Deutschkreuz and Vienna-Bratislava, the study analyzes how regenerative braking, infrastructure quality, and driver behavior affect energy consumption. The data were processed to evaluate energy consumption and pinpoint areas for potential efficiency improvements. The results demonstrate that regenerative braking and energy storage systems substantially reduce energy consumption, although external factors, such as track conditions and operational strategies, introduce variability in consumption. These findings support the development of energy-efficient railway operations in line with the European Union's sustainability objectives.*

Keywords – electric rail vehicles, electric multiple units, energy efficiency, regenerative braking, sustainable railways.

1. INTRODUCTION

This study explores the energy efficiency of electric rail vehicles, an essential factor in fostering sustainable railway systems, aligned with the EU's focus on environmentally sustainable, multimodal transportation [1]. Technological advancements, such as regenerative braking systems, enhance energy efficiency by transforming kinetic energy into reusable electrical power, reducing total energy consumption by as much as 45% under specific conditions. [2,3].

Integrating energy storage systems further enhances efficiency by capturing energy otherwise lost during braking [4]. Effective energy management requires a comprehensive approach that includes infrastructure quality, operational strategies, and driver behavior, which can significantly impact energy savings [5].

The research is partly related to optimizing train schedules and energy usage. Driver Assistance Systems (DAS) improve punctuality and efficiency through real-time data, reflecting the industry's commitment to sustainability. The study analyzes Siemens Ventus electric multiple units' energy consumption on routes between Vienna-Deutschkreuz and Vienna-Bratislava in early 2023. It identifies four primary factors affecting energy efficiency: infrastructure, regenerative braking, external factors, and human behavior [6].

While data limitations hindered a detailed analysis of driver styles, the study provides valuable insights into energy consumption and supports efforts to enhance rail transport sustainability [6].

2. APPLIED METHODS

This article analyzes data sourced from the on-board computers of Raaberbahn trains operating on the Vienna-Deutschkreuz and Vienna-Bratislava routes from January to May 2023. The data, provided in bulk Excel files from Siemens Ventus trains includes the following key points.

The data structure comprises five monthly data series recorded at 5-minute intervals, capturing details such as train numbers, GPS coordinates, and cumulative electricity consumption. Specific data points, including precise speeds, acceleration and deceleration times, and driver identities, are missing.

Supplementary data: the segment numbers for stations and stops were obtained from Raaberbahn and ÖBB reports, and GPS coordinates were determined accordingly. Speed limits for each section were sourced from ÖBB, Raaberbahn AG, and public data available on www.openrailwaymap.com.

Data processing: the trains were mapped to specific routes based on GPS coordinates. A Python program calculated distances between data points and determined the direction of travel. The data was filtered to focus on energy consumption and regenerative

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braking energy within a ±2 km range of stations, considering the direction of travel. The methodology outlines the process of focusing on data points within this ±2 km range around stations.

Statistical analysis: Excel files were generated with multiple worksheets for specific routes, calculating metrics such as minimum, maximum, average, standard deviation, and relative standard deviation for energy consumption and regenerative energy recovery.

The analyses were conducted using data from three different train datasets, covering the routes illustrated in Figure 1.

The datasets contain a month's worth of data, recorded at 5-minute intervals, and include GPS coordinates, time, energy consumption, and regenerative energy data. The data was stored based on time rather than distance, meaning that while continuous data was captured, the relationships between consecutive data points were not pre-defined.

Given that the bulk data represents trains operating over multiple sections, the first step in processing was to assign these sections to specific routes using GPS coordinates to determine both the route and the direction of travel. A reference line was established for each route. Distances from stations were recorded in a lookup table, with distances between points set at 50 meters. Subsequently, the incoming GPS coordinates were assessed to determine the distance from the departure station, allowing the train's real-time position to be calculated.

Fig.1. Map of the section to be analyzed with the railway stops

The data was then organized in alignment with the railway schedules, which included travel times, energy consumption, and regenerative braking energy values. It is important to note that these values represent instantaneous conditions.

Figure 2 illustrates the data points corresponding to each section. The x-axis (horizontal) represents the distance traveled, while the y-axis (vertical) shows the energy consumed. It is important to note that the energy values do not account for any deductions from regenerative braking. The numbered markers and vertical lines on the charts represent station locations. The data from different trains are represented by distinct colors: blue for train 300, gray for train 301, and yellow for train 303. The red line indicates the proportional average energy consumption.

The scatter plot reveals that many data points are either significantly above or below the average. Furthermore, there is no section where energy consumption consistently deviates significantly above or below the average.

Key considerations and unaddressed limitations include the following.

The analyses did not use machine manual data or other tractive force curves to calculate Siemens Ventus trains' acceleration and regenerative braking energies, nor were the measured values considered.

The analyses did not discuss or use the railway lines' layout and vertical geometry data.

The authors did not use official train timetables for each route and direction, and rolling axle load values were disregarded.

The allowed speeds for each section, presented in Section 2.1, were included for informational purposes only and were not factored into the detailed analysis.

The technical condition of the railway track and associated infrastructure (e.g., overhead contact line network) or the traction units (whether in poor or good condition) was also not considered.

The analyses relied solely on data from January to May 2023, and no attempt was made to extrapolate this data to estimate values for other months; the analysis is, therefore, based entirely on factual data from this period.

Each month was treated as a separate unit (without merging data), and energy consumption (kWh+/km) and regenerative braking (kWh–/km) values were analyzed separately for each month.

3. RESULTS AND DISCUSSION

The analyzed route between Vienna and Bratislava includes 11 stops, though trains do not stop at every station. The energy consumption data is presented in aggregate form, but the available information does not allow for determining the exact time spent at each stop. The main goal of this analysis is to observe average energy consumption across different segments and identify the factors affecting it.

Section A) of Fig. 3 shows cumulative energy consumption, highlighting the maximum and minimum values, while Section B) presents the average distribution, showcasing variability across segments. This helps pinpoint areas where consumption is unstable and requires further investigation. Section C) shows energy consumption per kilometer, indicating which segments consistently have higher average consumption, often due to inclines or initial delays. Section D) details the energy recovered through regenerative braking, giving a complete view of the regenerative contribution.

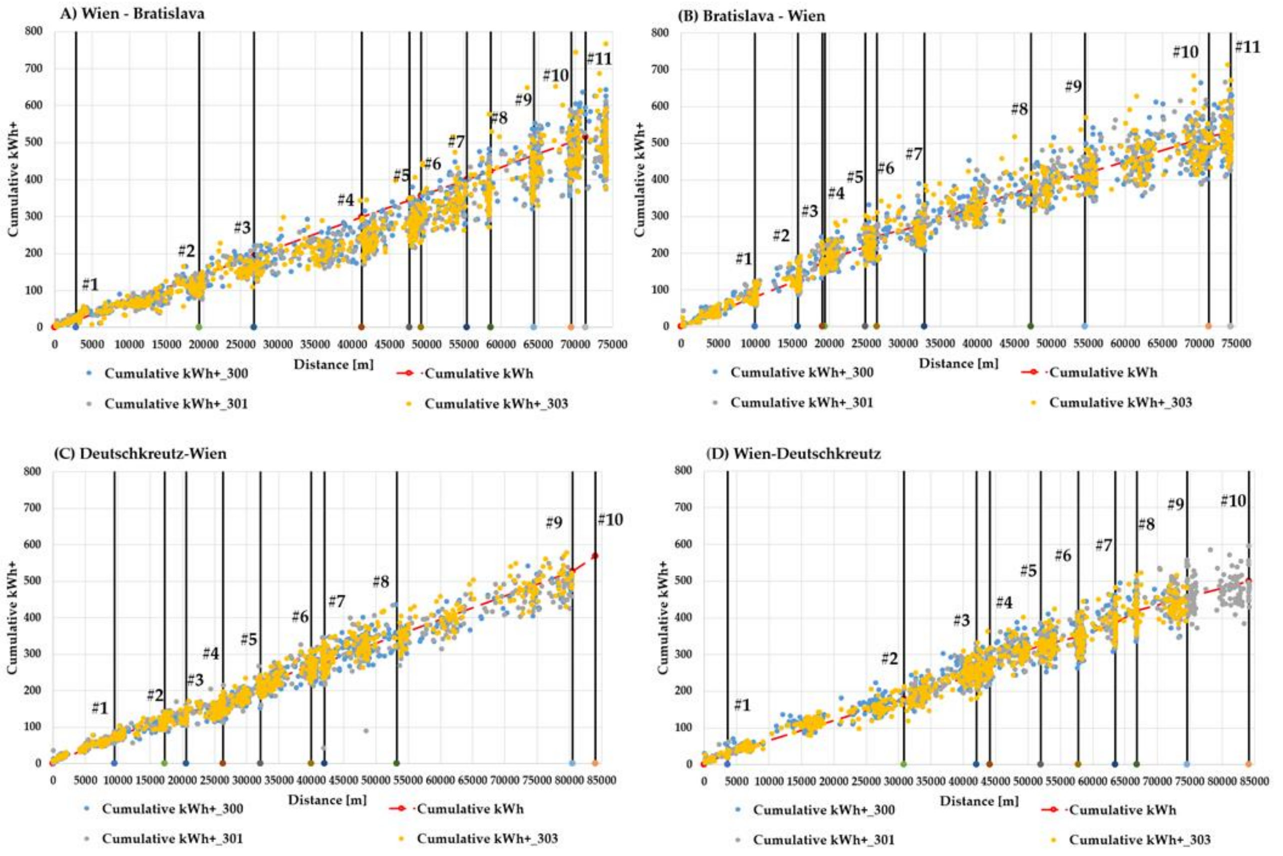

Fig.2. Stops and associated consumption data for each railway line (chainage "0" means the beginning section)

This method clarifies energy imbalances and allows for fitting curves to each segment's average consumption, generated energy, and total consumption. These curves reveal where and why energy balance deteriorates and help identify sections with the highest energy demand. The method can also detect track issues and areas of higher-than-average consumption. External factors like unplanned waiting times can also be spotted. Regenerative braking efficiency depends on how much energy the network absorbs, but larger datasets help account for this. Even the train operator's influence can be observed in lower regeneration or larger analyses. Curve fits from these evaluations are shown in Figure 4.

4. CONCLUSION

This study offers a detailed look at the energy efficiency of electric rail vehicles, focusing on the role of regenerative braking systems, infrastructure quality, and operational practices. Essential trends in energy use can be identified by examining critical factors like energy consumption, regenerative energy recovery, and overall energy balance for different rail segments.

The findings show that regenerative braking and energy storage systems significantly enhance efficiency. However, external factors like railway track conditions and driver behavior introduce variability in energy savings. The current analysis reveals that when energy consumption surpasses 110% of the average, even high levels of regenerative energy recovery are not enough to offset the increased demand.

This highlights the need for a comprehensive approach to managing railway energy consumption that combines technological innovation with optimized operational strategies. Going forward, efforts should focus on reducing the influence of external factors and refining predictive models to optimize real-time energy usage better.

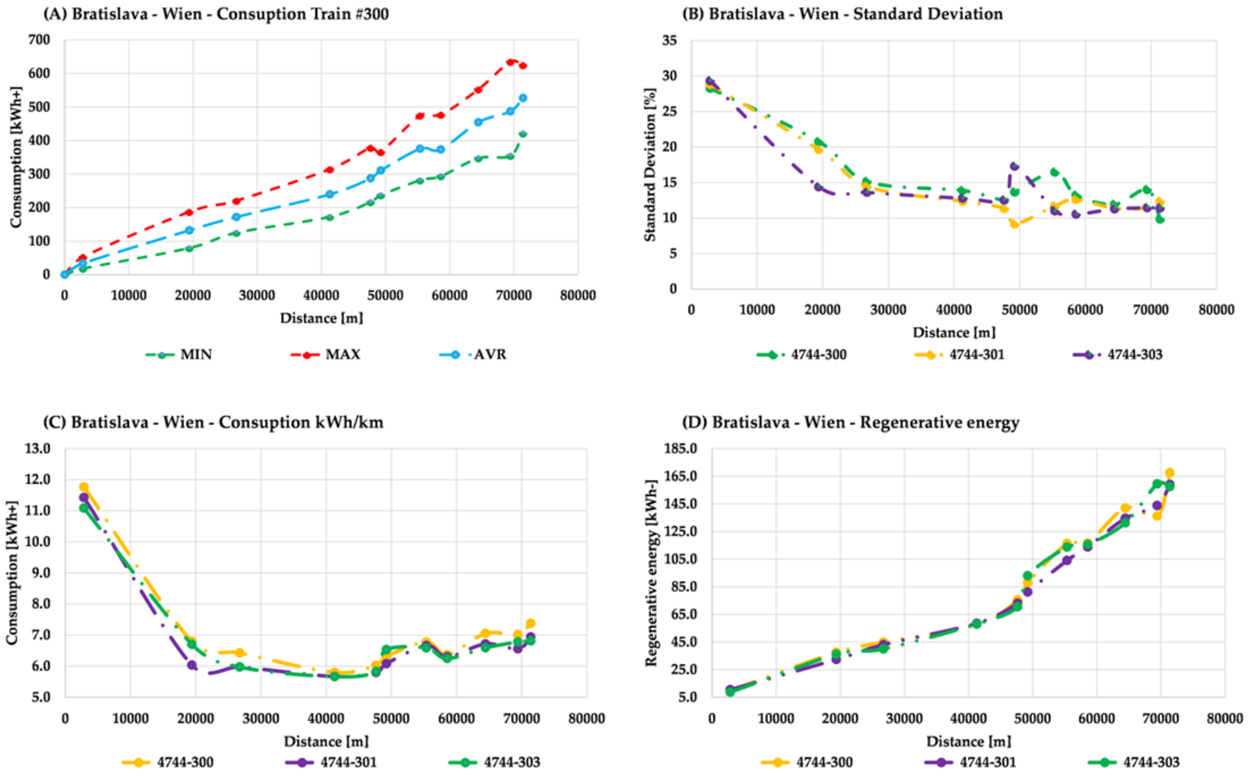

Fig.3. Analysis of consumption and approaches to energy efficiency in rail

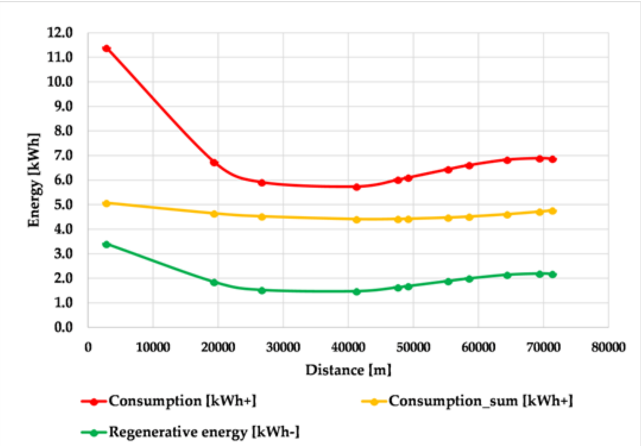

Fig 4. Curve fits obtained from the evaluation of the measurements

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