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THE POTENTIAL FOR ECODRIVING SAVINGS IN REGIONAL AND SUBURBAN RAIL TRAFFIC BASED ON STUDIES CONDUCTED IN 2024–2025 USING JOURNEYS OPERATED IN CENTRAL POLAND

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Abstract

With the growing share of electricity costs in the budgets of railway operators, the identification and utilization of the potential for traction energy savings is becoming an important issue from both an economic and an environmental perspective. As part of research work carried out during the testing and deployment of the SENSUM in-cab DAS recommendation system, telemetry and traffic data from train journeys operated in 2024–2025 in central Poland were analyzed, with a focus on the impact of driving technique on traction energy consumption. The research concentrated on the energy consumption necessary to set the vehicle in motion and to operate it in accordance with the timetable, i.e. on the aspect that is directly influenced by the train driver. The analysis was based on the basis that two elements of driving technique are key to the energy efficiency of a journey: the moment at which the maximum speed on a section is reached and the moment at which coasting without energy consumption is initiated. The presentation outline challenges and conclusions related to estimating the scale of achievable savings in the context of variability in transport operations, along with directions for further research, including the impact of rolling stock equipped with regenerative braking.

Keywords: traction energy, driving technique, energy-efficient train operation, coasting strategy, driver advisory systems

1 Introduction

Electric traction dominates passenger rail transport across Europe, making electrical energy a major component of operating costs and environmental impact for railway undertakings. Consequently, a substantial share of passenger services is operated under conventional driving regimes, in which the train driver retains significant influence over traction energy consumption, with Driver Advisory Systems (DAS) supporting energy-efficient driving strategies. Within this operational context, eco-driving has become a well-established concept in railway practice. Eco-driving encompasses driving strategies aimed at reducing energy consumption by shaping speed trajectories while respecting timetable constraints and operational safety. Prior studies indicate that such strategies can yield measurable reductions in traction energy, motivating analytical methods capable of assessing energy-saving potential under heterogeneous regional operating conditions [3, 4].

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1.1 Traction energy as the significant controllable share of total train energy consumption

The total energy consumption of an electric passenger train is commonly described as the sum of traction energy used for motion, auxiliary loads, system losses, and unrecovered braking energy. For commuter and regional passenger services, traction energy constitutes the dominant share of total final energy consumption and is directly influenced by driving technique. Even modest percentage reductions in traction energy can therefore translate into substantial absolute energy savings at the system level, providing strong motivation for their quantitative analysis under real operational conditions.

1.2 Timetable slack as the operational condition enabling traction energy savings

Timetable slack is introduced primarily to ensure operational flexibility and robustness of railway services, allowing disturbances to be absorbed and congestion to be avoided. From an energy perspective, the existence of slack creates a degree of freedom in train operation: when the full scheduled running time margin is not required to maintain punctuality, it can be converted into reduced traction energy demand. This conversion is achieved predominantly by lowering peak speeds and extending coasting phases, thereby reducing the energy required for acceleration and sustained traction. In this sense, timetable slack constitutes the elementary operational prerequisite of eco-driving, as it enables the driver to adapt the driving technique to current traffic and operational conditions without violating timetable constraints. The physical and operational relationship between timetable margins, achievable speed profiles, and traction energy consumption has been extensively discussed in the literature, which consistently identifies slack and running time margins as key enablers of energy-efficient train operation [3, 5].

1.3 Polish operational context and data availability enabling this study

In Poland, the SENSUM system, deployed in production operation since 2025, represents a practical implementation of a Driver Advisory System supporting energy-efficient train driving. The system generates advisory speed profiles based on timetable information, rolling stock characteristics, and a detailed graph-based representation of the national railway network. While recommendations are advisory and do not replace driver responsibility, a key feature of the system is the centralized logging of anonymized operational telemetry. The resulting datasets constitute the empirical basis for the analyses presented in this study and enable investigation of eco-driving potential under real regional railway operating conditions characterized by diverse routes, stopping patterns, and timetable structures.

1.4 Motivation and positioning of the study

Recent developments in railway energy management indicate a growing demand for analytical tools that support operator-level energy assessment, particularly in the context of eco-driving. While existing commercial solutions and research studies predominantly focus on online train control, detailed physical optimization, or post hoc reconstruction of energy consumption, a methodological gap remains in scalable approaches suitable for large-scale evaluation of real-world regional railway operations. Previous research has demonstrated that traction energy consumption is strongly constrained by timetable characteristics and speed profiles, and that feasible energy-saving potential can be described using boundary-based formulations derived from optimized trajectories or inferred from operational descriptors. In parallel, control-oriented studies have integrated energy estimation into online optimization and learning-based frameworks under punctuality and safety constraints.

Building on these findings, the present study adopts a boundary-based interpretation of traction energy consumption but pursues a different objective: the estimation of energy-saving potential at the operator level, rather than direct train control or trajectory optimization. Instead of reproducing established methods for deriving energy-optimal trajectories, modeled and empirical speed profiles are used to define feasible energetic boundaries for timetable-compliant train runs. Within this scope, the robustness of the proposed approach is examined for large-scale implementation, with particular emphasis on route-level energy assessment and the estimation of gross energetic potential embedded in current operations.

2 Methods

This section describes the data sources, quality considerations, and processing framework used to quantify traction energy consumption and to assess the potential energy savings associated with eco-driving strategies.

2.1 Data sources and data quality

The analysis is based on complementary datasets describing the railway system, planned operation, and realized train runs. System description data include rolling stock characteristics, a graph-based railway network, and timetable information. Realized train operation is characterized by aggregated indicators and spatio-temporal records of train motion. Runs that cannot be reliably reconstructed or interpreted are excluded from the analysis.

2.2 Data processing

The data processing workflow links planned operation with realized train runs through a set of comparable energetic descriptors. Timetable, infrastructure, and rolling stock data are used to derive simplified indicators and to construct a linear distance representation of each route. Realized runs are mapped onto this reference, positioned relative to derived boundaries, and aggregated into comparative operational baskets.

2.2.1 Timetable benchmarking

Timetable benchmarking introduces simple, physically grounded indicators for large-scale screening of timetable energy relevance based on planned operation data. The proposed indicator, denoted as KET (Key Energy Timetable indicator), is defined as:

$$ket = 1.071 \cdot 10^{-5}\, n_{sp}\, m'\, v_{max,\mathrm{km/h}}^{2}\ [\mathrm{kWh}] \tag{1}$$

with its distance-normalized counterpart:

$$ketn = \sum ket \,/\, \sum D\ [\mathrm{kWh/km}] \tag{2}$$

where n_{sp} denotes the number of scheduled stopping points, D the running distance and m' denotes the equivalent train mass expressed in tonnes. By design, these indicators capture the dominant timetable-driven contribution to traction energy associated with acceleration, while deliberately omitting secondary effects such as rolling resistance, gradients, or regenerative braking. This simplification preserves computational efficiency and interpretability, making the proposed indicators suitable as screening tools for identifying energetically significant relations and timetables to be examined in subsequent, more detailed analysis stages.

2.2.2 Train route linear representation

Each route is transformed from its schedule-graph-based representation into a linear distance domain to enable uniform comparison of realized runs with speed and energy boundaries.

2.2.3 Low speed/energy boundaries for timetable (timetable-based speed and energy profile optimization using nonlinear programming)

A lower speed and energy reference boundary is determined by solving a timetable-constrained nonlinear programming problem in the distance domain. The objective minimizes net traction energy under infrastructure, vehicle, and running-time constraints and serves solely as a comparative baseline for subsequent analysis of realized runs. The objective function minimized for each segment is expressed as:

$$J = \sum_i \Delta s_i \left(F_i^{\mathrm{tr}} / \eta - \eta_{re} F_i^{\mathrm{br}} \right) \tag{3}$$

where F_i^{tr} denotes the traction force, F_i^{br} braking force, η_{re} represents the efficiency of regenerative braking, and ΔS_i is the corresponding spatial discretization step. The resulting solution represents an energy-optimal speed profile under fixed running-time constraints and does not aim to reproduce operational driving strategies.

2.2.4 Boundary-based comparison and basket aggregation of realized runs

Realized train-run data from the data gathering system are mapped onto the same linear distance representation as the optimized route and compared with the timetable-derived lower speed–energy boundary. This comparison quantifies the gap between analytically defined reference operation and real-world driving behavior. Individual runs are positioned using key operational descriptors, most notably achieved maximum speed and deviations of segment running times from scheduled values. The upper energetic envelope is inferred empirically from the ensemble of realizations and reflects physically and operationally plausible driving behavior.

For scalable interpretation, runs are aggregated into comparative operational baskets defined by shared timetable, infrastructure, and rolling-stock characteristics, such as route length, number of scheduled stops, admissible speed range, rolling stock type, and basic temporal properties. Within each basket, observed traction energy is evaluated relative to the ket/ketn indicators and the analytical lower boundary. The resulting basket-level energy distributions are interpreted as gross energetic potential, defined as the envelope of all energetically feasible improvements relative to the analytical lower boundary across the set of realized runs, rather than as a single achievable saving for any individual journey.

3 Results

This section presents empirical results obtained using the proposed processing framework. The results are organized to illustrate: (i) timetable-driven energetic relevance, (ii) the relation between analytically derived lower boundaries and realized operation, and (iii) the structure of energetic dispersion observed at basket level.

3.1 Timetable-driven energetic relevance

This subsection examines how timetable structure alone differentiates railway services in terms of energetic relevance, prior to any consideration of realized operation. Figure 1 presents two-dimensional projections of timetable-based kinetic energy indicators derived exclusively from scheduled stopping patterns, admissible speed limits and rolling stock characteristics. The absolute indicator ket (figure 1a) exhibits a clear stratification of services primarily driven by the number of scheduled stop points, with rolling stock mass acting as a systematic offset and only minor sensitivity to relation length. In contrast, the distance-normalized indicator ketn (figure 1b) explicitly captures the effect of relation length, assigning higher energetic intensity to shorter relations with comparable stopping structure. Accordingly, ket characterizes absolute energetic significance, whereas ketn reflects energetic intensity per unit distance.
Together, these projections demonstrate that timetable structure alone is sufficient to systematically differentiate services in terms of energetic relevance. Relations with dense stopping patterns and higher admissible speeds consistently occupy regions of elevated energetic importance, indicating where subsequent boundary-based and realization-level analyses are expected to reveal the largest energetic envelopes.

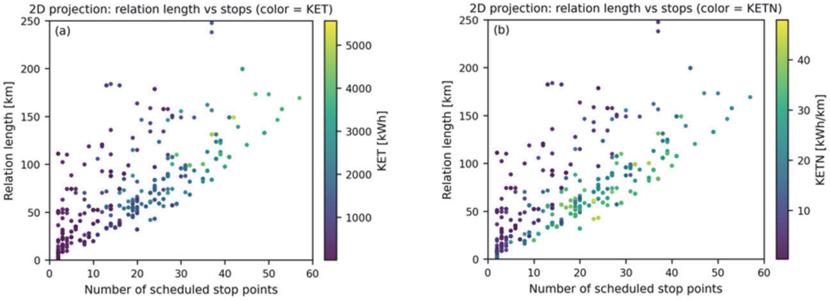

Figure 1 Timetable-driven energetic relevance

Two-dimensional projections of timetable-based kinetic energy indicators as a function of the number of scheduled stops and relation length: (a) absolute indicator ket and (b) distance-normalized indicator ketn. Point color denotes total train mass. Results based on 1 078 individual train timetables (daily timetable profile).

3.2 Lower boundary vs. realized operation

Realized train runs systematically remain above the analytically derived lower traction energy boundary when ordered by timetable-based energetic relevance (KET). The observed realizations form a bounded region whose lower edge is defined by the optimized reference profile, while the median and spread of realized energy increase with absolute energetic significance. This structure confirms that the analytical lower boundary constitutes a physically meaningful minimum for timetable-compliant operation and that realized driving behavior occupies a constrained energetic envelope above this reference. The resulting organization provides a consistent basis for subsequent envelope- and basket-level dispersion analysis.

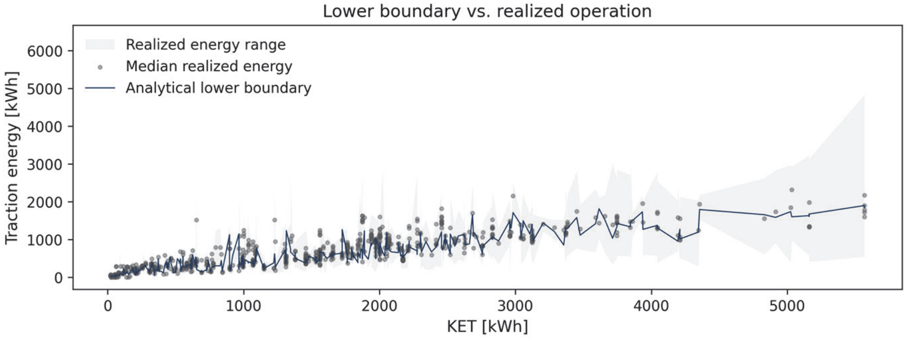

Figure 2 Lower boundary vs realized operation

3.3 Dispersion and basket-level structure

Even under identical timetable conditions, realized traction energy exhibits a substantial spread, reflecting operational variability beyond timetable structure alone. Aggregation at the relation level therefore conflates heterogeneous operating regimes and limits normalization-based interpretation (figure 3).

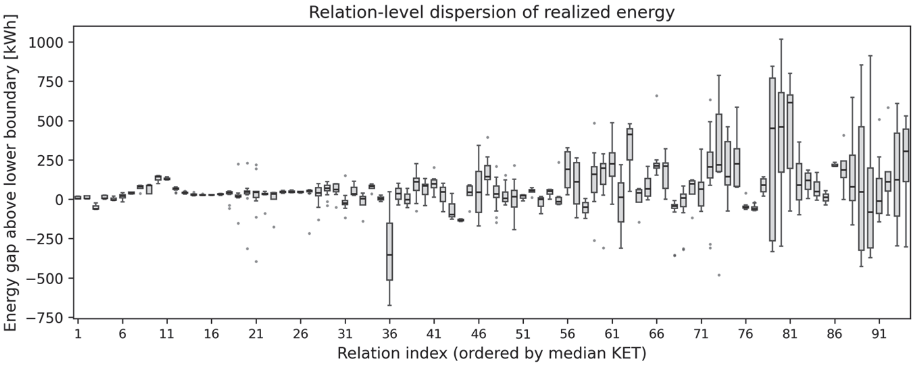

Figure 3 Dispersion and its structure

Aggregation into comparative operational baskets reduces random variability observed at the level of individual runs, while preserving the energetic envelope identified in the unaggregated data. The resulting distributions confirm the suitability of basket-based analysis for large-scale comparisons. To address this, operational baskets are introduced as a deliberately constructed normalization framework, defined to capture the dominant determinants of traction energy consumption (timetable structure, rolling stock, stopping pattern, and admissible speed profile). The purpose of basket-level aggregation is not to eliminate dispersion, but to isolate a reference space in which energy consumption can be meaningfully compared and normalized.

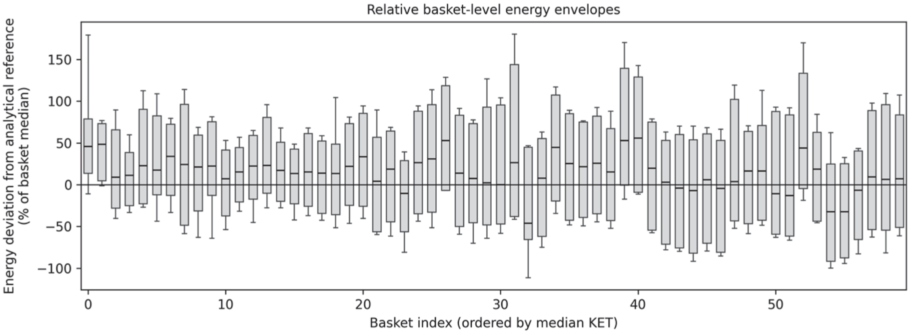

Figure 4 Relative basket-level energy envelopes

For each operational basket, the empirical envelope of realized traction energy is expressed relative to the analytical lower bound, with deviations shown as a percentage of the median basket-level consumption.

4 Conclusion

This study demonstrates that a boundary-based interpretation of traction energy consumption provides a scalable framework for assessing eco-driving energy-saving potential in regional and suburban railway operations. The results confirm that a substantial dispersion of traction energy consumption exists even for runs operated under identical timetable conditions. This dispersion is not random but is systematically related to a limited set of operational parameters directly influenced by driving technique. The relative position of realized runs with respect to the analytically derived lower energy boundary therefore constitutes a physically interpretable measure of energetic performance under comparable operational constraints. The application of comparative operational baskets further shows that aggregation stabilizes the analysis and enables robust comparison across heterogeneous routes, rolling stock types, and service patterns. At the basket level, the distribution of distances between realized traction energy consumption and the lower boundary defines a gross energetic potential embedded in current operations. While this potential cannot be directly equated with achievable savings, it provides a necessary empirical foundation for forecasting, sensitivity analysis, and the evaluation of eco-driving strategies at the scale of a railway operator. Overall, the proposed methodology bridges the gap between detailed optimization-based studies and operator-level energy assessment, providing a data-driven basis for the development of predictive and decision-support tools for energy-efficient railway operation.

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