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Rail to Digital automated up to autonomous train operation

D39.6 –Analysis of Automatic Driving benefits in energy saving

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EXECUTIVE SUMMARY

Automatic Driving is widely considered a key enabler for improving the efficiency and sustainability of railway operations. By controlling train speed profiles in a more consistent and anticipative way, it has the potential to reduce energy consumption, improve operational regularity, and support higher levels of system performance. However, these expected benefits need to be quantified using real operational data and consistent evaluation methods.

This deliverable addresses this need by analysing the impact of Automatic Driving on energy consumption and operational behaviour, within the framework of the FP2 R2DATO project. The work focuses on providing a data-driven assessment based on real commercial services and experimental runs, with the objective of comparing Automatic Driving and manual driving under comparable conditions.

The analysis is centred on a KPI-based approach, where a limited set of measurable and robust indicators is used to evaluate train performance. These include running time in relation to the available timetable, energy consumption derived from onboard measurements, the occurrence of braking events, and the interaction with the protection system. This approach allows both a global and a more detailed interpretation of the train behaviour, highlighting not only the overall performance but also how it is achieved.

The work is based on datasets collected from commercial passenger services operated along the Empoli–Siena line, complemented by additional data from controlled test environments. This combination makes it possible to analyse both real operational variability and more repeatable scenarios. At the same time, the work highlights practical aspects related to data availability and processing, which are an important part of the overall assessment.

The results show that Automatic Driving provides a more regular and consistent driving behaviour compared to manual operation. This is reflected in a more stable use of the available running time and a reduced variability between runs. From an energy perspective, the analysis indicates a general tendency towards lower consumption under Automatic Driving, which can be linked to a smoother management of traction and braking phases and a reduced need for corrective actions.

Additional indicators, such as the number of braking events and the interaction with the ATP system, support this interpretation by showing a more controlled and anticipative driving approach. Overall, the benefits of Automatic Driving appear more clearly when analysed at a detailed level, while purely aggregated indicators may not always capture these effects.

Some limitations have also been identified during the work. In particular, the structure and completeness of onboard data can affect the level of detail and the robustness of the analysis. Moreover, the impact of Automatic Driving is influenced by external factors, such as timetable constraints and infrastructure characteristics, which may limit the observable benefits in specific sections of the line.

In this context, the work can be considered a solid step towards a quantitative assessment of Automatic Driving, but further developments are needed. Future activities should focus on improving data integration, refining the definition of KPIs, and extending the analysis to more complex operational conditions.

Overall, this deliverable provides a consistent and realistic evaluation framework that contributes to a better understanding of Automatic Driving performance. It supports the ongoing efforts within

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Europe’s Rail to move from qualitative expectations to measurable and comparable results, and it provides a basis for future developments and potential large-scale deployment.

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
ACCU	Accumulator
AD	Automatic Driving
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CCS	Command Control and Signalling
DC	Direct Current
DMMS	Dynamic Maintenance Management System
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
GoA	Grade of Automation
GUI	Graphical User Interface
JP	Journey Profile
KPI	Key Performance Indicator
MP	Mission Profile
R2DATO	Rail to Digital automated up to autonomous train operation
SP	Segment Profile
TCMS	Train Control Management System
TRL	Technical Readiness Level
TSI	Technical Specification for Interoperability
WP	Work Package

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TABLE OF CONTENTS

AcknowledgementS 2
Report Contributors 2
Executive Summary 4
Abbreviations and Acronyms 6
Table of Contents 7
List of Figures 8
List of Tables 9
2 Introduction 10
3 Methodological Framework 12
3.1 Description of rationale for KPI based performance assessment and data sources. 12
3.1.1 Role and Benefits of a KPI-Based Approach 12
3.1.2 Principles for KPI Definition and Scope of Analysis 12
3.1.3 Macroscopic vs Microscopic Perspective in ATO Assessment 13
3.2 Data Set Acquisition Process and related Elaboration 15
3.2.1 Data Sources and Acquisition Infrastructure 16
3.2.2 Description of the Acquired Data Sets 17
3.3 Dataset Clustering to be used for KPI extraction 19
4 KPIs Definitions 20
4.1 Actual Running Time / Available Running Time 20
4.2 Energy Consumption 21
4.3 Number Of Braking Events 23
4.4 Number Of ATP Interventions 24
5 Analysis of the runs 26
5.1 Analysis of Siena-Empoli Logs 26
5.1.1 Description of monitored services 26
5.2 Analysis of S.Donato Logs 31
5.3 KPI-Based Comparison of Commercial, Laboratory Runs 31
5.3.1 Actual Running Time / Available Running Time 31
5.3.2 Energy Consumption 33
5.3.3 Number Of Braking Events 36
5.3.4 Number Of ATP Allerts/Interventions 38
6 Conclusions 42
References 44

Interne

LIST OF FIGURES

Figure 1: Example of microscopic comparison of manual and Automatic Driving over the same operational section. The figure shows the speed profile and corresponding traction/braking commands as a function of travelled distance. Automatic Driving achieves the required speed reduction through a smoother and more regular control strategy, while manual driving exhibits stronger corrective actions and more frequent command variations. 14

Figure 2: Example of macroscopic comparison between manual and Automatic Driving represented in the time–distance domain. The figure compares the overall evolution of the train along the route and illustrates how differences in driving strategies translate into different journey times at the scale of the complete run. Unlike the microscopic analysis, which focuses on local control actions, the macroscopic perspective highlights the resulting operational performance and supports the assessment of indicators such as travel time, punctuality and timetable adherence. 14

Figure 3: Example of DMMS graphical interface showing real-time train status, onboard subsystem health indicators, and vehicle localisation during a commercial service. 17

Figure 4: Overall electrical architecture of the Blues train (HTR312/412), showing the arrangement of traction converters, DC-link, onboard energy storage (ACCU), and auxiliary power systems across the vehicle units. The diagram highlights the main energy flows and the measurement points for line voltage and line current, DC-link power to the accumulator, and traction-related currents and voltages within the propulsion system. 23

Figure 5: Speed Profiles of commercial service Siena – Empoli; comparison between manual driving, automatic driving respecting arrival time and automatic driving minimizing the running time. 29

Figure 6: Speed Profiles of commercial service Empoli - Siena; comparison between manual driving, automatic driving respecting arrival time and automatic driving minimizing the running time. 29

Figure 7: Distribution of the KPI Actual Running Time / Available Running Time Focus on northbound (even-numbered services). Comparison between manual and automatic driving; the vertical line at 1.0 represents nominal timetable compliance. 32

Figure 8: Distribution of the KPI Actual Running Time / Available Running Time Focus on southbound (odd-numbered services). Comparison between manual and automatic driving; the vertical line at 1.0 represents nominal timetable compliance. 33

Figure 9: Comparison of energy consumption per section (even runs) between manual driving and Automatic Driving. 34

Figure 10: Comparison of energy consumption per section (odd runs) between manual driving and Automatic Driving. 34

Figure 11: Energy saving ratio per section – comparison between manual driving and Automatic Driving (even runs). Mean 22%. 35

Figure 12: Energy saving ratio per section – comparison between manual driving and Automatic Driving (odd runs). Mean 15% 35

Figure 13: Average of Braking Events per section – comparison between manual driving and Automatic Driving. (even runs) 37

Figure 14: Average of Braking Events – comparison between manual driving and Automatic Driving. (odd runs) 38

Figure 15: Average of ATP Allert Events – comparison between manual driving and Automatic Driving (even runs). No events during automatic driving. 39

Interne

Figure 16: Average of ATP Intervention Events – comparison between manual driving and Automatic Driving (even runs). No events during automatic driving. 40

Figure 17: Average of ATP Allert Events – comparison between manual driving and Automatic Driving (odd runs). No events during automatic driving. 40

Figure 18: Average of ATP Intervention Events – comparison between manual driving and Automatic Driving (odd runs). No events during automatic driving. 41

LIST OF TABLES

Table 1: List of train services travelling along the Empoli Siena line detailing the number of operational stops (including Origin and destination). 16

Table 2: List of selected services for focused analysis. 18

Table 3: List of specific occurences of selected services for analysis. 19

Table 4: Timetable service number *19032; normal running time; wide running time; short running time* 27

Table 5: Timetable service number *19040; normal running time; wide running time; short running time* 27

Table 6: Timetable service number *19046; normal running time; wide running time; short running time* 27

Table 7: Timetable service number *19033; normal running time; wide running time; short running time* 28

Table 8: Timetable service number *19039; normal running time; wide running time; short running time* 28

Table 9: Timetable service number *19049; normal running time; wide running time; short running time* 28

Interne

2 INTRODUCTION

This deliverable presents the analysis of the impact of Automatic Driving on energy consumption and operational performance, based on real data collected from commercial services and test activities.

The work is part of the WP39 activities within the FP2 R2DATO project and focuses on understanding, in a quantitative way, how Automatic Driving affects train behaviour. In particular, the objective is not only to confirm expected benefits, but to measure them using real data and consistent indicators.

The topic is relevant in the current railway context, where increasing efficiency and reducing energy consumption are key priorities. Automatic Driving is often considered a promising solution, since it directly controls the train speed profile and therefore how traction and braking are used. However, in many cases the benefits are still described in qualitative terms or evaluated through simulations. This work tries to move a step further by analysing real operations and comparing Automatic Driving with manual driving under similar conditions.

The analysis is mainly based on services operated on the Empoli–Siena line, which provide a good balance between repeatability and operational variability. In addition, some reference data from controlled tests (e.g. San Donato) have been used to better interpret the results.

A central point of the work is the use of a KPI-based approach. A set of simple and measurable indicators has been defined, such as:

- running time compared to available timetable time,
- energy consumption,
- number of braking events,
- interaction with ATP.

These KPIs are used to compare different driving modes and to understand how changes in driving behaviour translate into energy and operational effects. In addition, a more detailed (microscopic) analysis of the speed profiles has been performed, allowing to capture effects that would not be visible with aggregated indicators only.

From a technological point of view, the work reflects a maturity level around TRL 6–7, since it is based on real operational data and validated scenarios, rather than purely theoretical or simulated environments.

One of the key aspects addressed in this deliverable is the difficulty of working with onboard data. The available logs are heterogeneous and not always directly usable, so part of the effort has been dedicated to reconstructing consistent datasets (e.g. speed profiles derived from position data). This aspect is not only a technical detail, but also an important lesson learned for future developments.

The document is structured as follows. First, the methodological approach and the data sources are described. Then, the KPIs used in the analysis are introduced. The central part of the document presents the results obtained from the comparison between manual and automatic driving. Finally, the conclusions summarise the main findings and highlight possible next steps.

While the results confirm that Automatic Driving brings clear benefits in terms of regularity and energy efficiency, they also show that the impact is not uniform and depends on factors such as

Interne

available running time and infrastructure constraints. These aspects, together with data-related limitations, represent open points for future work within the Europe's Rail framework.

3 METHODOLOGICAL FRAMEWORK

3.1 DESCRIPTION OF RATIONALE FOR KPI BASED PERFORMANCE ASSESSMENT AND DATA SOURCES.

Assessing the performance of Automatic Driving (AD/ATO) requires more than a qualitative judgement and calls for a structured, quantitative approach. Automatic Driving directly affects several key operational dimensions, including running time, headway, buffer times, driving variability and overall operational stability. More broadly, its functionalities influence, either directly or indirectly, the train speed profile, the management of traction and braking, the regularity and smoothness of the run, and the reduction of energy dissipation.

As a result, Automatic Driving has a measurable impact on multiple aspects of the railway system such as capacity, energy efficiency, asset consumption and system robustness. This establishes a clear link between operational performance and higher-level objectives related to sustainability and energy efficiency. The underlying rationale can be described through a simple causal chain, in which Automatic Driving functions shape the dynamic behaviour of the train, leading to operational and energy impacts that can be captured through appropriate Key Performance Indicators (KPIs).

3.1.1 Role and Benefits of a KPI-Based Approach

KPIs are therefore required to properly understand and quantify these effects, and they also enable objective comparisons between different Automatic Driving implementations. This is particularly relevant in the current context, where multiple real-world applications of Automatic Driving are already in operation, making data collection and evidence-based evaluations feasible. In addition, KPIs play a key role as optimisation tools, providing feedback both for the evolution of ATO system definitions and for identifying optimal parameter settings in the tuning of Automatic Driving functions and of the railway system as a whole.

A KPI-based approach offers several advantages, including objectivity and repeatability of results, comparability between operating scenarios such as manual versus automatic driving, and transparency towards stakeholders and reviewers. It also supports the tuning of complex systems, including through laboratory tests and simulations, and avoids purely descriptive, subjective or scenario-dependent assessments. In this sense, KPIs are essential to monetise benefits such as travel time reduction, energy savings, staff costs and rolling stock wear, to evaluate trade-offs between competing objectives like capacity versus stability or time versus energy, and ultimately to justify investments and large-scale deployment of ATO technologies.

3.1.2 Principles for KPI Definition and Scope of Analysis

The definition of KPIs in this work is guided by a set of principles, including their relevance with respect to energy savings and efficiency goals, measurability using available data sources (diagnostic data from on-board systems), reproducibility of results, scalability across different operational contexts, and, where possible, independence from non-controllable variables such as environmental conditions, traffic disturbances, train load or operational restrictions. A specific focus is placed on comparisons between manual driving and Automatic Driving, while recognising that

future analyses may extend towards different levels of automation or different services and routes. For this reason, the analysis relies on a set of elementary KPIs, including energy consumption, travel time and distance.

3.1.3 Macroscopic vs Microscopic Perspective in ATO Assessment

Although ATO acts on the driving laws of the individual train based on static and dynamic information provided by infrastructure and signalling, its benefits do not necessarily translate into variations of aggregated indicators at the level of an entire run. Instead, they emerge in the temporal and operational structure of the journey and in local interactions along the route. From this perspective, a macroscopic analysis, while simple and robust, may fail to capture effects such as differences in the distribution of acceleration, coasting and braking phases, the reduction of corrective braking actions, or improvements in local robustness and smoothness, which may occur even when overall running time remains unchanged.

For this reason, the assessment of Automatic Driving effects requires a microscopic approach, intended not as a continuous fixed time-step simulation, but as a representation at the level of individual operational sections. This level of detail is sufficient to identify where and why Automatic Driving modifies train behaviour and to enable realistic comparisons between automatic and manual operation.

The example shown in Figure 1 highlights the type of evidence that can be obtained through a microscopic assessment. By analysing speed profiles together with the associated traction and braking commands at the level of individual operational sections, it becomes possible to identify differences in driving strategies that may remain hidden when considering aggregated indicators only. In particular, the microscopic perspective enables the observation of variations in the distribution of traction, coasting and braking phases, the occurrence of corrective control actions, and the smoothness of speed adaptation processes. These aspects provide a basis for interpreting potential impacts on performance indicators such as energy consumption, component wear, ride quality and operational robustness.

The complementary role of macroscopic analyses should also be recognised. While microscopic investigations reveal local behavioural differences and the underlying mechanisms generating ATO benefits, macroscopic analyses are more suitable for assessing the overall operational outcome of train movements and their interaction with the railway system. Figure 2 illustrates a typical macroscopic representation based on a time–distance diagram, where the train trajectory is observed over the complete route. This type of analysis focuses on the resulting operational performance rather than on the underlying control actions and supports the assessment of indicators such as journey time, punctuality, timetable adherence, traffic regularity, and, when extended to multiple trains, the management of conflicts and crossing operations on constrained infrastructures such as single-track lines.

The trade-off between macroscopic and microscopic approaches therefore does not lie in the temporal resolution adopted, but in the level of detail required for the effects of Automatic Driving to become observable. Microscopic analyses provide insight into the mechanisms through which Automatic Driving influences train behaviour, whereas macroscopic analyses evaluate the extent to which these behavioural changes translate into measurable operational benefits. The combined use of both perspectives therefore provides the most comprehensive assessment framework for ATO applications.

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Figure 1: Example of microscopic comparison of manual and Automatic Driving over the same operational section. The figure shows the speed profile and corresponding traction/braking commands as a function of travelled distance. Automatic Driving achieves the required speed reduction through a smoother and more regular control strategy, while manual driving exhibits stronger corrective actions and more frequent command variations.

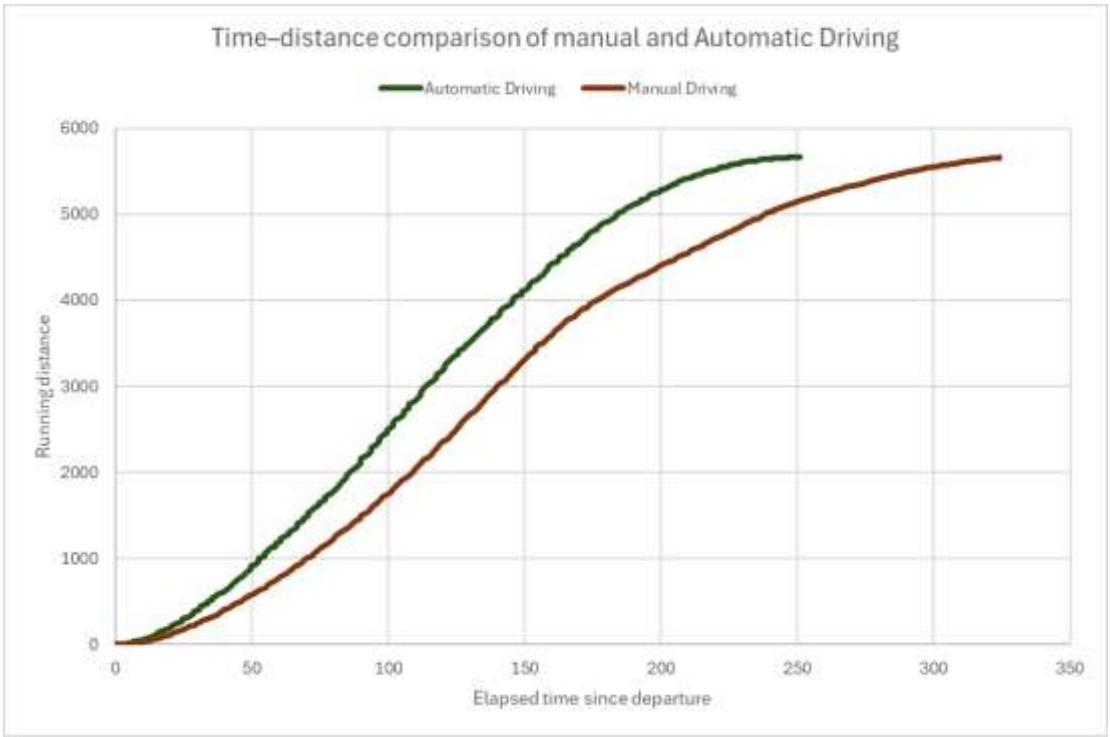


Figure 2: Example of macroscopic comparison between manual and Automatic Driving represented in the time–distance domain. The figure compares the overall evolution of the train along the route and illustrates how differences in driving strategies translate into different journey times at the scale of the complete run. Unlike the microscopic analysis, which focuses on local control actions, the macroscopic perspective highlights the resulting operational performance and supports the assessment of indicators such as travel time, punctuality and timetable adherence.

3.2 Data Set Acquisition Process and related Elaboration

The analysis focuses on commercial passenger services operated along the Empoli–Siena railway line, selected as a representative regional line characterised by frequent stops, mixed traffic operation.

An initial screening was performed on all scheduled services running on the line, considering both southbound (odd-numbered services) and northbound (even-numbered services). For each service, the total number of stops, including origin and destination, was analysed in order to identify homogeneous operational patterns.

Based on this preliminary assessment, the study was further refined by restricting the scope to services with origin and destination exclusively at Empoli and Siena. This choice ensured:

- consistency in the operational mission profile,
- comparable journey lengths and stopping patterns,
- reduction of bias caused by partial-line services or turn-back operations.

The resulting subset consists of:

Empoli → Siena services (odd direction), typically featuring around 10 intermediate stops and scheduled travel times of approximately 65–75 minutes;

Siena → Empoli services (even direction), with comparable stopping patterns and overall journey duration.

This filtering step resulted in a set of services suitable for comparative energy and operational analysis under consistent boundary conditions.

Odd service number	Number of stops	Even service number	Number of stops
18201	8	18194	8
18203	8	18200	12
18205	8	18204	7
18207	8	18206	7
18209	8	18208	13
18211	8	18210	10
18213	8	18212	14
18215	8	18214	9
18217	8	18216	9
18219	8	18218	9
18221	8	18220	9
18223	8	18222	9
18225	8	18224	9
18227	8	18226	9
18229	8	18228	9
18233	13	18230	9
18259	8	18232	9
18851	19	18234	9

19031	10	18236	9
19033	10	18238	9
19035	10	18242	9
19037	10	18278	17
19039	10	18328	11
19041	10	18852	17
19043	10	19030	6
19045	10	19032	10
19047	10	19034	10
19049	10	19036	10
19051	10	19038	10
19053	10	19040	10
19055	10	19042	10
19057	10	19044	10
19059	10	19046	10
		19048	8
		19114	13
		19130	10
		4010	6

Table 1: List of train services travelling along the Empoli Siena line detailing the number of operational stops (including Origin and destination).

3.2.1 Data Sources and Acquisition Infrastructure

The Dynamic Maintenance Management System (DMMS) is a digital platform developed by Trenitalia to support the transition from traditional time- and mileage-based maintenance towards a condition-based and predictive maintenance approach. DMMS is widely recognized as a reference implementation of data-driven maintenance in the railway sector.

DMMS is designed to continuously monitor the health of rolling stock by integrating data from onboard sensors, diagnostic subsystems, and maintenance information systems. Modern trains are equipped with hundreds of sensors measuring parameters such as temperature, vibration, electrical currents, and operational states of critical components.

A key capability of DMMS is the computation of health and life indicators for components and subsystems. Using statistical methods and advanced analytics, the system supports early anomaly detection and degradation trend assessment. Maintenance actions can therefore be planned based on the actual condition of assets, allowing maintenance schedules to dynamically adapt to real operational profiles rather than relying on predefined thresholds.

DMMS acts as an integration layer between onboard systems, maintenance depots, and enterprise IT environments. It interfaces with maintenance management systems, work order tools, and asset databases, ensuring traceability from anomaly detection to corrective action. Digital dashboards and condition monitoring tools support maintenance planners and technicians during both planning and execution phases.

The DMMS architecture is open and scalable, capable of handling large volumes of heterogeneous data. The adoption of Big Data and in-memory processing technologies enables near real-time analytics and supports deployment across different fleets and service types.

Operational benefits include improved fleet availability, reduced in-service failures, and increased punctuality. By anticipating failures, trains can be routed to maintenance facilities in a controlled manner, minimizing service disruptions. Optimized maintenance intervals also contribute to more efficient use of spare parts, workforce, and workshop capacity, with positive impacts on lifecycle costs and sustainability.

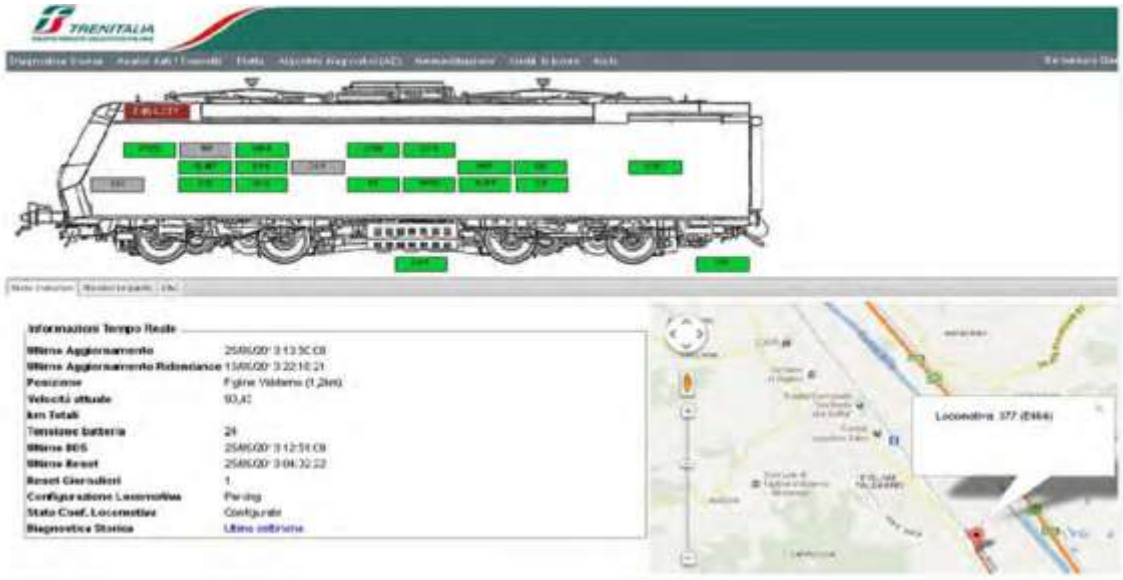


Figure 3: Example of DMMS graphical interface showing real-time train status, onboard subsystem health indicators, and vehicle localisation during a commercial service.

From an operational point of view, DMMS is mainly designed to support data retrieval on a per-vehicle basis. Data extraction queries are natively structured around the identification of a specific trainset and a defined time interval.

Queries directly indexed by commercial service number are not available as a primary search key; nevertheless, the system allows the user to select a specific commercial service, which is then translated into an equivalent query based on the vehicle identifier and the time window corresponding to the planned execution of the service of interest.

As a consequence, when multiple realizations of the same commercial service are required (e.g. runs performed on different days or by different vehicles), the data download process must be reiterated for each individual run, adjusting vehicle identifiers and time intervals accordingly.

3.2.2 Description of the Acquired Data Sets

The data set includes log files extracted from commercial services operated with different trainsets and rolling stock types, mainly belonging to the HTR312 and HTR412 fleets. The files are structured as Excel datasets generated by the onboard recording systems and downloaded via DMMS.

The acquired data can be grouped into two main categories:

Commercial Service Log Files

As an introductory note, the analysis was deliberately focused on a selected subset of commercial services operated between Empoli and Siena, chosen on the basis of their homogeneity in terms of service pattern, stopping scheme, and operational mission.

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This selection allows a meaningful comparison between runs performed under comparable commercial conditions, limiting the influence of external variability factors such as partial routes or non-uniform stopping profiles.

The selected services, detailed in the following tables for both running directions, correspond to revenue service operations between Empoli and Siena (and vice versa).

Service number	Origin	Departure Time	Destination	Arrival Time
19031	EMPOLI	06:21	SIENA	07:31
19033	EMPOLI	07:26	SIENA	08:42
19035	EMPOLI	08:06	SIENA	09:17
19037	EMPOLI	09:08	SIENA	10:16
19039	EMPOLI	12:08	SIENA	13:15
19041	EMPOLI	13:08	SIENA	14:16
19043	EMPOLI	14:08	SIENA	15:17
19045	EMPOLI	14:08	SIENA	15:16
19047	EMPOLI	15:08	SIENA	16:14
19049	EMPOLI	16:08	SIENA	17:14
19051	EMPOLI	18:08	SIENA	19:16
19053	EMPOLI	19:08	SIENA	20:16
19055	EMPOLI	20:08	SIENA	21:16
19057	EMPOLI	21:08	SIENA	22:16
19059	EMPOLI	22:08	SIENA	23:17
19030	SIENA	05:00	EMPOLI	05:58
19032	SIENA	10:41	EMPOLI	11:54
19034	SIENA	11:45	EMPOLI	12:54
19036	SIENA	12:41	EMPOLI	13:54
19038	SIENA	13:41	EMPOLI	14:54
19040	SIENA	14:41	EMPOLI	15:54
19042	SIENA	15:41	EMPOLI	16:54
19044	SIENA	16:41	EMPOLI	17:52
19046	SIENA	17:41	EMPOLI	18:52
19048	SIENA	18:47	EMPOLI	19:54
19130	SIENA	19:41	EMPOLI	20:54

Table 2: List of selected services for focused analysis.

For these services, multiple onboard recording sessions were available, in some cases including repeated attempts for the same train service, thereby increasing the robustness and representativeness of the dataset.

The acquired log files mainly include:

HTR312 recordings dated 27/03/2026,

HTR412 recordings dated between 30/03/2026 and 08/04/2026,

multiple data sets per service, reflecting segmented acquisitions or restarted recording sessions.

This collection forms the reference dataset used for the subsequent analysis phases.

San Donato Reference Log Files

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Additional log files were collected at the San Donato test site, providing complementary reference data acquired in a controlled environment. These datasets are especially useful for:
cross-checking signal consistency,
validating data completeness,
supporting interpretation of operational behaviours observed during commercial runs.

Mapping Between Services, Dates, and Rolling Stock

3.3 DATASET CLUSTERING TO BE USED FOR KPI EXTRACTION

Each selected service was explicitly mapped to the date of operation, the train identifier, the rolling stock type used for that run.

Servizio Treno Siena->Empoli	Note
19032	30/03; treno 66; HTR412
19040	03/04; treno 53; HTR412
19046	03/04; treno 53; HTR412
19046	27/03: treno 015; HTR312
Servizio Treno Empoli->Siena	**Note**
19033	08/04; treno 12; HTR412
19033	01/04; treno 56; HTR412
19039	30/03; treno 66; HTR412
19049	03/04; treno 53; HTR412

Table 3: List of specific occurences of selected services for analysis.

This mapping ensured traceability between operational conditions, rolling stock characteristics, and recorded data streams, allowing later normalization and comparison during the analysis phase.

Only datasets covering the full commercial journey between Empoli and Siena were retained. Partial runs, incomplete recordings, or datasets affected by acquisition anomalies were excluded from the final database.

The resulting consolidated dataset constitutes a coherent and homogeneous basis for subsequent analyses of operational profiles, driving behaviour, and energy consumption, serving as a reference for assessing the potential benefits of automatic driving solutions.

4 KPIS DEFINITIONS

The KPIs defined in this chapter are derived from the methodological framework introduced in Chapter 3 and are intended to capture the operational and energy-related effects of Automatic Driving in a structured and measurable manner.

As discussed previously, the impact of Automatic Driving does not always emerge through aggregated or macroscopic indicators, but rather through changes in the driving profile, the distribution of traction and braking phases, and the interaction with signaling and protection systems.

For this reason, the selected KPIs combine direct measurements, such as energy consumption, with a set of elementary operational indicators that act as proxies for driving quality, smoothness, and robustness.

Some KPIs directly quantify energy usage, while others do not measure energy explicitly but provide insight into the underlying causes of energy dissipation, such as corrective actions, unnecessary braking, or deviations from optimal speed profiles.

All KPIs are defined to be measurable using available onboard data, reproducible across different runs, and suitable for comparative analyses between manual driving and Automatic Driving.

Together, these indicators form a coherent set that enables a microscopic interpretation of train behavior, supporting the assessment of Automatic Driving benefits in terms of energy efficiency, operational stability, and overall driving performance.

4.1 ACTUAL RUNNING TIME / AVAILABLE RUNNING TIME

The KPI Actual Running Time / Available Running Time is defined to assess how effectively the train operation complies with the temporal constraints defined by the planned Journey Profile.

Running time provides a macroscopic assessment of train operation, as it evaluates the journey from a global perspective and summarizes the overall outcome of the driving strategy.

For this reason, it is explicitly identified as a fundamental dimension for evaluating the effects and quality of Automatic Driving, as it directly reflects the system’s ability to follow a planned and controlled driving strategy.

Respecting the scheduled running time increases operational predictability and controllability by removing at least one major source of instability.

In particular, excessive anticipation with respect to the planned arrival time may require unplanned actions, such as identifying an alternative platform to accommodate an early-arriving train and setting up the corresponding route.

In more critical situations, early arrival may result in the train being stopped at the station protection signal, leading to inefficiencies and reduced operational robustness.

The Available Running Time corresponds to the time allocated in the Journey Profile and is defined as the difference between the departure time at the origin station and the arrival time at the destination station.

Under nominal conditions and in the absence of perturbations, this value coincides with the running time specified in the timetable.

Interne

The Actual Running Time represents the effective time measured during real operation between the same two stations.

The ratio between Actual Running Time and Available Running Time provides a normalized indicator that is coherent with well-established concepts such as buffer time utilization and operational robustness analysis.

As an elementary KPI, this normalized form represents a meaningful extension, enabling direct comparability among homogeneous services and operating conditions.

Furthermore, this ratio provides an indirect evaluation of the quality of the driving profile, as consistent and smooth driving strategies tend to adhere closely to the available time without exploiting excessive margins.

Operating a train with an Actual Running Time shorter than the Available Running Time does not bring operational benefits and may instead trigger undesirable effects.

On routes characterized by nominal gradients, downhill sections, and flat segments, reducing running time generally implies increased traction effort to reach higher speeds and additional dissipation of kinetic energy during braking phases.

This results in higher energy consumption, increased wear of the braking system, and greater mechanical and electrical stress on both onboard traction equipment and the ground-based traction power system.

For these reasons, this KPI is particularly suitable for assessing the impact of Automatic Driving on timetable compliance, operational robustness, and energy-efficient train operation.

4.2 ENERGY CONSUMPTION

The Energy Consumption KPI is defined as a direct KPI, as it provides a direct quantitative measure of the electrical energy consumed during train operation, derived exclusively from onboard measurements without the need for intermediate modelling assumptions or external post-processing.

This KPI is based on the variables S_ACCU1_ACCU1_POWER_DC_SIDE and S_ACCU2_ACCU2_POWER_DC_SIDE, which are acquired directly from the onboard megaconverter modules, as shown in Figure 4.

These variables represent the electrical power measured on the DC side of the onboard accumulator systems and are sampled at a rate of 1 Hz, enabling a detailed time-domain analysis of the vehicle energy demand.

The total energy consumption is obtained by integrating these power signals over time, thus providing a direct and traceable measurement of the electrical energy used during operation.

The two power signals together represent the total power exchanged through the DC-link and therefore include all electrical contributions supplied by the onboard energy storage system.

As a result, the measured power is not limited to traction demand only, but also includes other onboard electrical loads connected to the DC-link.

This characteristic is particularly evident when the train speed is equal to zero, where the measured power is not always null.

Interne

The non-zero power observed during stationary phases is mainly associated with the activation of auxiliary services, such as control systems, climate control, cooling devices, compressors, and other onboard equipment.

An exception to this behavior can be observed during initial heating phases, when a significant power demand is required to reach comfortable climatic conditions starting from low initial ambient temperatures.

During these transient phases, the power consumption is temporarily higher than the typical stationary baseline and is primarily driven by the heating system rather than by traction-related functions.

An analysis of the power trends at zero speed during commercial services highlights a stable baseline consumption, which can be consistently attributed to these auxiliary loads.

During train motion, the power signals show a strong correlation with speed and driving phases, confirming that traction represents the dominant contribution to energy consumption during operation.

Therefore, while auxiliary services contribute to the overall energy balance, the Energy Consumption KPI remains strongly representative of traction-related energy usage and constitutes a reliable reference for energy performance assessment.

For these reasons, the Energy Consumption KPI provides a robust and objective basis for quantifying energy consumption and evaluating energy savings, ensuring full consistency with the onboard electrical architecture and complete traceability to measured data.

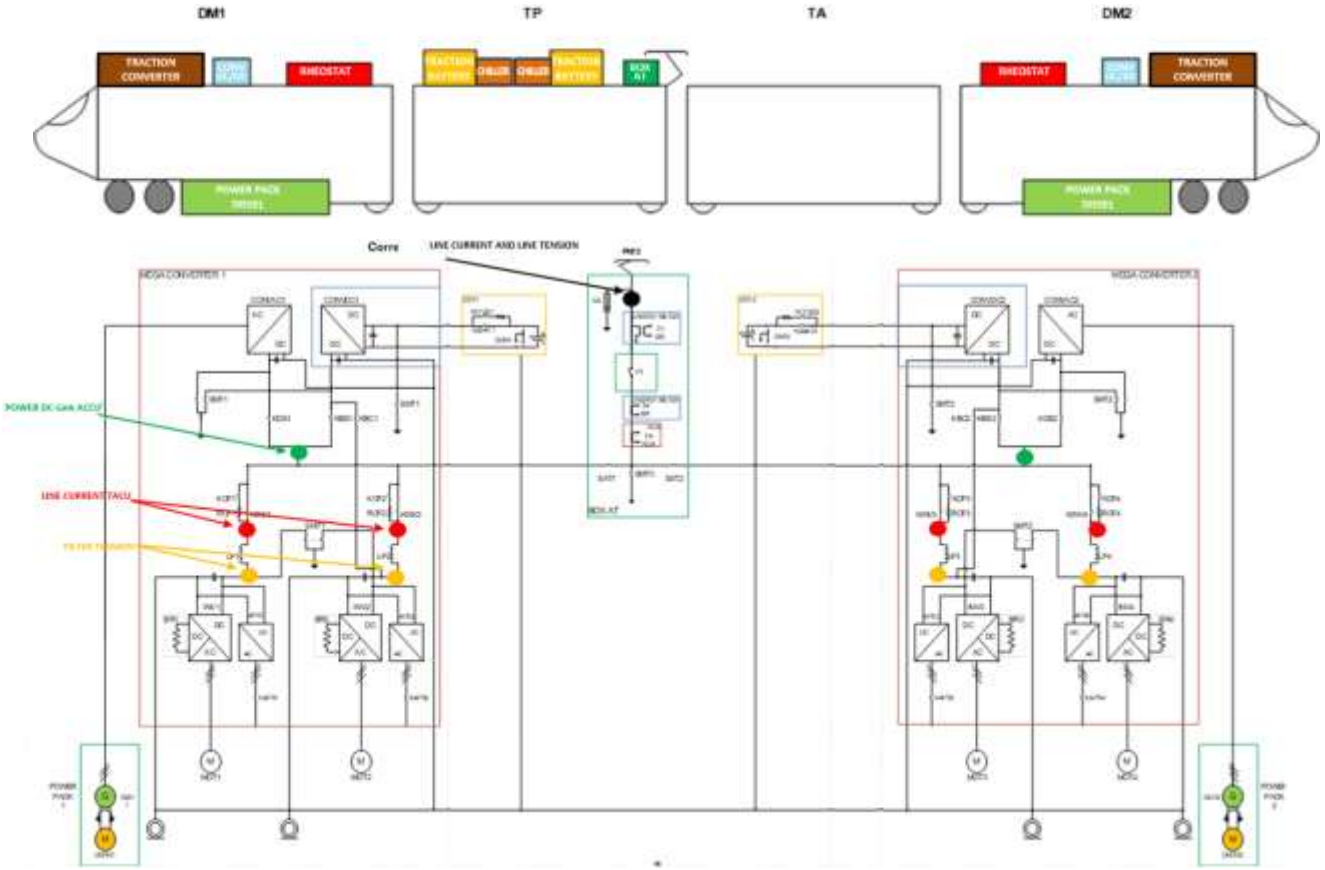


Figure 4: Overall electrical architecture of the Blues train (HTR312/412), showing the arrangement of traction converters, DC-link, onboard energy storage (ACCU), and auxiliary power systems across the vehicle units. The diagram highlights the main energy flows and the measurement points for line voltage and line current, DC-link power to the accumulator, and traction-related currents and voltages within the propulsion system.

4.3 Number Of Braking Events

The Number of Braking Events KPI is introduced to characterize the braking behavior observed during train operation and to provide an indirect assessment of the quality of the driving profile.

This KPI is intentionally defined as an elementary indicator, based on the identification and counting of braking commands, rather than as a direct physical measure of braking energy or mechanical wear.

In this sense, it is explicitly considered a proxy KPI, meaning an indicator that indirectly reflects relevant system properties—such as energy efficiency, passenger comfort, and component stress—without measuring them directly.

As a first-level KPI, a simple count of braking events represents a robust and reproducible metric, suitable for comparative analyses among homogeneous services and driving strategies.

However, it is acknowledged that not all braking events have the same physical impact.

From a qualitative and energetic perspective, and within the constraints imposed by passenger comfort limits on acceleration and jerk, a short and intense braking action may be broadly equivalent to a prolonged sequence of lighter braking actions in terms of energy dissipation and wear of braking components.

Interne

For this reason, a pure event count does not aim to quantify braking effort, but rather to capture patterns in driving behavior.

A key aspect of this KPI is its strong relationship with the smoothness of the run.

A driving strategy characterized by excessive acceleration or prolonged traction application often requires subsequent braking to correct deviations from the planned speed trajectory.

These corrective braking actions are indicative of an imperfect modulation of traction commands and of a reduced ability to anticipate future constraints along the route.

Conversely, smoother and more predictive driving profiles tend to minimize unnecessary braking events.

It is also important to note that not all braking actions should be weighted equally from an operational perspective.

Braking events generated by external constraints, such as sudden changes in Movement Authority or signaling conditions, are not directly attributable to the driving strategy itself and may therefore be excluded from the KPI computation in future extensions.

This distinction would allow a more accurate focus on braking actions that genuinely reflect driving quality.

Based on these considerations, a possible evolution of this KPI could involve the definition of complementary sub-indicators.

One sub-KPI could quantify the overall braking effort by accounting for braking intensity and duration, thus establishing a clearer link with energy dissipation, comfort, and system wear.

A second sub-KPI could specifically target corrective braking events, providing a direct indicator of speed-profile adjustment actions.

In its current form, the Number of Braking Events KPI emphasizes run smoothness and driving profile quality, and serves as a meaningful proxy for assessing the effectiveness of Automatic Driving strategies with respect to energy efficiency, passenger comfort, and operational robustness.

4.4 Number Of ATP Interventions

The Number of ATP Interventions KPI is introduced to quantify the frequency of automatic protection system interventions during train operation and to assess the robustness of the applied driving strategy.
Under nominal operating conditions, and in the absence of variations in the granted Movement Authority, any intervention of the Automatic Train Protection (ATP) system can be clearly interpreted as an indicator of an inadequate or sub-optimal driving strategy.
In this context, ATP interventions typically occur when the train exceeds speed limits or violates braking curves enforced by the protection system.
Therefore, this KPI directly reflects the ability of the driving strategy to anticipate signaling constraints and to remain within the safe operating envelope defined by the ATP.
The relevance of this indicator becomes particularly evident when comparing manual driving and Automatic Driving modes.
In manual driving, the driver is simultaneously engaged in multiple tasks, including train supervision, signaling observation, and operational coordination, which naturally increases the probability of late reactions or slight overshoots of ATP-imposed speed ceilings or braking curves.
As a consequence, a higher likelihood of ATP interventions can reasonably be expected during manual operation.

Interne

In contrast, Automatic Driving systems operate with continuous knowledge of signaling constraints and braking curves, allowing a more consistent and predictive control of train speed.
This difference makes the Number of ATP Interventions KPI especially suitable as a performance indicator when comparing Automatic Driving against manual driving, highlighting the benefits of automation in terms of compliance with protection constraints.
The importance of this KPI is further emphasized in the ATO context, where ATP service brake interventions, when in Automatic Driving mode, are disabled by design.
This configuration provides the Automatic Driving system with additional margins to compute and follow an optimized speed profile without relying on reactive braking actions.
Within this framework, any ATP intervention represents a clear boundary violation and a strong indication of insufficient robustness or excessive aggressiveness in the speed profile.
The KPI can therefore be interpreted as an indicator of driving robustness and, at the same time, as a proxy for the quality of integration between Automatic Driving functions and the signaling system.
A low number of ATP interventions reflects a conservative, well-integrated, and resilient driving strategy, while frequent interventions may indicate a sub-optimal or poorly tuned approach.
For these reasons, the Number of ATP Interventions KPI represents a meaningful metric for evaluating the performance gap between manual and automatic driving and for assessing the maturity and reliability of Automatic Driving solutions in real operational conditions.

5 ANALYSIS OF THE RUNS

5.1 ANALYSIS OF SIENA-EMPOLI LOGS

5.1.1 Description of monitored services

The analysis presented in this chapter is based on a detailed examination of a selected set of commercial passenger services operated along the Empoli–Siena railway line. The monitored services were chosen to ensure homogeneity in terms of route, stopping pattern, and operational conditions, enabling meaningful comparisons of operational performance and energy-related indicators.

For each monitored service, the corresponding timetable has been analysed in detail, with particular attention to two key temporal components of the journey: dwell time and running time. Dwell time is defined as the time elapsed between arrival and departure at a given station, while running time is defined as the time elapsed between the departure from one station and the arrival at the subsequent station.

The timetable data highlight that dwell time is highly standardised across the monitored services. In almost all cases, the dwell time at intermediate stations is equal to 60 seconds, indicating a consistent operational rule applied along the line and limiting variability introduced by station stop management.

In contrast, differences are observed in the running times between stations. For even-numbered services (northbound direction, Siena → Empoli), running times for the same track sections are largely uniform across different services. This suggests a stable and repeatable driving pattern along these sections. Conversely, for odd-numbered services (southbound direction, Empoli → Siena), running times for identical track segments show a higher degree of variability, indicating a wider dispersion in driving behaviour or operational constraints in this direction.

To better interpret these observations, laboratory simulations were performed to estimate the minimum achievable running time for each track section. These simulations were conducted by considering the applicable speed profiles, signalling constraints, and the traction and braking characteristics of the Blues train. The resulting minimum running times represent the lower bound achievable under optimal driving conditions, without violating speed limits or train performance constraints.

By comparing the scheduled running times from the timetable with the simulated minimum running times, the buffer time available to the driver or the Automatic Driving system for each section was estimated. This buffer time represents the temporal margin between the scheduled running time and the minimum feasible running time and provides an important indicator of operational flexibility.

The analysis reveals that, for most track sections, a positive buffer time is available, allowing some degree of flexibility in the driving strategy. However, a critical situation is observed on the section between Castelfiorentino and Granaiolo, where the scheduled running time is shorter than the simulated minimum running time. In this case, the buffer time becomes null or negative, implying that the train must be driven continuously at the maximum allowed performance to comply with the timetable. This section therefore represents a structurally constrained segment of the route, where any deviation from optimal driving behaviour may directly impact punctuality and energy efficiency.

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Overall, the combined analysis of timetable data, dwell times, running times, and simulated minimum running times provides a coherent representation of the operational context of the monitored services. This framework establishes the basis for the subsequent assessment of driving behaviour, buffer time utilisation, and energy performance, and supports the evaluation of potential benefits offered by Automatic Driving solutions under real commercial service conditions.

Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	SIENA	--:--	10:41			
7,956	Badesse	10:49	10:50	60	480	115
14,233	Castellina Ch.	10:56	10:57	60	360	40
25,141	Poggibonsi	11:07	11:08	60	600	85
29,798	Barberino V.E	11:12	11:13	60	240	20
38,152	Certaldo	11:20	11:21	60	420	85
46,761	Castelfiorentino	11:27	11:28	60	360	35
52,472	Granaiolo	11:32	11:33	60	240	-10
58,301	Ponte a Elsa	11:42	11:43	60	540	265
63,01	EMPOLI	11:54	--:--		660	435

Table 4: Timetable service number *19032; normal running time; wide running time; short running time*

Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	SIENA	--:--	14:41			
7,956	Badesse	14:49	14:50	60	480	115
14,233	Castellina Ch.	14:56	14:57	60	360	40
25,141	Poggibonsi	15:07	15:08	60	600	85
29,798	Barberino V.E	15:12	15:13	60	240	20
38,152	Certaldo	15:20	15:21	60	420	85
46,761	Castelfiorentino	15:27	15:28	60	360	35
52,472	Granaiolo	15:32	15:33	60	240	-10
58,301	Ponte a Elsa	15:42	15:43	60	540	265
63,01	EMPOLI	15:54	--:--		660	435

Table 5: Timetable service number *19040; normal running time; wide running time; short running time*

Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	SIENA	--:--	17:41			
7,956	Badesse	17:49	17:50	60	480	115
14,233	Castellina Ch.	17:56	17:57	60	360	40
25,141	Poggibonsi	18:07	18:08	60	600	85
29,798	Barberino V.E	18:12	18:13	60	240	20
38,152	Certaldo	18:20	18:21	60	420	85
46,761	Castelfiorentino	18:27	18:28	60	360	35
52,472	Granaiolo	18:32	18:33	60	240	-10
58,301	Ponte a Elsa	18:42	18:43	60	540	265
63,01	EMPOLI	18:52	--:--		540	315

Table 6: Timetable service number *19046; normal running time; wide running time; short running time*

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Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	EMPOLI	--:--	07:26			
4,709	Ponte a Elsa	07:34	07:36	120	480	255
10,538	Granaiolo	07:41	07:42	60	300	30
16,249	Castelfiorentino	07:47	07:48	60	300	50
24,858	Certaldo	07:55	07:56	60	420	110
33,212	Barberino V.E	08:04	08:05	60	480	150
37,869	Poggibonsi	08:10	08:11	60	300	65
48,777	Castellina Ch.	08:21	08:22	60	600	80
55,054	Badesse	08:29	08:30	60	420	95
63,01	SIENA	08:42	--:--		720	340

Table 7: Timetable service number *19033; normal running time; wide running time; short running time*

Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	EMPOLI	--:--	12:08			
4,709	Ponte a Elsa	12:12	12:13	60	240	15
10,538	Granaiolo	12:17	12:18	60	240	-30
16,249	Castelfiorentino	12:23	12:24	60	300	50
24,858	Certaldo	12:30	12:31	60	360	50
33,212	Barberino V.E	12:38	12:39	60	420	90
37,869	Poggibonsi	12:44	12:45	60	300	65
48,777	Castellina Ch.	12:59	13:00	60	840	320
55,054	Badesse	13:06	13:07	60	360	35
63,01	SIENA	13:15	--:--		480	100

Table 8: Timetable service number *19039; normal running time; wide running time; short running time*

Km.	Station	Arrival [hh:mm]	Departure [hh:mm]	Dwell Time [sec]	Running Time [sec]	Buffer Time
0	EMPOLI	--:--	16:08	--:--	--:--	
4,709	Ponte a Elsa	16:12	16:13	60	240	15
10,538	Granaiolo	16:17	16:18	60	240	-30
16,249	Castelfiorentino	16:23	16:24	60	300	50
24,858	Certaldo	16:30	16:31	60	360	50
33,212	Barberino V.E	16:38	16:39	60	420	90
37,869	Poggibonsi	16:44	16:45	60	300	65
48,777	Castellina Ch.	16:59	17:00	60	840	320
55,054	Badesse	17:06	17:07	60	360	35
63,01	SIENA	17:14	--:--		420	40

Table 9: Timetable service number *19049; normal running time; wide running time; short running time*

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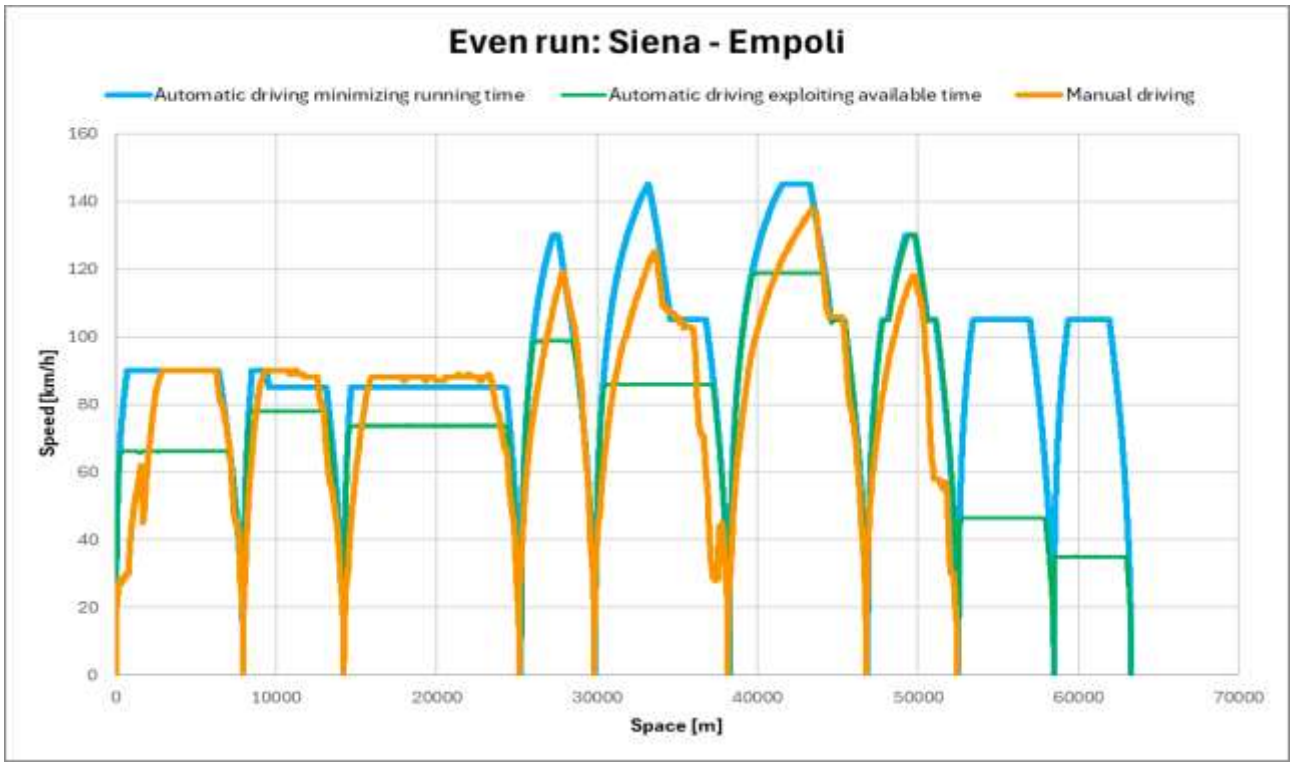


Figure 5: Speed Profiles of commercial service Siena – Empoli; comparison between manual driving, automatic driving respecting arrival time and automatic driving minimizing the running time.



Figure 6: Speed Profiles of commercial service Empoli - Siena; comparison between manual driving, automatic driving respecting arrival time and automatic driving minimizing the running time.

Interne

A first observation from Figure 5 and Figure 6 is that, in some local sections, the manually driven train reaches speeds slightly higher than those achieved by the Automatic Driving profile optimized for minimum running time. At first sight, this behaviour may appear counterintuitive, since the minimum running time profile is specifically designed to maximise operational performance.

The explanation lies in the control strategy adopted by the Automatic Driving system. The minimum running time profile is generated by pursuing the highest admissible speed along the route while maintaining a configurable safety margin below the maximum speed permitted by infrastructure, signalling and train protection constraints. As a consequence, the ATO speed target is intentionally offset from the theoretical speed ceiling by a predefined threshold.

When analysing the speed–distance diagrams, it can be observed that the ATO minimum running time profile remains generally higher than the manually driven profile over most of the route. The limited number of local exceptions correspond to sections where the driver operated very close to the infrastructure speed limit, temporarily reducing or eliminating the margin normally present between manual driving and the line speed ceiling.

Despite the speed offset introduced by the configurable threshold, the Automatic Driving system still achieves shorter overall running times than manual driving. This result confirms that journey performance is not determined solely by local speed peaks, but also by the ability to maintain an optimal speed profile throughout the entire route. More accurate speed regulation, smoother transitions between traction and braking phases, and a more consistent exploitation of the available speed envelope contribute to the overall performance improvement.

It should also be noted that the threshold adopted in the analysed configuration reflects a conservative tuning approach appropriate for the current stage of technology deployment. In more mature ATO implementations, and subject to the required operational validation and safety demonstration, this margin could be reduced, potentially allowing the automatic driving system to operate even closer to the admissible speed envelope and further improve running-time performance.

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5.2 Analysis of S.Donato Logs

The experimental activities have been carried out in a controlled test environment, namely the San Donato test ring, where train movements are performed according to predefined operational scenarios. These scenarios are designed to reproduce representative train operations by combining different driving modes within a structured mission profile.

More specifically, the executed tests include sequences of manual driving, remote driving and Automatic Driving at GoA4 level. The typical execution consists of an initial phase in manual or remote driving, followed by the activation of Automatic Driving for the execution of one or more journey profiles, including station stops, passenger service and end-of-service procedures. This configuration allows the behaviour of the system to be evaluated under repeatable and well-defined operational conditions.

The structure of the scenarios ensures that different operational phases, such as train transfer, passenger service and train stabling, are consistently represented within the same test sequence, enabling a coherent analysis of the system performance across the various KPIs considered in this document.

It should be noted that additional runs performed on the Empoli–Siena line have been analysed in terms of available logs; however, due to the different operational conditions and the nature of the datasets, no direct comparison with the San Donato results has been carried out. The related data are therefore used only as complementary information and not within the framework of the quantitative comparison presented in the following sections.

5.3 KPI-Based Comparison of Commercial, Laboratory Runs

This section presents a comparative analysis of selected Key Performance Indicators (KPIs) measured on different categories of runs, namely:

- commercial services operated on the Empoli–Siena line,
- laboratory runs performed under controlled conditions,
- reference runs acquired at the San Donato test site.

The objective of this analysis is twofold. On the one hand, it provides a first quantitative assessment of the differences between manual driving and Automatic Train Operation (ATO) in terms of temporal behaviour. On the other hand, it highlights the role of the test environment (commercial operation versus laboratory and test track conditions) in shaping KPI distributions and variability.

5.3.1 Actual Running Time / Available Running Time

As an initial focus, the analysis considers the KPI Actual Running Time / Available Running Time, as defined in Chapter 4. This indicator provides a normalized measure of timetable compliance and buffer time utilisation, allowing direct comparison among runs with identical or comparable journey profiles.

For each run, the Actual Running Time is computed from onboard measurements, while the Available Running Time is derived from the corresponding Journey Profile and timetable data. The resulting ratio is evaluated separately for:

- manual driving runs,

Interne

- ATO runs performed in laboratory conditions.

The laboratory dataset is particularly suitable for this comparison, as it minimizes the influence of external disturbances such as traffic interactions, operational perturbations, and infrastructure-related variability. As a consequence, differences observed in this context can be more directly attributed to the driving strategy itself.

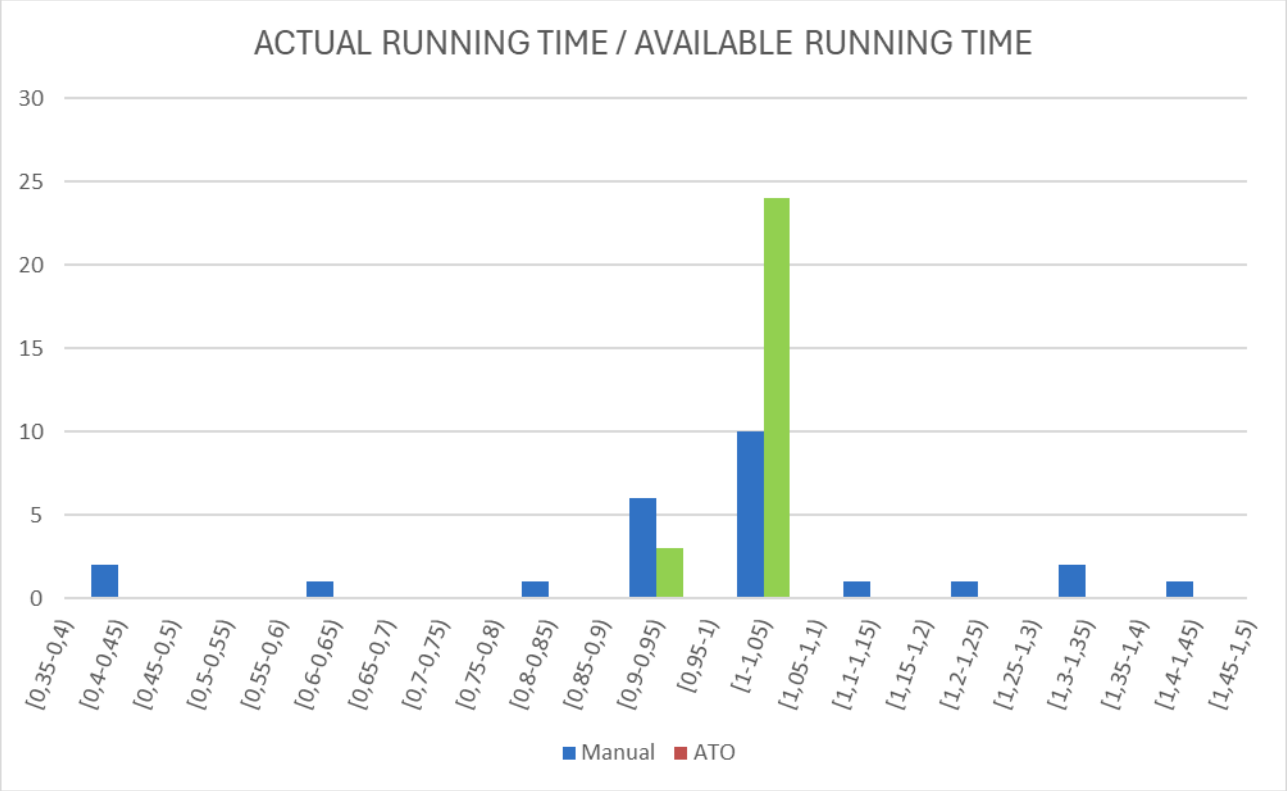


Figure 7: Distribution of the KPI Actual Running Time / Available Running Time Focus on northbound (even-numbered services). Comparison between manual and automatic driving; the vertical line at 1.0 represents nominal timetable compliance.

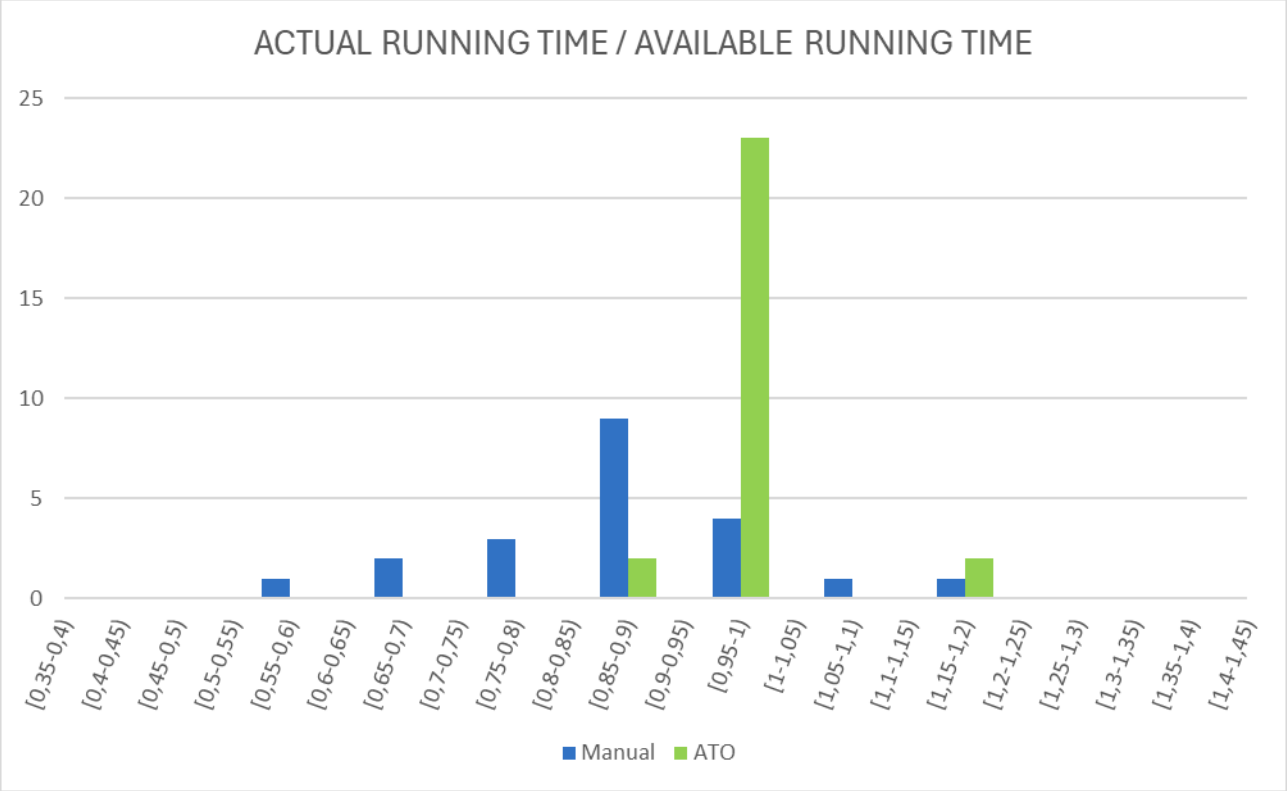


Figure 8: Distribution of the KPI Actual Running Time / Available Running Time Focus on southbound (odd-numbered services). Comparison between manual and automatic driving; the vertical line at 1.0 represents nominal timetable compliance.

The distribution of the KPI values highlights distinct behavioural patterns between manual and automatic driving. Manual runs tend to exhibit a wider dispersion of the ratio, indicating higher variability in buffer time exploitation and greater dependence on individual driving style. ATO runs, on the contrary, show a more compact distribution around the nominal value, reflecting a more consistent and reproducible adherence to the Available Running Time.

These observations confirm that, even at a macroscopic level, Automatic Driving contributes to increased operational regularity and predictability. This effect is particularly relevant from an energy consumption perspective, as systematic anticipation or excessive exploitation of time margins is typically associated with higher traction effort and additional braking actions.

5.3.2 Energy Consumption

The comparison of energy consumption between manual driving and Automatic Driving has been further investigated at the level of individual track sections, with the aim of highlighting how differences in driving behaviour translate into variations of energy usage along the route.

To this end, the total energy consumption has been evaluated for each section by considering corresponding occurrences of the same segments under comparable operational conditions. This approach allows a more detailed interpretation of the energy behaviour, consistently with the microscopic perspective adopted in the previous analyses.

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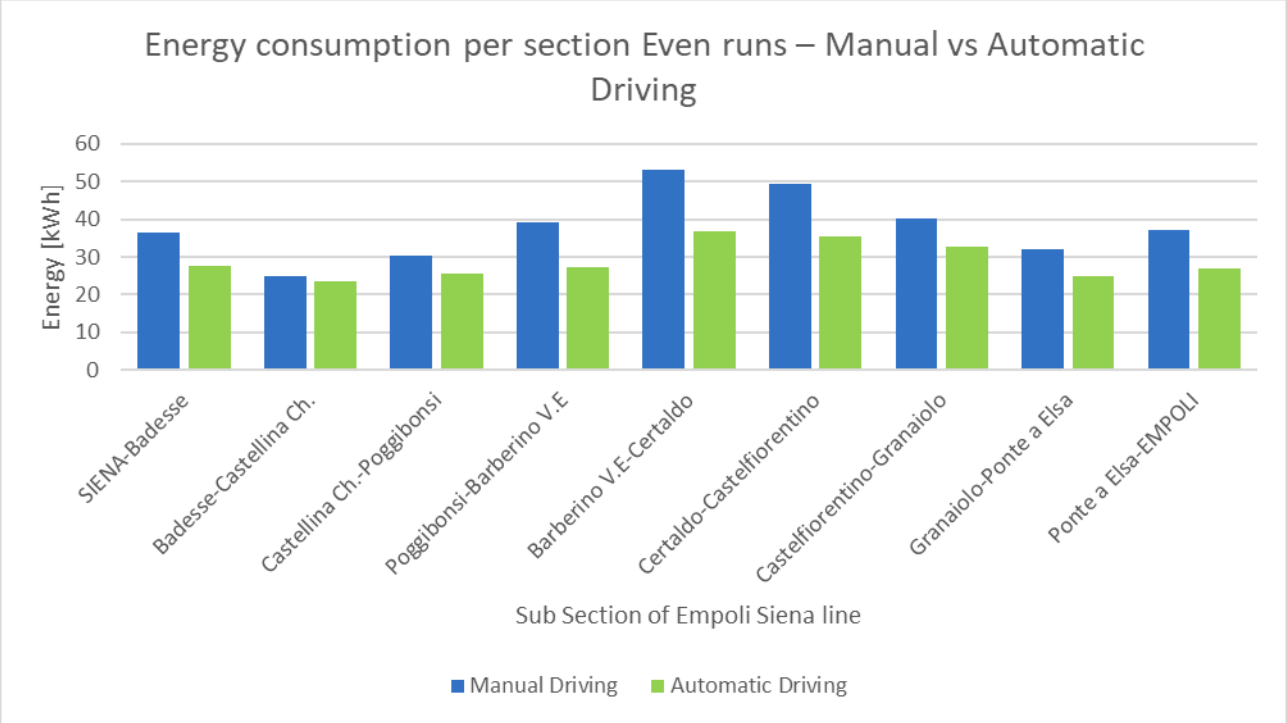


Figure 9: Comparison of energy consumption per section (even runs) between manual driving and Automatic Driving.

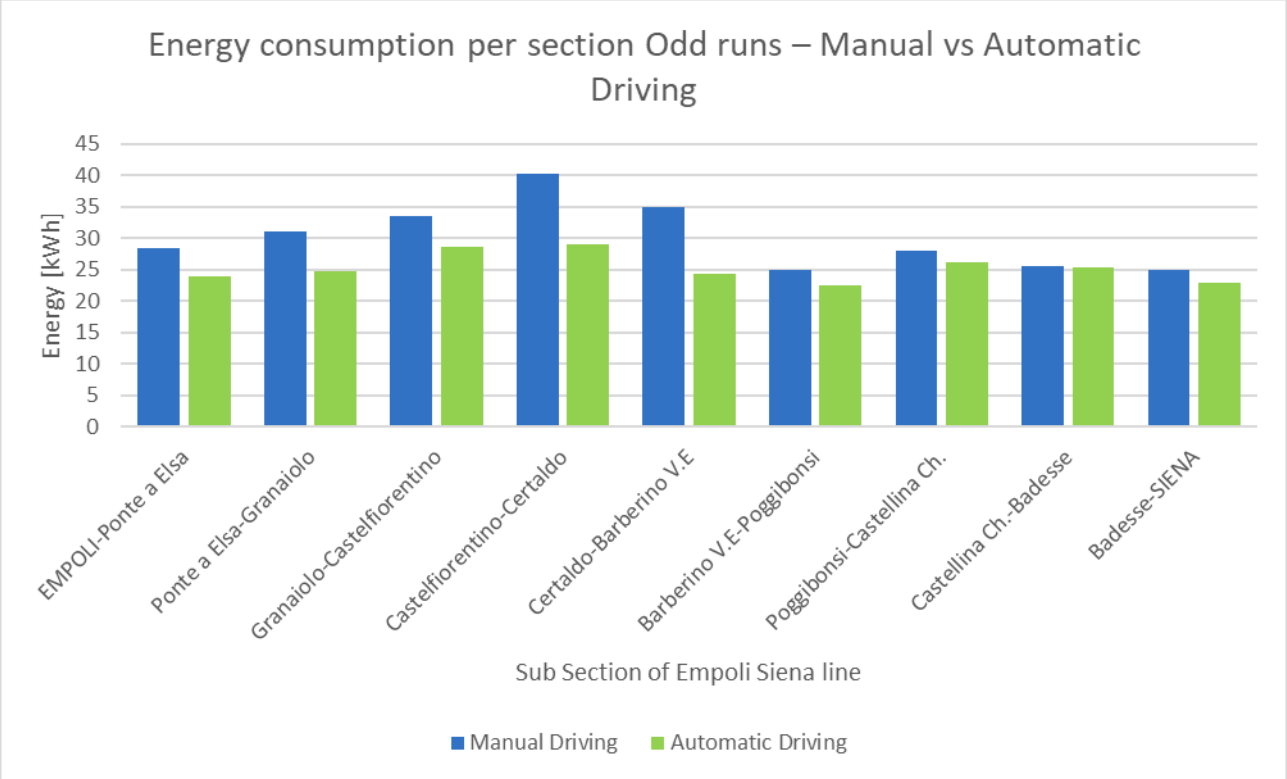


Figure 10: Comparison of energy consumption per section (odd runs) between manual driving and Automatic Driving.

The results show a clear tendency for Automatic Driving to be associated with lower energy consumption with respect to manual driving across the analysed sections. This behaviour is observed systematically, even when considering different runs and rolling stock configurations, indicating that the differences are primarily linked to the characteristics of the driving strategy rather than to external conditions.

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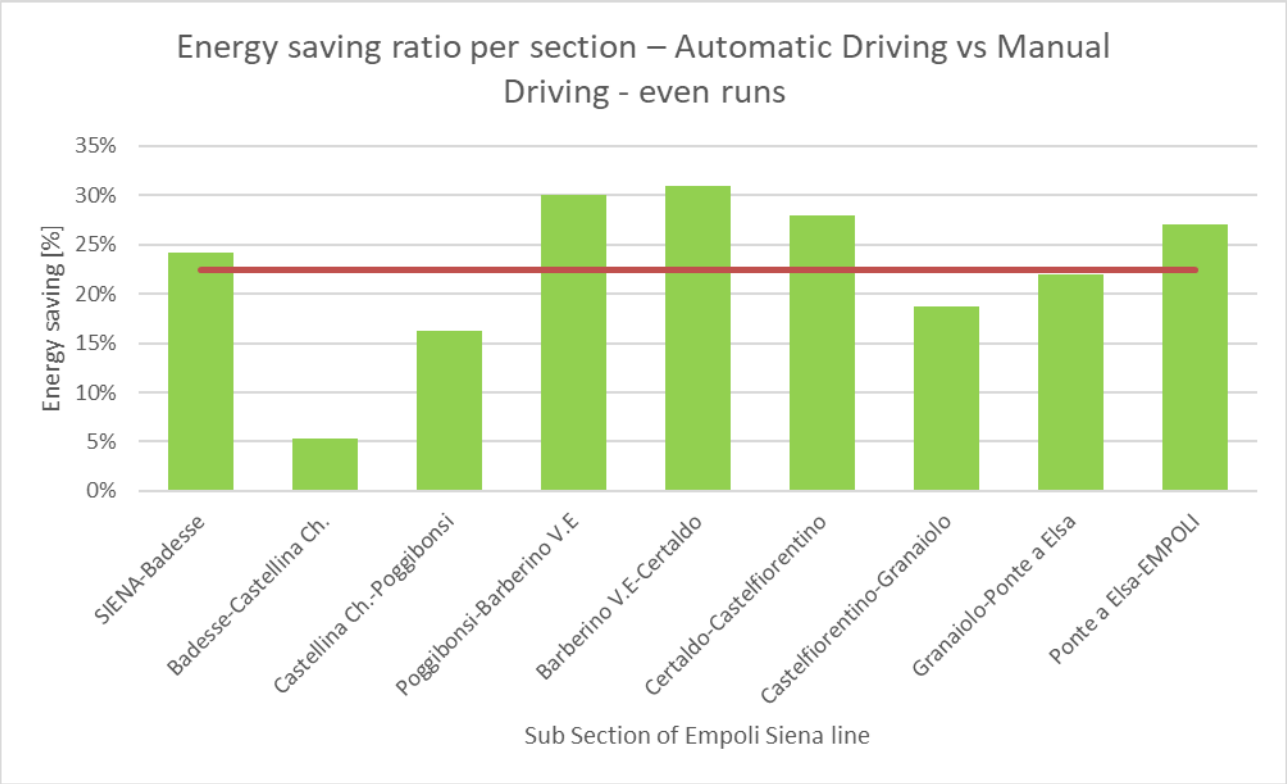


Figure 11: Energy saving ratio per section – comparison between manual driving and Automatic Driving (even runs). Mean 22%.

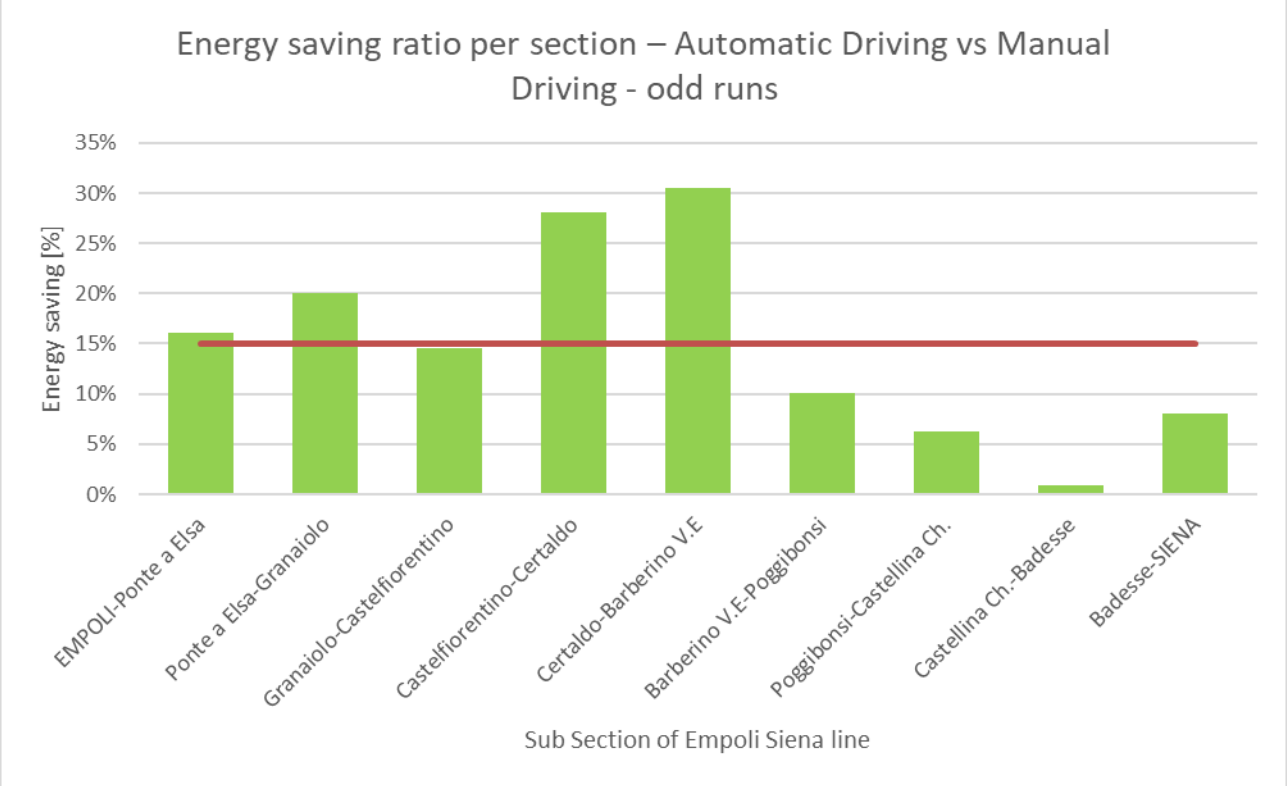


Figure 12: Energy saving ratio per section – comparison between manual driving and Automatic Driving (odd runs). Mean 15%

Interne

When analysed in relation to the operational context, these differences can be interpreted in connection with the way the available running time is exploited. In sections where a non-negligible buffer is present, manual driving tends to exhibit a more variable use of the available margin, often resulting in higher traction effort followed by subsequent braking actions. Automatic Driving, on the contrary, shows a more regular and anticipative behaviour, leading to a smoother evolution of the speed profile and a reduction of unnecessary energy exchanges. This confirms that energy savings are strongly correlated with the availability of buffer time: higher margins enable Automatic Driving to apply energy-efficient strategies such as coasting and smoother braking, while constrained sections significantly limit the achievable benefits.

In sections where the available running time is more constrained, the difference between manual and automatic driving appears less pronounced. In these cases, the limited operational flexibility imposes similar constraints on both driving modes, reducing the impact of the driving strategy on the overall energy consumption.

These observations are consistent across the different occurrences considered in the dataset, suggesting that the effect is not related to specific runs but reflects a general characteristic of the driving approach. The analysis therefore confirms that the modulation of traction and braking phases plays a central role in determining the energy performance of the train.

A clear asymmetry emerges between the two running directions. The average energy saving reaches approximately 22% for even-numbered services, while it is reduced to about 15% for odd-numbered services. This difference can be interpreted in relation to the infrastructure profile of the line. In particular, Automatic Driving proves to be more effective when it can exploit favourable gradients and available buffer time, allowing longer coasting phases and reducing energy dissipation.

Overall, the section-level comparison provides further evidence that the benefits of Automatic Driving can be directly related to the regularity and smoothness of the driving profile. By reducing variability and limiting corrective actions, Automatic Driving contributes to a more efficient use of the available energy along the route, in line with the considerations previously developed in the analysis of the operational KPIs.

5.3.3 Number Of Braking Events

The analysis of the Number of Braking Events KPI has been performed at section level, considering for each segment the average value computed over multiple occurrences of the same service. The results shown in Figure 13 and Figure 14 therefore provide a representative indication of the braking behaviour along the route.

It should be noted that the braking events considered in this analysis are only those of operational relevance, namely braking actions required to comply with signalling constraints, to perform station stops, and to follow the prescribed speed profile (driving style of the driver in GoA0/1 or processed for optimisation by ATO in GoA2/3/4) in accordance with the timetable.

Overall, the results indicate a slight reduction in the number of braking events when Automatic Driving is applied. This reduction is not uniform across all sections, but can be observed in several segments, suggesting a generally smoother management of the speed profile.

An interesting aspect of the results is the presence of a clear symmetry between corresponding sections in opposite running directions. For several segments, similar patterns can be observed when comparing the two directions, indicating that the behaviour is strongly influenced by the

Interne

physical characteristics of the line. In particular, the effect of longitudinal gradients can be identified as a key factor affecting the need for braking, as they directly influence the natural evolution of train speed.

In some sections, the number of braking events remains comparable or slightly increases under Automatic Driving. This behaviour can be related to local constraints, such as limited buffer time or infrastructure characteristics, which reduce the flexibility of the driving strategy and lead to similar control actions in both driving modes.

Overall, the results confirm a tendency of Automatic Driving to slightly reduce the number of braking events and to produce a more regular distribution of braking actions along the route, in line with the smoother driving behaviour observed in the previous analyses.

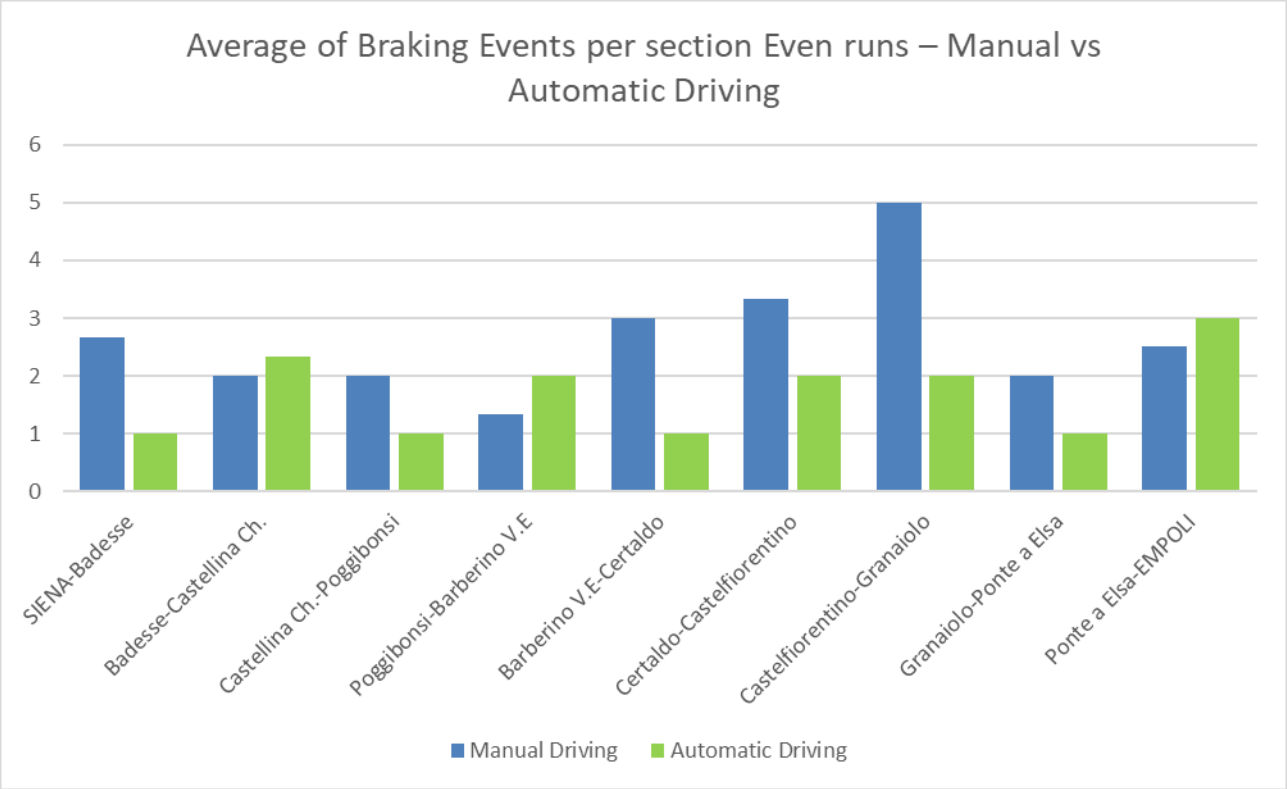


Figure 13: Average of Braking Events per section – comparison between manual driving and Automatic Driving. (even runs)

Interne

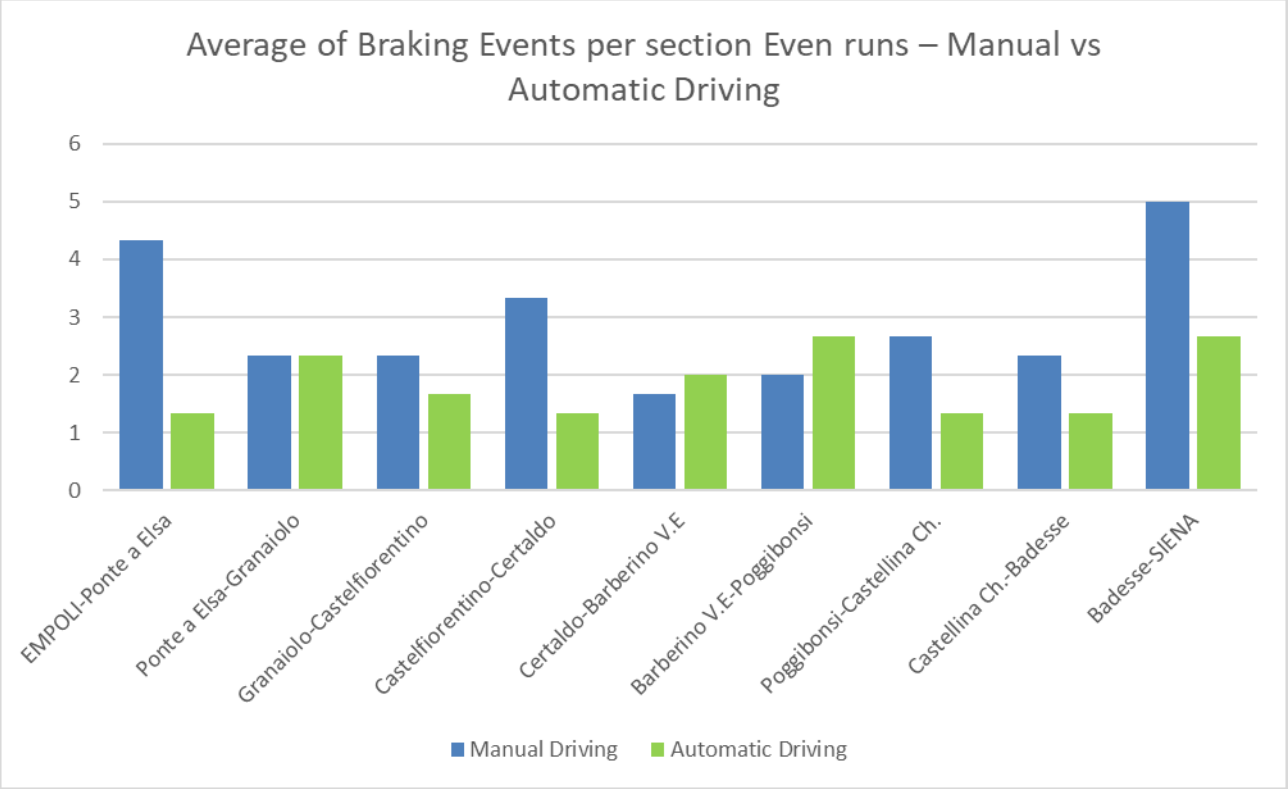


Figure 14: Average of Braking Events – comparison between manual driving and Automatic Driving. (odd runs)

5.3.4 Number Of ATP Allerts/Interventions

The analysis of the Number of ATP Interventions KPI has been carried out by comparing the occurrence of warning events and intervention events under manual driving and Automatic Driving, considering both running directions. The results are summarised in Figure 15, Figure 16, Figure 17, Figure 18, where the distributions of events are reported separately for even and odd services.

The analysis shows that some ATP service brake interventions have been detected in manual driving. In addition, the occurrence of warning events highlights a tendency of manual driving to operate close to the limits imposed by the ATP system. This behaviour suggests that, the driving strategy often approaches the boundaries defined by the protection system, requiring corrective actions to maintain compliance with the permitted speed profile and in some case this driving style triggers the intervention of ATP.

In contrast, no warning or intervention events are observed under Automatic Driving. This behaviour indicates that the control strategy remains consistently within the limits imposed by the ATP, avoiding approaches to the protection thresholds and resulting in a more conservative and stable speed control.

The comparison between the two driving modes therefore does not highlight differences in terms of safety margins in a strict sense (no emergency brake triggered in manual or automatic mode), as no critical limit violations are observed in either case, but rather emphasises a different operational behaviour. Manual driving appears to be characterised by a closer interaction with ATP limits, while Automatic Driving maintains a more regular margin with respect to the protection constraints.

Interne

Overall, the results confirm that Automatic Driving provides a more robust adherence to signalling constraints, reducing the need for corrective actions and limiting the occurrence of situations approaching ATP intervention thresholds.

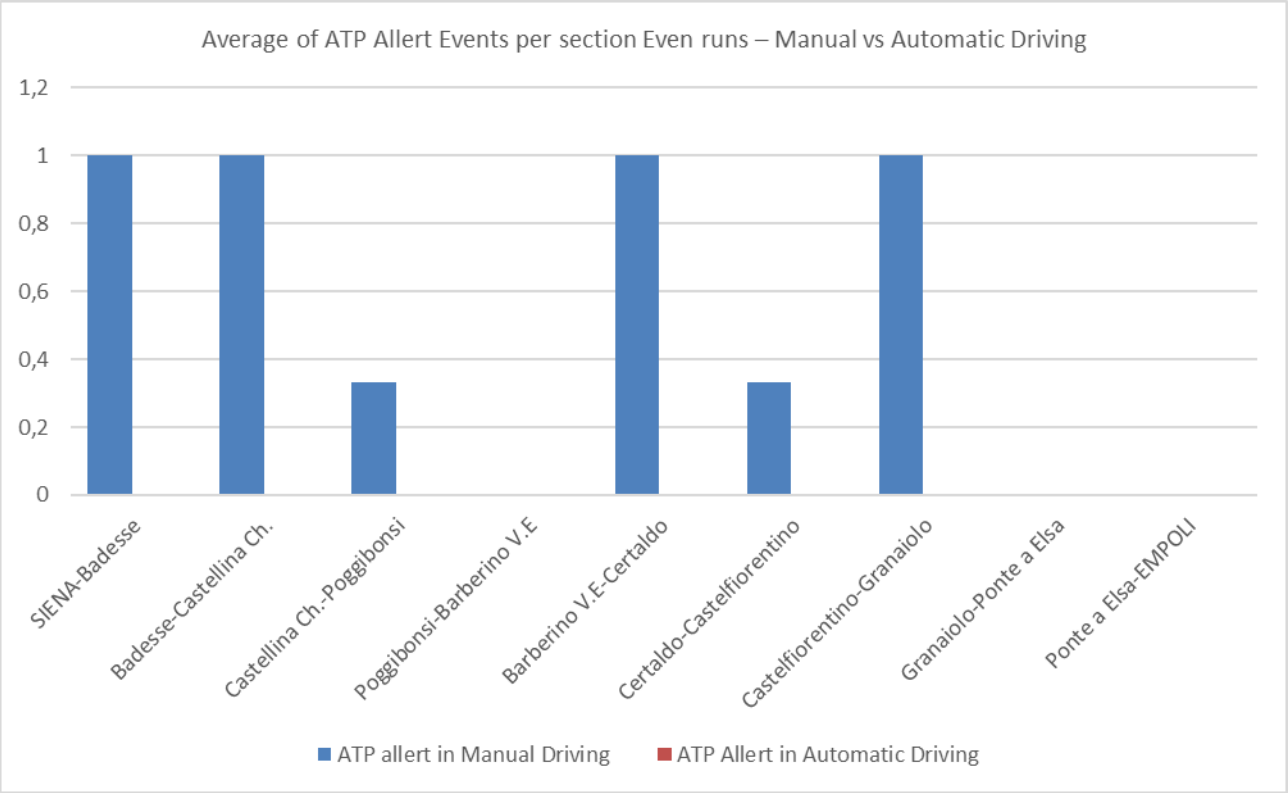


Figure 15: Average of ATP Allert Events – comparison between manual driving and Automatic Driving (even runs). No events during automatic driving.

Interne

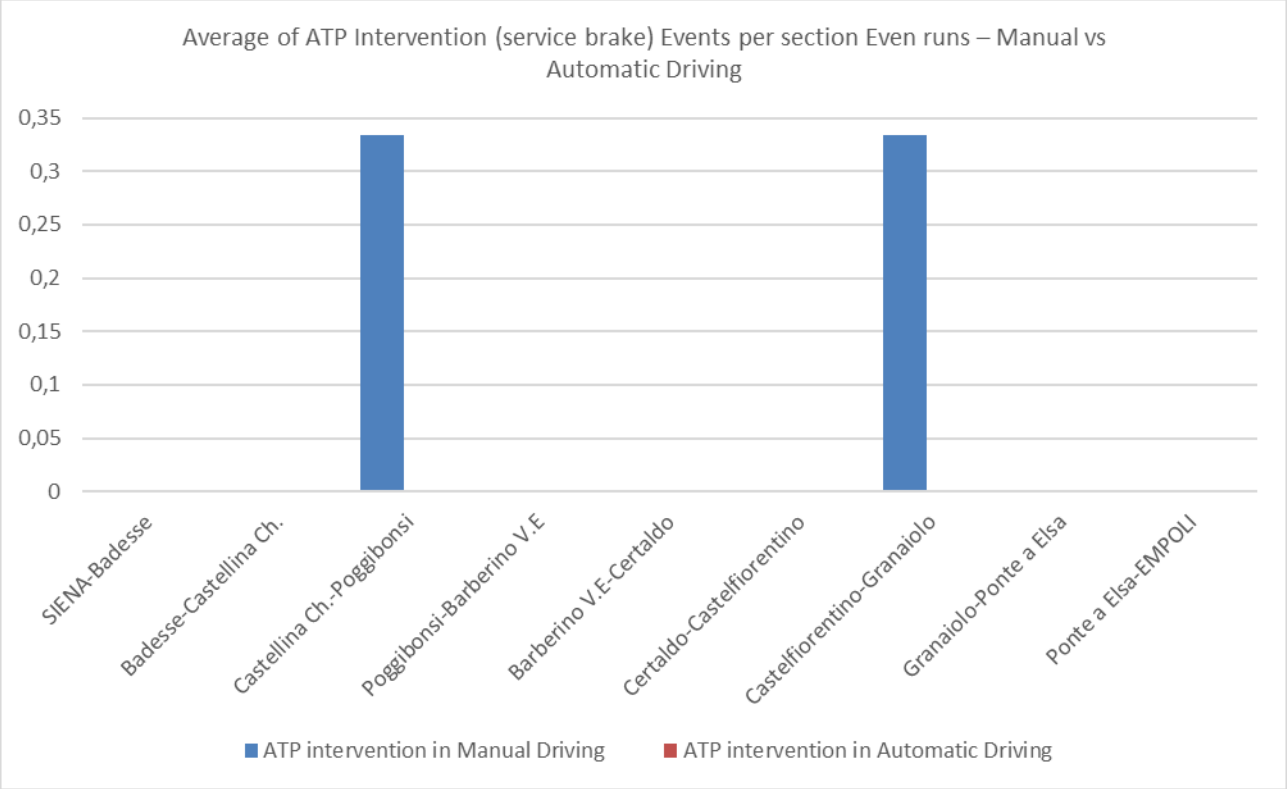


Figure 16: Average of ATP Intervention Events – comparison between manual driving and Automatic Driving (even runs). No events during automatic driving.

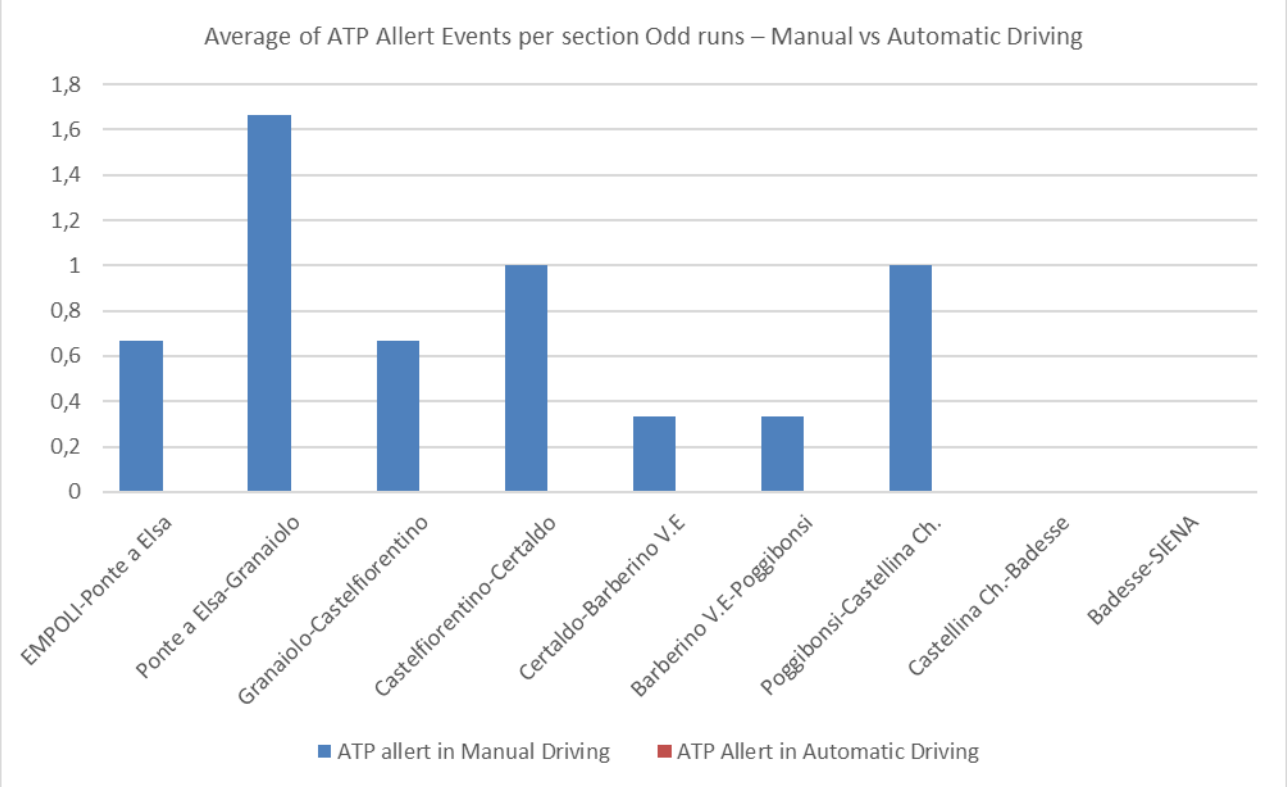


Figure 17: Average of ATP Allert Events – comparison between manual driving and Automatic Driving (odd runs). No events during automatic driving.

Interne

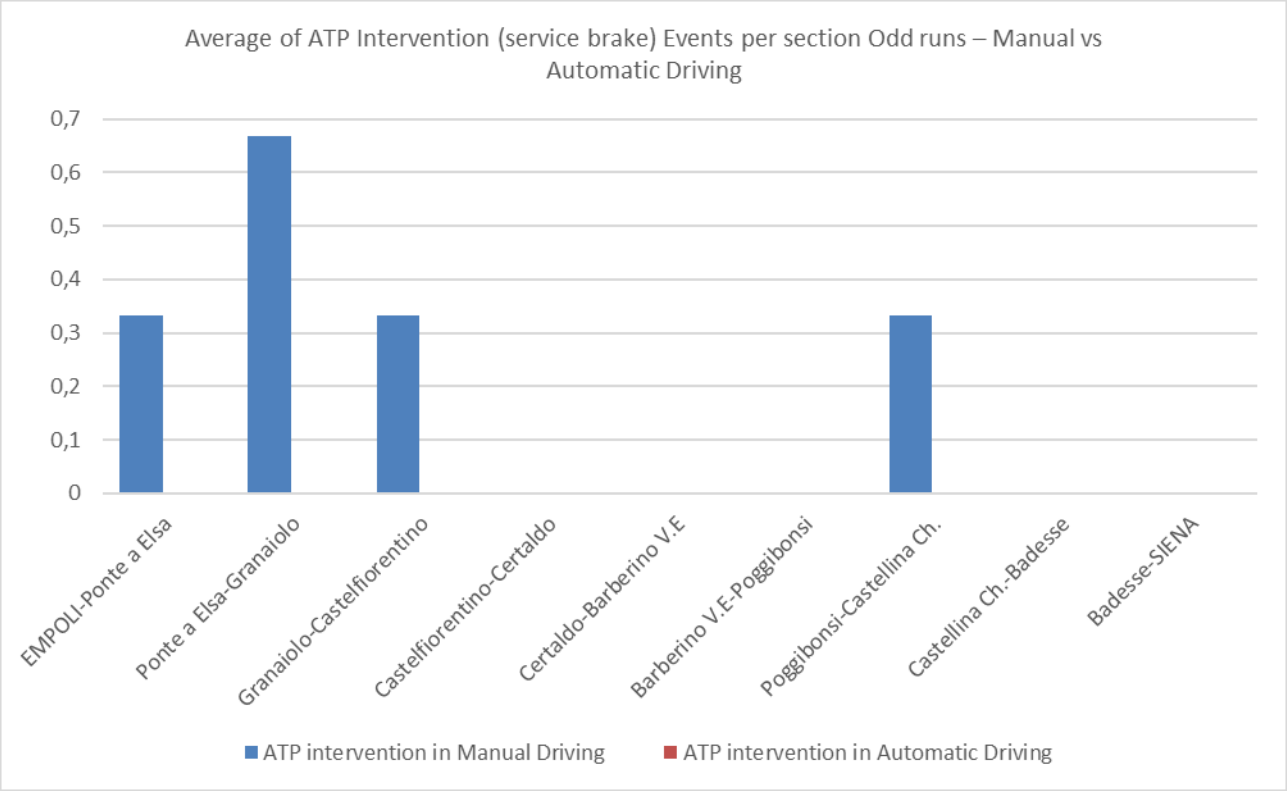


Figure 18: Average of ATP Intervention Events – comparison between manual driving and Automatic Driving (odd runs). No events during automatic driving.

6 CONCLUSIONS

This deliverable has presented a comprehensive analysis of the impact of Automatic Driving on energy consumption and operational performance, based on a KPI-driven assessment of real commercial services and controlled experimental runs.

The main objective of the work was to quantify, through measurable and reproducible indicators, the benefits introduced by Automatic Driving in comparison with manual driving, with particular focus on energy efficiency, running time management, and driving behaviour. This objective has been successfully achieved by defining a consistent methodological framework, identifying a coherent set of KPIs, and applying them to a representative dataset of services operated along the Empoli–Siena line.

A key outcome of the deliverable is the confirmation that Automatic Driving enables a more regular and controlled exploitation of the available running time. While manual driving exhibits a wider variability and a stronger dependence on individual driving style, Automatic Driving produces a more stable distribution of the ratio between actual and available running time, improving operational predictability and robustness.

From an energy perspective, the analysis has demonstrated that Automatic Driving systematically leads to reduced energy consumption at section level. The results consistently show lower energy usage compared to manual driving across the analysed runs, highlighting the effectiveness of a smoother and more anticipative driving strategy. The reduction of unnecessary traction peaks and corrective braking actions plays a central role in this improvement, confirming the strong linkage between driving profile regularity and energy efficiency. Although the dataset is limited in size, the consistency of the observed trends across different runs and rolling stock configurations suggests that the identified effects are representative of the underlying driving behaviour, rather than being driven by specific operating conditions.

The microscopic analysis approach adopted in this work has proven to be particularly effective in capturing these effects. By analysing the driving behaviour at section level, it has been possible to identify how Automatic Driving modifies the distribution of acceleration, coasting, and braking phases, even in cases where macroscopic indicators such as total running time remain unchanged. This approach has provided additional insight into the mechanisms underlying energy savings and operational improvements.

Further evidence of improved driving quality is provided by the analysis of braking events, which shows a general tendency towards a reduction in the number of braking actions under Automatic Driving. This behaviour reflects a smoother and more anticipative control of speed, contributing not only to energy savings but also to improved passenger comfort and reduced mechanical stress on components.

In addition, the analysis of ATP-related indicators confirms that Automatic Driving ensures a more robust adherence to signalling constraints. While manual driving frequently approaches ATP warning thresholds, Automatic Driving maintains a more stable margin, avoiding both alerts and interventions. This result highlights the improved integration between the driving strategy and the signalling system and contributes to overall operational safety and stability.

Interne

Despite these positive results, several challenges and limitations have been identified. The availability and quality of onboard data represent a critical aspect, as log completeness and structure directly influence the accuracy of KPI computation. In particular, the extraction and reconstruction of dynamic variables such as speed profiles from heterogeneous log formats require dedicated processing strategies and introduce additional complexity in the analysis workflow. Furthermore, some sections of the line are characterized by limited or even negative buffer times, constraining the flexibility of both manual and automatic driving and reducing the observable impact of the driving strategy.

Another important observation concerns the dependence of the results on local infrastructure characteristics, such as gradients and signalling constraints, which may influence the effectiveness of Automatic Driving and limit the generalization of conclusions across different contexts. This highlights the need for careful interpretation of results when extending the analysis to other lines or operational scenarios.

Based on the work carried out, several open points remain. These include the need to improve data acquisition processes, to refine the definition of proxy KPIs (e.g., braking events) towards more physics-based indicators, and to extend the analysis to a broader set of operational conditions, including disturbed traffic scenarios and high-density network configurations.

Future activities should therefore focus on enhancing the integration between onboard data sources and analytical tools, improving the robustness and automation of data processing pipelines, and extending the KPI framework to include additional dimensions such as capacity, resilience, and lifecycle cost. In the context of Europe’s Rail, further work should also investigate the scalability of the proposed approach to different networks and rolling stock types, as well as its integration into system-level optimisation processes.

In conclusion, this deliverable demonstrates that Automatic Driving represents a key enabler for improving energy efficiency and operational performance in railway systems. By enabling more consistent, anticipative, and optimized driving behaviour, Automatic Driving contributes to reducing energy consumption, enhancing regularity, and supporting the transition towards a more sustainable and efficient rail transport system.

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