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D37.5 – Assessment of ETCS HTD/HL3 deployment report

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DISCLAIMER

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EXECUTIVE SUMMARY

The **ETCS Hybrid Train Detection / Hybrid Level 3 (HTD/HL3)** concept represents a key evolution of the European railway signalling system, enabling a progressive transition from trackside-based train detection towards solutions relying on **train position and integrity reporting**. Within the **FP2-R2DATO** project, and in alignment with the objectives of **Europe's Rail**, HTD/HL3 is considered as an enabler for increased network capacity.

Deliverable D37.5 has been developed within **WP37** to assess the feasibility and implications of deploying HTD/HL3 in real railway contexts. The deliverable builds on previous WP37 work that defined deployment strategies, engineering methodologies, requirements, and capacity simulations, and complements these results by addressing both **life-cycle impacts** and **economic performance** of HTD/HL3 deployment.

The assessment is based on a qualitative and a quantitative methodology:

- A **qualitative Product Life-Cycle Analysis**, structured according to relevant CENELEC standards, to evaluate the impact of HTD/HL3 across the different system life-cycle phases.
- A **quantitative Project Life-Cycle Analysis**, estimating **CAPEX and OPEX** associated with both *greenfield* deployments and **migration scenarios from ETCS Level 2**.

The analysis relies on **representative case studies and scenarios** derived from other WP37 deliverables. The scenarios cover different European countries, line typologies, and traffic densities, ensuring a realistic and consistent assessment basis.

- Deployment principles and evaluation criteria from **D37.1** [06]
- Infrastructure adaptation and Virtual Subsection placement methodology from **D37.2** [01]
- Market segments, use cases and scenarios from **D37.3** [07]
- Capacity performance from simulations documented in **D37.4** [02]

The deliverable is structured as follows:

- A definition of methodological assumptions and analytical framework.
- Identification of relevant **market segments and deployment scenarios**.
- A **qualitative analysis** of HTD/HL3.
- A **quantitative analysis** of infrastructure and rolling-stock CAPEX and OPEX, including maintenance and energy-related effects.
- A compendium of results and a consolidated view of economic indicators.
- Final conclusions identifying critical challenges and success factors.

Both infrastructure and rolling-stock domains are considered, with particular attention to **RBC software evolution**, **Train Integrity Monitoring Systems (TIMS)**, and the interaction between on-board and trackside components.

The assessment confirms that **ETCS HTD/HL3 is technically feasible and strategically relevant**, offering clear potential benefits in capacity utilisation, operational flexibility, and long-term efficiency. However, HTD/HL3 deployment constitutes a **system-level transformation**, not a simple incremental upgrade of ETCS Level 2.

From a qualitative perspective, the main challenges relate to:

- Fleet-wide deployment of **TIMS**.
- Increased complexity of **RBC software development and certification.**
- The need for a **revised safety case** reflecting the new train detection paradigm.
- Organisational and operational changes affecting staff, procedures, and maintenance strategies.

From a quantitative perspective, the results show that:

- HTD/HL3 deployment requires **significant upfront investment**, particularly for signalling upgrades and rolling-stock retrofitting.
- **OPEX reductions** driven by the removal of trackside detection equipment can partially offset these costs over time.
- The economic attractiveness of HTD/HL3 is **strongly context-dependent**, with the most favourable outcomes observed on high-density and capacity-constrained lines.

Overall, HTD/HL3 emerges as a **key enabler of future railway** provided that deployment is conducted through **phased migration strategies**, with early stakeholder engagement, robust testing arrangements, and alignment with wider standardisation activities.

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ABBREVIATIONS AND ACRONYMS

ASTP	**A**dvanced **S**afe **T**rain **P**ositioning
ATP-OB	**A**utomatic **T**rain **P**rotection **– O**n **B**oard
AxL	**Ax**le **C**ounter
C5	**C**ercanías **5** (Madrid commuter line)
CAPEX	**CA**Pital **EX**penditures
CCS	**C**ontrol, **C**ommand, and **S**ignalling
CCS-OB	**C**ontrol, **C**ommand, and **S**ignalling **- O**n **B**oard.
CCS-TR	**C**ontrol, **C**ommand, and **S**ignalling **- TR**ackside
CENELEC	**C**omité **E**uropéen de **N**ormalisation **ÉLEC**trotechnique
ConOps	**Con**cept of **Op**eration**s**
DR-OB	**D**igital **R**egister **O**n **B**oard
ERTMS	**E**uropean **R**ail **T**raffic **M**anagement **S**ystem
ETCS	**E**uropean **T**rain **C**ontrol **S**ystem
EVC	**E**uropean **V**ital **C**omputer
FRMCS	**F**uture **R**ailway **M**obile **C**ommunication **S**ystem
GNSS	**G**lobal **N**avigation **S**atellite **S**ystem
GSM-R	**G**lobal **S**ystem for **M**obile Communications for **R**ailways
HL3	**H**ybrid **L**evel **3**
HS	**H**igh **S**peed
HTD	**H**ybrid **T**rain **D**etection
IADT	**I**nspection, **A**nalysis, **D**iagnostic & **T**est
IVV	**I**ntegration **V**erification **V**alidation
IxL	**I**nter**L**ocking
KMC	**K**ey **M**anagement **C**entre
LNOBPL	**L**iaisons **N**ouvelles **O**uest **B**retagne-**P**ays de la **L**oire
MCA	**M**ulti-**C**riteria **A**nalysis
NSA	**N**ational **S**ecurity **A**gency
OPEX	**OP**erational **EX**penditures
PKI	**P**ublic **K**ey **I**nfrastructure
R2DATO	**R**ail to(**2**) **D**igital automated up to **A**utonomous **T**rain **O**peration
RAMS	**R**eliability, **A**vailability, **M**aintainability, and **S**afety
RBC	**R**adio **B**lock **C**entre

RCA	**R**eference **C**CS **A**rchitecture
ROI	**R**eturn **O**f **I**nvestment
SAAL	**S**chiphol – **A**msterdam – **A**lmere – **L**elystad
TC	**T**rack **C**ircuit
TIM	**T**rain **I**ntegrity **M**onitor(ing)
TIMS	**T**rain **I**ntegrity **M**onitor **S**ystem
TSI	**T**echnical **S**pecification for **I**nteroperability
TTD	**T**rackside **T**rain **D**etection
VSS	**V**irtual **S**ub-**S**ection

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1 INTRODUCTION

This document, Deliverable D37.5 – Assessment of ETCS Hybrid Train Detection / Hybrid Level 3 (HTD/HL3) deployment, has been developed within the framework of the FP2-R2DATO project (Rail to Digital automated up to Autonomous Train Operation), funded by the Europe's Rail Joint Undertaking (ERJU) under the Horizon Europe research and innovation programme. The deliverable is part of Work Package 37 (WP37), which focuses on assessing the technical, operational, and economic impacts of advanced signalling solutions based on ETCS Hybrid Level 3, as an intermediate step towards a more digitalised and automated railway system.

To ensure consistency and traceability, D37.5 explicitly builds on the results and methodologies developed in other WP37 deliverables, in particular:

- **D37.1 –** Standardisation and Deployment Approach, which establishes the strategic principles and evaluation criteria for HTD deployment. [06]
- **D37.2 –** Methodology for Optimised Placement of (Virtual) Blocks, which defines the engineering methodology used for VSS deployment and infrastructure adaptation in the analysed scenarios. [01]
- **D37.3 –** Requirements Specification to FA1 WP8/9, which identifies the relevant market segments and case studies. [07]
- **D37.4 –** Determining ETCS HTD capacity impact analysis using simulations, whose capacity simulation results constitute a key input for the economic assessment performed in this document. [02]

In addition, D37.5 is closely linked with the HL3 specification activities carried out in WP15, particularly with Deliverable D15.1 – HL3 System Specification with identification of use cases and related engineering rules [08], which provides the technical and functional baseline ensuring alignment with the target HL3 system architecture.

The evolution from conventional ERTMS/ETCS architectures, relying on trackside train detection systems (TTD), towards hybrid solutions supported by Train Integrity Monitoring Systems (TIMS) and Virtual Sub-Sections (VSS), represents one of the main levers for improving railway capacity, efficiency, and sustainability in Europe. However, this transition also introduces significant challenges from a systems engineering, functional safety, railway operations, and life-cycle economics perspective. Deliverable D37.5 addresses these challenges through a structured assessment aligned with the overall work carried out in WP37 and with related activities across the FP2-R2DATO project.

The main objective of D37.5 is to assess the deployment of ETCS HTD/HL3 solutions from a dual perspective:

- On the one hand, by means of a qualitative product life-cycle analysis, focusing on the impacts introduced by HTD on the different system life-cycle phases (concept, requirements, design, integration, validation, operation, and maintenance), in alignment with the applicable CENELEC standards.
- On the other hand, through a quantitative project life-cycle analysis, providing estimations of CAPEX and OPEX for both greenfield deployments and migration scenarios from ETCS Level 2, considering different countries, line typologies, and railway market segments.

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The assessment carried out in this deliverable is based on a set of representative scenarios and case studies selected to cover different railway market segments, traffic profiles, and infrastructure characteristics. These scenarios are derived from other WP37 deliverables. In particular:

- The market segments and use cases considered in this document (e.g., high-speed, commuter and mixed-traffic main lines) are identified in D37.3 – Requirements Specification to FA1 WP8/9, which establishes the reference operational contexts for simulation and assessment activities.
- The infrastructure configurations and migration options analysed in the scenarios are defined using the methodology for Virtual Sub-Section placement and infrastructure adaptation developed in D37.2 – Methodology for Optimised Placement of (Virtual) Blocks [01]. This ensures consistency in how HTD is applied across different lines and countries.
- The capacity performance results associated with each scenario are taken from D37.4 – Determining ETCS HTD capacity impact analysis using simulations [02], which provides the quantitative input required to evaluate the economic implications of HTD/HL3 deployment.
- The deployment strategies, evaluation criteria and high-level step-changes guiding the selection and comparison of scenarios are aligned with D37.1 – Standardisation and Deployment Approach [06]

As a result, the scenarios assessed in D37.5 should be understood as integrated case studies, built on a common baseline across WP37, and covering both:

- Greenfield comparisons, where ETCS Level 2 and HTD/HL3 are evaluated for newly deployed infrastructure; and
- Migration scenarios, where existing ETCS Level 2 lines evolve towards HTD/HL3 with varying degrees of trackside train detection reduction.

The selected scenarios include real-world railway lines in different European countries, with heterogeneous characteristics in terms of length, traffic density, number of interlockings and signalling assets, thereby enabling a realistic and representative assessment of the deployment impacts. Regarding its structure, the document is organised as follows:

- Chapter 1 – Introduction, presenting the context, objectives and organisation of the study.
- Chapter 2 – Methodology, describing the qualitative and quantitative approaches adopted for the life-cycle analysis.
- Chapter 3 – Market Segments and Scenarios, defining the railway market segments and case studies considered.
- Chapter 4 – Qualitative Analysis for Product Development, analysing the impact of HTD/HL3 across the different system life-cycle phases.
- Chapter 5 – Quantitative Analysis for Project Development, presenting CAPEX and OPEX analyses for infrastructure and rolling stock across the selected scenarios.
- Chapter 6 – Compendium of Results, summarising the main outcomes of the analyses.
- Chapter 7 – Conclusions, consolidating the qualitative and quantitative findings and identifying key success factors for the deployment of ETCS HTD/HL3.

2 METHODOLOGY

This chapter will describe the methodology used to analyse the life cycle of both parts of this deliverable, product and project. As the document has a different scope in the analysis of Product and Project approaches, different methodologies have been developed to improve the results.

2.1 QUALITATIVE PRODUCT LIFE CYCLE ANALYSIS

2.1.1 Purpose

The purpose of this chapter is to complement the quantitative simulation results with a qualitative analysis. While quantitative data can demonstrate gains in line capacity and efficiency, this analysis focuses on the "how": the processes, functional changes, and engineering efforts required for a successful and safe migration from a conventional ETCS Level 2 system to a system with HTD, often referred to as Hybrid Level 3. The goal is to identify the main challenges, risks, and critical success factors from a lifecycle and project governance perspective.

2.1.2 Methodology

The analysis is structured according to the critical systems engineering lifecycle phases, as defined by the CENELEC EN 50126 [15], EN 50716 [16] (former EN 50128), and EN 50129 [17] standards, which are the railway industry's benchmark for Reliability, Availability, Maintainability, and Safety (RAMS). A typical Product Quality Plan for a Radio Block Centre (RBC) will be used as a reference framework, as the RBC is the core of the signalling system affected by this migration. Each lifecycle phase will be examined to determine the specific impact of introducing HTD technology.

2.2 QUANTITATIVE PROJECT LIFE CYCLE ANALYSIS

This Life Cycle Analysis (LCA) is separated into two independent analyses, Infrastructure LCA and Rolling Stock LCA.

The Infrastructure LCA focuses on all the changes needed to migrate to HTD from a previous ETCS L2 infrastructure, or all the new trackside components if HTD is implemented from a greenfield. In both cases, the analysis considers only the differences between HTD and a standard Level 2 deployment; specifically, the new elements or the adaptations to existing elements that are introduced and are not part of a typical ETCS Level 2 installation (e.g., RBC and IxL engineering to include VSS information). The Infrastructure LCA is completed with the operation cost concepts that are necessary to consider when the HTD is deployed.

The Rolling Stock LCA is consistent with the applied criteria in infrastructure and therefore only considers the costs related to updates needed to make the trains operable in an HTD line, parting from a ETCS Level 2 equipped train (e.g., EVC updates or TIMS installation).

Using the conclusions from “D37.2 – Methodology for optimised placement of (virtual) blocks” [01] and HTD simulations and their results, summarized in “D37.4 – Determining ETCS HTD capacity impact analysis using simulations” [02], the different elements that must be considered for cases of line evolution from L2 to HTD are stablished, as well as for those cases in which a new HTD deployment is carried out, in greenfield scenarios.

Once these differentiating elements have been identified, the aim is to determine their cost, both for their installation or uninstallation, and for their maintenance and other costs associated.

Using the ADIF price database [03], as Spanish Infrastructure Manager, ensures a good estimate of these costs for quantitative analysis. To further validate this data, recent real-world projects have been used, providing a more realistic and market-based perspective on costs. Because each general element considered in our process requires other secondary elements or associated activities, the data is supplemented. For this part of the analysis, a breakdown structure has been created, which unfolds from top to bottom to the necessary element in each case.

According to Eurostat (December 2025) [04] and (2Q-2025) [05], a correction from these costs, industry and labour costs, respectively, is made to adapt to every studied country (see table and pictures below). This is because country-specific information to apply national prices to each scenario is not available.

Table 1. EUROSTAT information index according to [04] and [05]

Country	INDEX	
	Domestic Industrial Activities	Labour Costs
Euro Area (EA)	118,90	124,80
European Union (EU)	117,90	127,80
France (FR)	120,30	116,50
Netherlands (NL)	132,50	147,50
Spain (ES)	112,90	114,60
Sweden (SE)	128,30	122,80

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Figure 1. Index for domestic industrial activities. Source EUROSTAT [04] Index 2021 = 100

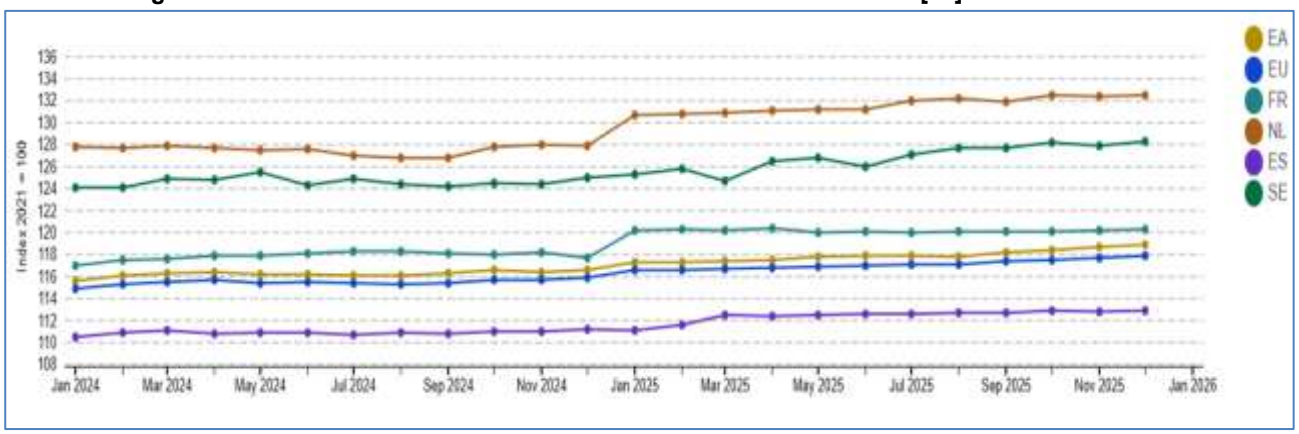
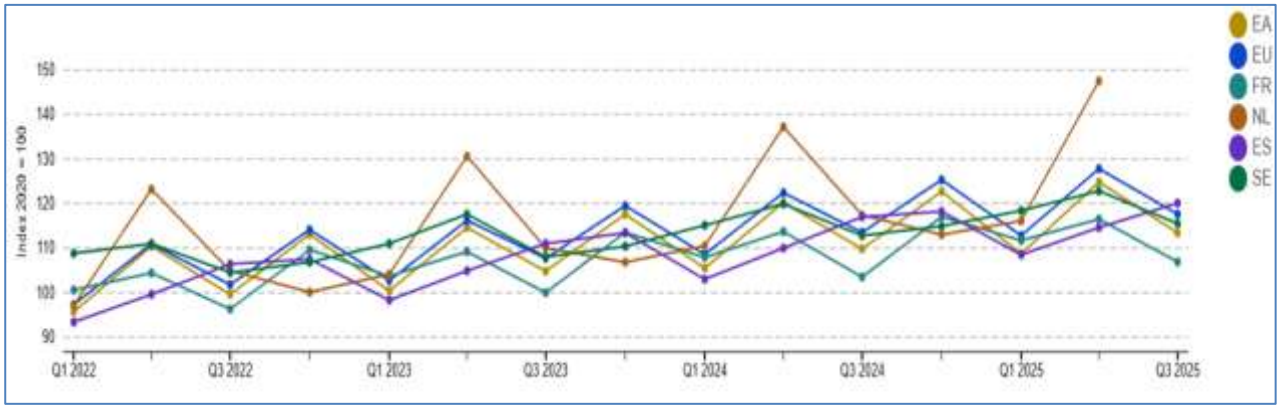


Figure 2. Index for labour cost – Industry. Source EUROSTAT [05] Index 2020 = 100



According to the simulations, this analysis offers the results for each scenario under the scope of this Work Package.

In the specific case of rolling stock, the same scheme is applied, but in this case, the need is estimated not only for the requirements imposed on every train that can run on an HTD infrastructure in order to take advantage of its new capabilities, but an estimate is also made of the size of the new fleet that could exploit the theoretical capacity increase obtained after the application of the improvements.

Energy consumption calculation is based on EUROSTAT Electricity prices for non-household consumers [09], this information is used to estimate the electricity savings for the owner of all the elements those are dismantling from the infrastructure. The table below summarizes these prices in Euro per Kilowatt-hour in the first half 2025.

Table 2. EUROSTAT Electricity prices for non-household consumers [09]

Country	Kilowatt-hour (2025-S1)
Euro Area (EA)	0,1614
European Union (EU)	0,1560
France (FR)	0,1372
Netherlands (NL)	0,1633
Spain (ES)	0,1240
Sweden (SE)	0,0958

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2.2.1 Assumptions and limitations

The analysis of the results requires considering that the different combined infrastructure and fleet scenarios may require different infrastructure management, which can be maintained or eliminated, so it will be necessary to define what assumptions have been considered.

Assumptions

A-01. Needs in communication systems are excluded. For a greenfield comparison between L2 and HTD, the cost of radio systems remains the same, in the case of a migration analysis from L2, the communication system is already available.

A-02. No need for updating communication systems is foreseen at this stage, and a possible evolution to Future Radio Mobile Communication System (FRMCS) is outside the scope of this study.

A-03. Train positioning system is out of the scope of this analysis.

A-04. Additional costs related to upgrade Global Navigation Satellite System (GNSS) equipment and other technical solutions to enhance positioning are not considered.

A-05. The track circuit and axle counter removal decision is taken specifically for every case study according to the particular characteristics of the track.

A-06. The maximum length for a Track Circuit (TC) is assumed to be 1,5 km, so when the new distance is greater than this, TC must be changed to an Axle Counter (AxC) to guarantee the detection of the rolling stock in the track.

A-07. Whenever the migration to HTD is performed, it will be considered an update of the RBC and to the related Interlockings (IxL) in the track.

A-07 bis. The relative cost of RBCs upgrades considered in all scenarios is always per complete RBC, without taking into account that this element could be serving a larger area than the one analysed and, therefore, the cost in a detailed economic analysis should be weighted according to the criteria of the analysis itself and the design of the infrastructure.

A-08. The cost for the software update and the specific application in an RBC is independent of the number of VSS deployed in the line.

A-09. The TIM availability, which is key in HTD lines, so all the trains must be upgraded to include TIM functionality, depending on the equipment migration strategy. For a whole analysis, out of the scope of this document, it is necessary to consider the costs of fleet immobilization. For simplicity, it is assumed that all actions will be carried out in conjunction with scheduled maintenance, thus eliminating the immobilization cost, which is already factored into preventive maintenance.

A-10. As a result of the new TIM functionality, an update of the European Vital Computer (EVC) is also assumed.

A-11. In no case is a double EVC being considered for each unit of the fleet, neither in the cases of high speed, where this duplication is frequent, nor in the cases of double compositions, common in commuter services.

A-12. Regarding to TIMS, it is assumed that there is only one price for the system, independently of the type of rolling stock being considered.

A-13. For the power consumption of Axle Counters and Track Circuits, the reference is a mean value from different installed infrastructure equipment from Adif, Spain. The same values are considered for all the countries.

A-14. The movement of track equipment is always prioritized over its dismantling and reinstallation, taking advantage of existing material and reducing the impact on CAPEX.

A-15. When the fleet serving a particular scenario is unknown, an estimate is made that considers the new maximum capacity of the line and the duration of the entire round-trip, thus determining the maximum number of simultaneous units in the section under analysis.

A-16. Additionally, for cases where the fleet is estimated according to the previous assumption, a 10% reserve fleet is estimated, rounding its value up to the nearest whole number.

A-17. The analysis of the work teams for carrying out the different maintenance tasks was performed in accordance with ADIF's internal regulations and Spanish legislation. This data is used as a reference for the same tasks regardless of the country where the scenario is being analysed.

Limitations

L-01. Maintenance analysis is limited to preventive operations; corrective costs are out of the scope of this document.

L-02. Greenfield scenarios are limited to common elements with different cost for comparison between ETCS-L2 and HTD deployments; infrastructure elements and activities common for all deployments like earthworks, layout, track structures, tunnels, switches, point heater systems, auxiliary detection system, stations, etc., are out of the scope of this document.

2.3 Relations with other Flagships, Work packages and Deliverables in Europe's Rail

The deliverable D37.5 is a core component of WP37 and closely interlinked with several other documents, work packages and strategic initiatives across Europe's Rail. Its successful development is dependent on a combination of simulation inputs, specification outputs, and methodological frameworks established throughout the project ecosystem.

Dependencies within WP37, D37.5 is reliant on the other four deliverables of this work package:

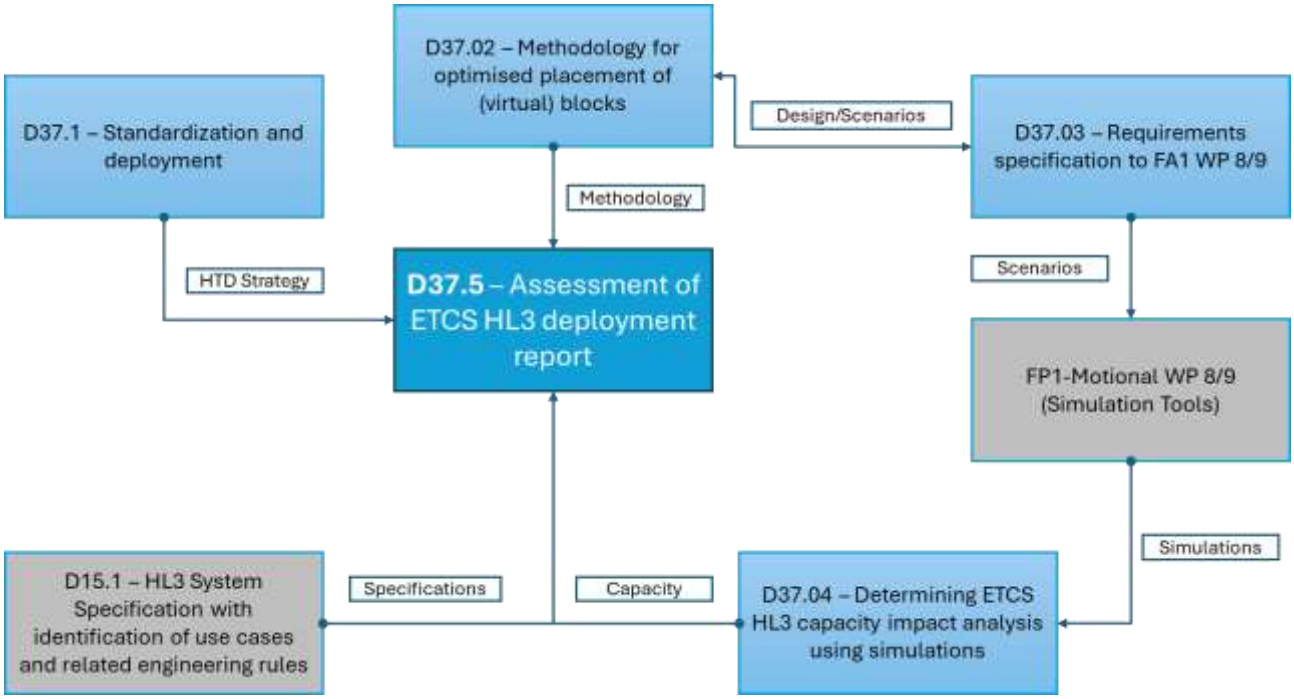
- **D37.1 – Standardisation and Deployment Approach** [06] provide a complete, structured framework and analysis for how Europe can deploy ETCS Hybrid Train Detection (HTD) efficiently, safely, and strategically. It does this by combining stakeholder input, technical analyses, standardisation/harmonisation insights, multi-disciplinary impact assessment, and detailed scenario-based deployment strategies.
- **D37.2 – Methodology for Optimised Placement of (Virtual) Blocks** [01] serves as the engineering foundation for infrastructure modelling and simulation design that will be used in D37.5. A new methodology to deploy Virtual Subsections in a track was developed and used to modify the infrastructure in different simulations. Results from D37.2 are used in D37.5.
- **D37.3 – Requirements Specification to FA1 WP8/9** [07] identifies different market segments and case studies that would also are used in the D37.5 scenarios.
- **D37.4 – Capacity Impact Analysis Using Simulations** [02]: The capacity results were used as an input for this deliverable. These results are based on the simulations executed in **Flagship Project 1 (FP1-Motional)**

- WP8: Development simulations offering operational feedback for better deployment planning.
- WP9: Demonstration scenarios simulating real-world traffic patterns relevant to D37.5 test cases.

Relation between D37.5 and WP15 (FP2-R2DATO): "WP15 – Hybrid Level 3 Specification" was finished on December 2024, from the work done on "T15.1 – HL3 - System Definition – System Interfaces, Requirements and Use Cases" and "T15.3 – HL3 - Engineering Rules" has resulted a deliverable, "D15.1 – HL3 System Specification with identification of use cases and related engineering rules" [08] that offers valid information according to the new system, engineering rules and deployment strategies principles that will be taken into account throughout this document.

The following picture shows the D37.5 ecosystem and summarizes the relations among different tasks and delivarables inside WP37, and also with other work packages from FP2-R2DATO and other flagship projects.

Figure 3. Work Package Collaboration Framework for D37.5 Assessment.



In D37.1 "Standardisation and Deployment"[06] where the deployment strategies of ETCS HTD are provided, a first CAPEX-OPEX analysis was presented and confirmed. Then, based on it, the current deliverable develops a methodology including some minor modifications and applies it to each specific scenario of the different chosen lines, which include real cases of infrastructure, market segments and rolling stock characteristics in Section 5 "Quantitative Analysis for Project Development".

Deeping on the D37.2 "Methodology for optimised placement of (virtual) blocks" [01] as a source of this deliverable, the methodology described in D37.2 dictates how the different scenarios analysed should be modified in the event of a migration from L2 to HTD, or how they would be deployed if new infrastructures are considered. This information, along with the general and specific assumptions, determines the number of elements included in the quantitative analysis. It is worth noting that two

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deployment methodologies were defined in the development of deliverable D37.2: one applied to all Spanish case studies and the other to the remaining scenarios. It is important to point out that these methodologies are defined not only based on theoretical approach but also using the feedback from the simulations under the scope of FP1-Motional WP8/WP9 “Simulation Tools” that are defined inside D37.3 “Requirements specification to FA1 WP8/9” [07]

In the FP2-R2DATO project there are other WPs dedicated to HL3/HTD technology. In particular, WP15 has produced D15.1 “HL3 System Specification with use cases and related engineering rules” [08], which is related to this deliverable due to its content and that was produced earlier in time than D37.5. Therefore, this document provides specifications that are taken into account in the decision-making, both of the simulations and of the modifications applied to the infrastructure, in such a way that they guarantee a general alignment throughout FP2.

3 MARKET SEGMENTS AND SCENARIOS

This section provides a brief description of terms used in the document of the relevant railway market segments based on the kind of traffic and use.

High-Speed
Railway services designed to operate at speeds above 200 km/h under certain conditions and all services above 250 km/h, with strict requirements for signalling, interoperability, and capacity. Often the infrastructure is separated from conventional rail so the tracks are dedicated to this kind of traffic and not open to rolling stock with different characteristics.

Conventional/MainLine
Services covering long distances connecting cities in national or international trips from which branch lines, yards or sidings emerge. These infrastructures are usually double tracks and they are shared by both, passenger and freight services, requiring advanced traffic management and prioritization solutions.

Regional
Services connecting cities and towns within a region, in most cases this infrastructure is single-track, which will be used in both directions. Today, these infrastructures have level crossings that have been eliminated on other kind of tracks. The maximum speed through the facilities are variable, without reaching high-speed, and the traffic is heterogeneous, accommodating all types of trains, passangers and freight. The operating frequencies of these lines are moderate, and they generally do not present capacity problems.

Urban/Suburban (Transit systems)
Urban and suburban services, offering reliable, scheduled service with infrastructure tailored to cover these needs: high frequency that could benefit from a capacity increase, multiple stops, and a strong dependence on punctuality. The commuter train fleet is usually homogeneous, with all its elements having the same characteristics.

Freight
Cargo transport operations involve specialised infrastructure, logistic and also intermodal facilities. However, this deliverable focuses on the different characteristics of freight rolling stock and the compatibility with signalling and control systems, that is not always guarranted for HTD and the size of the fleet and its heterogeneity do not allow the migration in the short or medium term. Under the

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point of view of infrastructure, the heterogeneous traffic in regional and main lines demands routing flexibility that allows adapting routes to demand, disruptions or capacity constraints.

For more insight and a more complete definition of the market segments Deliverable D37.4 “Determining ETCS HTD capacity impact analysis using simulations.” [02], under the same WP37 can be consulted.

4 QUALITATIVE ANALYSIS FOR PRODUCT DEVELOPMENT

4.1 SCOPE AND METHODOLOGY

The purpose of this chapter is to complement the quantitative simulation results documented in FP2-R2DATO deliverable, “D37.4 – Determining ETCS HTD/HL3 capacity impact analysis using simulations” [02]. While quantitative data can demonstrate gains in line capacity and efficiency, this analysis focuses on the "how": the processes, functional changes, and engineering efforts required for a successful and safe migration from a conventional ETCS Level 2 system to a system with Hybrid Train Detection (HTD). The goal is to identify the main challenges, risks, and critical success factors from a lifecycle and project governance perspective.

The analysis is structured according to the critical systems engineering lifecycle phases, as defined by the CENELEC EN 50126, EN 50716 (former EN 50128), and EN 50129 standards, which are the railway industry's benchmark for Reliability, Availability, Maintainability, and Safety (RAMS). A typical Product Quality Plan for a Radio Block Centre (RBC) will be used as a reference framework, as the RBC is the core of the signalling system affected by this migration. Each lifecycle phase will be examined to determine the specific impact of introducing the HTD technology.

4.2 LIFECYCLE IMPACT ASSESSMENT FOR HTD MIGRATION

This section analyses the qualitative impact on each phase of the system lifecycle, from initial concept to eventual decommissioning.

4.2.1 Impact on Concept and Planning Phase

Development of a dedicated "Migration Plan": The migration cannot be treated as a mere software update. It requires a detailed strategic plan that addresses the gradual transition, the coexistence of technologies (track circuits and axle counters alongside TIMS-based detection), and the management of a mixed fleet (trains equipped and not equipped with TIMS). This plan must define the intermediate states of the system and the conditions for progressing from one to the next.

Redefinition of the "Concept of Operations" (ConOps): The ConOps must be thoroughly revised. Traffic management changes fundamentally when moving from fixed-block occupancy detection to one based on train integrity and position. New operational procedures must be described for traffic controllers, such as authorizing movements based on train-reported integrity and managing train joining and splitting, which are critical operations in a Level 2 environment.

4.2.2 Impact on Requirements Specification Phase

Definition of new functional requirements for HTD: The new system logic must be formally specified. This includes requirements for "Virtual Sub-Sections" (VSS), which allow the RBC to subdivide blocks to optimize capacity. Requirements for processing data from the Train Integrity

Monitoring System (TIMS) must also be detailed, including reporting frequency and the information they must contain (e.g., integrity confirmed, integrity lost).

Specification of requirements for degraded modes: A crucial aspect is defining how the system will behave when new components fail. Requirements must be specified for scenarios such as an on-board TIMS failure, loss of communication with a train, or inconclusive integrity data. The system must be able to safely revert to a more restrictive mode of operation, possibly relying on the remaining traditional trackside train detection (axle counters or track circuits).

4.2.3 Impact on System Architecture and Design Phase

Functional redesign of the RBC software architecture: The RBC is the most affected component. Its software architecture must be modified to include new modules that manage HTD logic. This involves processing TIMS integrity messages, managing a VSS database, and correlating the train's position with its integrity status to ensure safety.

On-board architecture modifications for TIMS integration: The train architecture must be adapted to install and power the TIMS, as well as to integrate its outputs with the on-board EVC (European Vital Computer), which communicates with the RBC.

Trackside engineering design for TTD rationalization: The migration allows for the progressive reduction of Trackside Train Detection (TTD) equipment like axle counters. This requires a detailed engineering design to plan which assets are removed and at which phase, ensuring that safe detection coverage is maintained at all times during the transition.

4.2.4 Impact on System Integration Phase

New integration strategy for modified RBC, TIMS, and IxL: Integration is more complex than in a standard Level 2 system. The interaction between the modified RBC, EVC (with TIMS integrated) from different suppliers (if applicable), and the existing interlocking (IxL) must be tested. The strategy must include exhaustive interface testing to ensure data flows correctly between all subsystems.

Crucial role of laboratory testing and simulation environments: Given the complexity and risk, it is essential to have a robust laboratory environment that can simulate the behaviour of a TIMS-equipped fleet interacting with the new RBC. This allows most integration issues to be debugged before field tests, reducing costs and operational risks.

4.2.5 Impact on System Validation and Acceptance Phase

Development of a new Validation Plan with HTD-specific test cases: The existing validation plan will not be sufficient. New test cases must be created to specifically verify HTD functions: train integrity confirmation after startup, detection of integrity loss, correct handling of train joining or splitting, and proper functioning of degraded modes, among others.

The critical need for a new or significantly updated Safety Case (as per EN 50129): This is, perhaps, the greatest qualitative challenge. The fundamental safety principle for train detection is changing from "the track is clear" to "the track according to TTD and train information is complete and has integrity". This invalidates much of the previous Safety Case. A new safety argument must be developed to demonstrate that the HTD system is at least as safe as the previous system, presenting the necessary evidence for approval by the National Safety Authority (NSA).

4.2.6 Impact on Operation and Maintenance Phase

Adaptation of operational rules for traffic controllers and train drivers: Staff must receive comprehensive training on the new concepts. Traffic controllers must understand the new indications on their screens and know how to act in case of an integrity loss alert. Drivers must be familiar with new startup procedures and potential on-board system alarms.

Shift in maintenance paradigm – from a trackside-heavy to an on-board systems focus: Maintenance will shift significantly. Interventions on trackside equipment (TTD) will decrease, but the need to maintain, diagnose, and repair on-board TIMS systems will increase. This requires new skills, tools, and different maintenance logistics.

4.2.7 Impact on Decommissioning Phase

Planning the removal of redundant TTD assets: Once the HTD system is fully operational and its reliability has been proven, the reduction of trackside detection equipment can begin. This process must be carefully planned and executed to avoid interfering with operations and to ensure that system documentation (plans, schematics, etc.) is updated to reflect the actual state of the infrastructure.

4.3 Impact on Core Governance and Support Processes

This section analyses the impact on the cross-functional processes that ensure project quality and safety.

4.3.1 RAMS (Reliability, Availability, Maintainability, and Safety) Management

Re-evaluation of the Hazard Analysis: The introduction of TIMS and VSS logic introduces new potential hazards (e.g., an undetected TIMS failure). The entire hazard log must be reviewed and updated, and new mitigation measures must be defined to control these risks to an acceptable level (Tolerable Hazard Rate).

Management of the new Safety Case throughout the project: The Safety Case is not a document delivered at the end. Its management is an ongoing process that begins in the concept phase and requires the systematic collection of evidence (test results, safety analyses, audits) throughout the entire lifecycle to demonstrate compliance with safety requirements.

4.3.2 Quality Management

Updating the Quality Plan to cover HTD-specific activities: The project's Quality Plan must be expanded to include the new software development and validation processes for the RBC, EVC+TIMS certification procedures, and HTD-specific integration tests.

New quality audits and reviews: Additional audits, both internal and external, will be required to verify that the new HTD-related processes are being followed correctly, especially regarding safety-critical software development (per EN 50716 [16]) and Safety Case management (per EN 50129) [17].

4.3.3 Configuration and Change Management

Increased complexity in managing software and hardware versions: The interdependence between the RBC software, the on-board EVC software, the TIMS hardware & software, and the

interlocking configuration dramatically increases the complexity of configuration management. Compatibility between the different versions of the subsystems must be ensured at all times.

Formal change control process for every modification: Due to the extremely high level of safety required, any change, no matter how small, to the RBC software, HTD logic, or system configuration must go through a formal change control process. This process must assess the impact of the change on safety and ensure that the necessary verification and validation activities are performed again.

5 QUANTITATIVE ANALYSIS FOR PROJECT DEVELOPMENT

This chapter describes the Project Development Lifecycle applied to the development of HTD in different scenarios, which includes scenarios from different countries, with different types of lines in different market segments.

This study aims to cover both rolling stock and infrastructure domains and offers economic CAPEX (CAPital EXpenditures) and OPEX (OPerational EXpenditures) depending on the scenario for greenfield situation and for a migration from ERTMS/ETCS Level 2 to HTD.

5.1 ANALYSIS RELATED TO INFRASTRUCTURE MANAGEMENT

5.1.1 Lines and Scenarios under analysis

This subsection summarizes the scenarios under analysis and their main characteristics. It also provides the key factors that will determine subsequent decisions for the economic analysis in each case, ultimately resulting in cost figures comparing an ERTMS/ETCS Level 2 with an HTD or the migration from the first to the second.

The decisions made in each of the scenarios are based on the simulation analyses carried out in the different works of this same WP37 to provide consistent information about them and thus be able to carry out a more complete analysis of the new technology from the different studied aspects.

Below are the general characteristics of each of the lines used, where *Track km* is the total distance for the tracks and *Max Distance* is the distance of the line between its terminal stations.

Table 3. Lines under analysis

Line	Country	Lenghts		Equipment	
		Track km	Max Distance	RBC	IxL
SAAL Corridor	Netherlands	291,515	-	2	12
Flevo Line[1]	Netherlands	65,462	-	1	7
Atocha Conmmuter Tunnel	Spain	18,4	8 km	1	4
Cercanías C5 Madrid	Spain	103,500	45 km	1	13
HS Madrid-Torrejón de Velasco	Spain	82,8	36 km	1	4
Barcelona-Figueras	Spain	311,551	135,5 km	2	8
León-Guardo	Spain	29,687	27 km	1	3
Lérida-Reus	Spain	104,897	91 km	1	15
Cercanías Barcelona	Spain	19,305	19,3 km	1	4

[1] Flevo line is part of the SAAL Corridor.

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Lille	France	98	-	1	3
Bretagne Pays de Loire (LNOBPL)	France	212	-	1	6
Stockholm Citybanan	Sweden	12	6 km	1	1
Southern Mainline	Sweden	158	-	3	3

Scenarios

The next table offers the list of scenarios and the kind of economic analysis that are used for, where *Greenfield* means that it is a comparison between deployment in a new line for ERTMS/ETCS L2 and HTD. *Migration* is the analysis for an original Level 2 scenario and the CAPEX and OPEX related to the HTD deployment on it.

Table 4. Scenarios under analysis

Sim ID	Line	Description	Analysis
NL I1-S	SAAL Corridor	Half-reduction: VSS + aprox. 50% TTD reduction.	Migration
NL I4-S	SAAL Corridor	Max-reduction: VSS + with maximun TTD reduction.	Migration
		ETCS-L2 vs HTD deployments comparison	Greenfield
NL I1-F	Flevo Line	Half-reduction: VSS + aprox. 50% TTD reduction.	Migration
NL I4-F	Flevo Line	Max-reduction: VSS + with maximun TTD reduction.	Migration
ES A1.4	Atocha Commuter Tunnel	HTD migration from L2 with TTD reduction	Migration
ES A2.4	C5 Madrid	HTD migration from L2 with TTD reduction	Migration
		ETCS-L2 vs HTD deployments comparison	Greenfield
ES A3.2	HS Madrid-Torrejón de Velasco	HTD migration from L2 with TTD reduction	Migration
ES A4.2	Barcelona-Figueras	Only HTD deployment without TTD reduction	Migration
ES A5.4	León-Guardo	HTD migration from L2 with TTD reduction	Migration
		ETCS-L2 vs HTD deployments comparison	Greenfield
ES A6.2	Lérida-Reus	Only HTD deployment without TTD reduction	Migration
ES A7.1	Cercanías Barcelona	Only HTD deployment without TTD reduction	Migration
FR S1.1	Lille	Only deployment of HTD, no TTD reduction	Migration
FR S2.1	LNOBPL	Reduction of TTD scenario 1 & 1bis	Migration
FR S2.2	LNOBPL	Reduction of TTD scenario 2 & 3	Migration
		ETCS-L2 vs HTD deployments comparison	Greenfield
SW S1.0	Stockholm Citybanan	Only HTD deployment without TTD reduction	Migration
		ETCS-L2 vs HTD deployments comparison	Greenfield
SW S3.0	Southern Mainline	Only HTD deployment without TTD reduction	Migration

Factors for the analysis

For the greenfield analysis, both the ETCS Level 2 scenario and the best approach of the design for HTD are considered. In that case common elements between both deployments (e.g., costs for the fixed communications, auxiliar buildings and technical shelters) are not considered and the results offer a difference only related to Command and Control System (CCS) costs. Key factors are:

- Number of RBC and interlockings, common for L2 and HTD.
- The number of deployed axle counters and track circuits, different values for each system.
- Other factors.

In the case of a migration analysis, only the new elements, those who need update or the cost related to dismantling are considered, both for CAPEX and OPEX analysis.

- The removal or new installation of axle counters.
- The removal, moving or new installation of track circuits.
- Different devices and accessories needed for the installation, moving or removal of Axle Counters and Track Circuits.
- Equipment for diagnostic associated to Axle Counters and Track Circuits.
- Update in RBC, specific application, and review and update for interlockings.

See 2.2.1 Assumptions and limitations, for further details.

Following, the next table shows the specific data required for each of the scenarios according to the new design of track equipment.

Table 5. Key factors for each migration scenario under analysis

Sim ID	Axle Counters				Track Circuits			
	Initial	Removed	New	Final	Initial	Removed	New or Moved	Final
NL I1-S	1085	570	0	515	N/A			
NL I4-S	1085	678	0	407	N/A			
NL I1-F	220	139	0	81	N/A			
NL I4-F	220	163	0	57	N/A			
ES A1.4	0	0	2	2	61	32	9	38
ES A2.4	0	0	22	22	221	156	6	71
ES A3.2	0	0	8	8	109	88	4	25
ES A4.1	N/A				345	N/A		
ES A5.4	32	15	0	17	N/A			
ES A6.2	N/A				127	N/A		
ES A7.1					30	N/A		
FR S1.1	72	0	0	72	N/A			
FR S2.1	260	54	0	206	N/A			
FR S2.2	260	78	0	182	N/A			

5.1.2 CAPEX Analysis for infrastructure

According to 2.2 Quantitative Project Life Cycle Analysis, this OPEX and CAPEX study uses different price information from various sources, not only extracting values for each item in projects carried out on railway infrastructure in Spain but also based on the Adif price base [03].

For each component included in the study, an average value is calculated based on the different prices of each component. This allows us to assume in our scenario proposals that all elements have a single price, normalizing their characteristics, and in some cases, this price could be converted to a price per kilometer or price per element, this previous work simplifies the cost estimation.

The prices depend on manufacturer's catalogue prices, the national market, and agreements between the rail operator or infrastructure manager and each manufacturer, for both new installations, infrastructure migration and maintenance.

5.1.2.1 CAPEX for migration scenarios

In the migration scenarios, these are also influenced by the existing ETCS level and baseline installed on the network, and each country requires different homologation and validation processes.

The next items are considered for the CAPEX analysis:

- RBC – Specific Application Update Budget.
- Retrofit for Interlockings.
- Axle Counter removal.
- Track Circuit retrofit.
- Axle Counter Installation.
- Other elements.

All the mean prices are related to Spanish market and for each national scenario must be weight according to EUROSTAT Index [04] and [05]. Specific elements are considered for each kind of budget item and general costs must be included for completeness, and mandatory in some countries, that cover Environmental Procedures, General Documentation and Courses, Project Management, and Safety & Health. The values for these items are estimated from mean values of different projects from the last two years in Renfe and ADIF (also for rolling stock study). Those percentages apply the total amount of the previous cost for the project.

Table 6. RBC – Specific Application Update Budget

Element	Activity		Description		Reference
RBC.01	Engineering		Engineering for new specific application including VSS. Estimated for 1 RBC.		300.000,00 €
RBC.02	IMTC		Integration, management, test & Commissioning		110.000,00 €
RBC.03	Documentation		Documentation specifically related to engineer analysis		22.000,00 €
RBC.04	RAMS (on Engineering & IMTC)	Base	410.000,00 €	7,50%	30.750,00 €
RBC.05	Environmental Procedures	Base	462.750,00 €	1,00%	4.627,50 €
RBC.06	Gen.Documentation & Courses			1,00%	4.627,50 €
RBC.07	Project Supervision			2,00%	9.255,00 €
RBC.08	Health & Safety			1,00%	4.627,50 €
			TOTAL RBC Reference	Cost/RBC	**485.887,50 €**

Table 7. IxL – Retrofit for Interlockings

Element	Activity	Description	Reference
IxL.01	Engineering	Engineering for adaptation to the new specific application including VSS. Estimated for 1 IxL.	240.000,00 €
IxL.02	IMTC	Integration, management, test & Commissioning	270.000,00 €
IxL.03	Documentation	Documentation specifically related to engineer analysis	22.000,00 €

IxL.04	RAMS (on Engineering & IMTC)	Base	510.000,00 €	7,50%	38.250,00 €
IxL.05	Environmental Procedures	Base	570.250,00 €	1,00%	5.702,50 €
IxL.06	Gen.Documentation & Courses			1,00%	5.702,50 €
IxL.07	Project Supervision			2,00%	11.405,00 €
IxL.08	Health & Safety			1,00%	5.702,50 €
			TOTAL IxL Reference	Cost/RBC	**598.762,50 €**

For the following elements, the analysis considers individual costs, when it exists, and the proportional cost for each element when the known cost for the activity refers to a set of individual axle counters, track circuits, etc. This is not an exact budget, but it can be a good estimation. It can be a good approximation without going so far as to carry out an exhaustive analysis of the project.

In the case of axle counters, their dismantling is mainly considered, since thanks to the implementation of HTD and the configuration of VSS it is possible to reduce their number. Basically, it involves the work of disassembling the sensor itself and disconnecting it from other elements, the evaluator, and the updating of the diagnostic systems.

Table 8. Axle Counter Removal. Individual Costs.

Element	Activity	Description	Reference (# of AxL)	Reference
AC-R.01	Wheel sensor. Dismantling	One action per Axle Counter removed	143,03 € (1)	143,03 €
AC-R.02	Interlocking connection rack. Dismantling	Interlocking connection rack (affected # elements disconnection) Cost for a complete rack (64 AxC) adjusted to individual Axel Counter modification	982,81 € (64)	15,36 €
AC-R.03	Interface IxL-Evaluator. Modification	Interface IxL-Evaluator (affected # elements disconnection) Cost for a complete interface (64 AxC) adjusted to individual Axle Counter modification	108,00 € (64)	1,69 €
AC-R.04	Evaluator. Dismantling.	Evaluator (affected # elements disconnection) Cost for a complete interface (16 AxC) adjusted to individual Axle Counter modification	244,93 € (16)	15,31 €
AC-R.05	Diagnostic System (HW disassembly)	Diagnostic System (affected # Axle counters removed, HW disassembly), Cost for a complete unit (12 AxC)	766,79 € (12)	63,90 €
AC-C.01	Diagnostic System (SW config)	Software configuration for a complete unit (12 AxC), apply to kept Axle Counter.	1.634,34 € (12)	136,20 €

In the case of track circuit retrofits, there are several factors to consider, unlike axle counters, which are primarily based on their removal. In this case, it is necessary to manage the removal of track circuits, their relocation, or even their replacement with axle counters when the new distance of the circuit to be monitored exceeds the maximum theoretical length the track circuit can handle, see A-06 in 2.2.1 Assumptions and limitations.

The different elements that make up these track devices are considered, in addition to some auxiliary components shared along their location on the track and the associated costs of the diagnostic equipment.

Table 9. Track Circuit Retrofit. Individual Costs.

Element	Activity	Description	Reference (# of TC)	Reference

Interne

TC-R.01	Track Circuit. Dismantling	Consider the dismantling of the indoor and outdoor equipment, the loop	88,55 € (1)	88,55 €
TC-M.02	Track Circuit Moving	Removing TC position and new installation.	560,58 € (1)	560,58 €
TC-N.03	New Track Circuit Installation	Include indoor and outdoor equipment installation, protectors, cables, loop, and adjustment.	11.733,12 € (1)	11.733,12 €
TC-D.04	Diagnostic System installation	Also, for new TC and moved TC, price for an equipment (valid for 12 TC)	3.301,60 € (12)	275,13 €
TC-C.05	Adjustment and configuration	For each the number of final TC in the line	213,88 € (1)	213,88 €
TC-R.06	Diagnostic System ((HW disassembly)	Diagnostic System (affected # Track Circuits removed or moved, HW disassembly), Cost for a complete unit (12 TC)	766,79 € (12)	63,90 €
AC-C.01	Diagnostic System (SW config)	Software configuration for a complete unit (12 AxC or TC), apply to final number of Track Circuits.	1.634,34 € (12)	136,20 €

Table 10. Axle Counter Installation (Migration). Individual Costs.

Element	Activity	Description	Reference (# of AxC)	Reference
AC-N.01	Wheel sensor. Install.	New installation	8.717,36 € (1)	8.717,36 €
AC-N.02	Interlocking connection rack.	Interlocking connection rack (affected # elements connected) Cost for a complete rack (64 AxC) adjusted to individual new Axel Counter.	16.826,76 € (64)	16.826,76 €
AC-R.03	Interface IxL-Evaluator.	Interface IxL-Evaluator (affected # elements connected) Cost for a complete interface (16 AxC) adjusted to individual new Axle Counter	9.335,47 € (16)	583,47 €
AC-R.04	Evaluator	Evaluator (affected # elements connected) Cost for a complete interface (16 AxC) adjusted to individual new Track Circuit.	19.920,54 € (16)	1.245,03 €
AC-R.05	Diagnostic System installation	Diagnostic System HW deploy and installation, each system homes 12 Axle Counter connections.	3.301,60 € (12)	275,13 €
AC-C.01	Diagnostic System (SW config)	Diagnostic System SW configuration per Axle Counter.	136,20 € (1)	136,20 €

The above individual prices must be increased by the overall project costs described in the next table, where is not specifically indicated.

Table 11. General Costs for Migration Projects.

Cost	Percentage
Environmental Procedures.	1,00 %
Gen.Documentation & Courses	1,00 %
Project Supervision	2,00 %
Health & Safety	1,00 %

Other elements

According to Technical Document Harmonised ERTMS Marker Boards 011REC1053 V1.04 [13] an ETCS location marker may be used on lines equipped with ETCS to unambiguously identify the end of a block section, among others. The Infrastructure Manager may choose whether to install an ETCS Location Marker at the point dividing two VSS. This decision depends on national regulations and the manager's own criteria. A study of possible costs associated with this part of the investment

is offered below, but it is not included in all individual analyses, nor is it considered in those where it is carried out, for comparisons between all scenarios or for the calculation of aggregate data.

As in the previous section, these amounts must be supplemented by the common elements shown in Table 11. General Costs for Migration Projects.

Table 12. Location Markers installation.

Element	Activity	Description	Reference
LM.01	Location Markers	Installation of the location marker.	304,72 €
LM.02	Location Markers. Other works.	Basement works for installation.	145,57 €

General Costs

Added to the information from the previous tables: Axle counters removal, track circuit retrofit, location markers installation, some elements common to all projects must be considered. The following table shows those considered elements to complete the budget, according to engineering costs, IMTC, RAMS, among others.

Table 13. General costs for projects

Element	Activity	Description	Rate
GEN.01	Project Engineering	Previous elements[2] Information in previous tables[3]	5,00%
GEN.02	IMTC		10,00%
GEN.03	RAMS	Applies on Engineering and IMTC.	7,50%
GEN.04	Environmental Procedures	All of the previous elements.	1,00%
GEN.05	Gen.Documentation & Courses		1,00%
GEN.06	Project Supervision		2,00%
GEN.07	Health & Safety		1,00%

5.1.2.2 CAPEX for greenfield scenarios

Considering the qualitative analyses included in this document, an estimate has been made of the additional cost that would be involved for certain activities of the deployment of a greenfield line. Remember that this is a best-effort because there is currently not enough experience in the deployment of ETCS-L3 infrastructure nor prices in the catalogues of manufacturers or infrastructure managers that serve as a reference.

According to the limitation L-02, see 2.2.1 Assumptions and limitations, for further details, from the general items of ADIF projects, the following list is identified, which will be included in the comparative analysis between a deployment of a new line with ETCS-L2 and HTD. The percentage indicated next to the chapter is the average value that this item represents on the track project.

Table 14. Items considered in the analysis vs out of scope

Code	Item	Considered	%
C01	Signalling System	Yes	35 % - 40 %
C02	Train Protection Systems	Yes	30 % - 35 %
C03	Centralised Traffic Control (CTC)	Yes	< 10 %

[2] Consider for the sum the agregate for each item proportional to the number of axle counters, removed or kept, based on the specific project requirements.

C04	Fixed Telecommunication	No	5 % - 10 %
C05	Auxiliary Detection Systems	No	< 10 %
C06	Technical buildings	No	< 10 %
C07	Civil Works	No	< 10 %
C08	Power Supply Systems	No	< 5 %
C09	Video Surveillance & Access Control	No	< 5 %
C11	Point Heater Systems	No	< 2 %

In summary, from this point onwards, the analyses will only take into account the following budget items.

- Signalling Systems.
- Train Protection Systems.
- CTC.
- Application of the estimated percentage of the general chapters that are modified by the changes above: Environmental actions, general documentation, Construction Project Supervision and Health and Safety.

On the next tables, the items used for the valuation are summarised including the over cost assumed for each HTD activity versus ETCS-L2 reference. The standard cataloguing carried out by ADIF in the tender budgets is used, identifying and detailing those chapters in which differences are assumed.

Table 15. Greenfield cost for Signalling Systems. Spanish Projects Average

Element	Activity	ETCS-L2	Weigth	HTD
SIG.01	Local Operation positions, Signalling Controllers, Signals, Racks, Cabling, Dismounts	94.845,33 €/km	1	94.845,33 €/km
SIG.02	Engineering	5.441,77 €/km	1,5	8.162,65 €/km
SIG.03	Integration, Test and Commissioning	5.305,89 €/km	1,5	7.958,84 €/km
SIG.04	RAMS	Over SIG.01+SIG.02+SIG.03, tipically between 0,8% and 1,3% (used 1,13 %)		
SIG.05	Documentation & Courses	Over SIG.01+SIG.02+SIG.03, tipically between 0,8% and 1,5 % (used 1,38 %)		

In the projects used to estimate average values, it was established that 20% of the signalling cost is dedicated to train detection equipment and 2% to its cabling, based on the total cost, excluding engineering, integration, and commissioning services. Therefore, a potential reduction in this category could be determined depending on the percentage of train detectors used in the HTD deployment compared to ETCS-L2, this 22% of reduction and the SIG.01 cost of the previous table.

Table 16. Greenfield cost for Train Protection Systems. Spanish Projects Average

Element	Activity	ETCS-L2	Weigth	HTD
TPS.01	ERTMS & Legacy	5.431.840,74 €/RBC	1	5.431.840,74 €/RBC
TPS.02	Engineering	812.175,77 €/RBC	1,2	974.610,93 €/RBC
TPS.03	Integration, Test and Commissioning	317.172,46 €/RBC	2	634.344,92 €/RBC
TPS.04	RAMS	Over TPS.01+TPS.02+TPS.03, tipically between 1% and 2% (used 1,3 %)		
TPS.05	Documentation & Courses	Over TPS.01+TPS.02+TPS.03, tipically between 0,4% and 0,65 % (used 0,57 %)		

Table 17. Greenfield cost for Centralised Traffic Control. Spanish Projects Average

Element	Activity	ETCS-L2	Weigth	HTD

Interne

CTC.01	CTC (HW, SW, licences)	1.151,22 €/km	1	1.151,22 €/km
CTC.02	Software Engineering	1.964,84 €/km	1,2	2.357,80 €/km
CTC.03	Integration, Test and Commissioning	546,75 €/km	1	546,75 €/km
CTC.04	RAMS	Over CTC.01+CTC.02+CTC.03, tipically between 0,8% and 1,3% (used 1,03 %)		
CTC.05	Documentation & Courses	Over CTC.01+CTC.02+CTC.03, tipically between 2% and 5% (used 3,30 %)		

The overall cost values for any new infrastructure deployment are adjusted according to the percentages shown in the following table.

Table 18. General Costs for Greenfield Projects.

Cost	Percentage
Environmental Procedures.	0,50 %
Gen.Documentation & Courses	1,00 %
Project Supervision	1,00 %
Health & Safety	0,60 %

5.1.3 OPEX Analysis for infrastructure

For the saving analysis, the same economic criteria as for the CAPEX and new values for the different elements were used to offer a figure. After that, an estimation of the possible savings for a period based on the statistical duration for each element is presented.

This analysis includes the following items:

- Savings in maintenance. Due to limitations, only an estimated OPEX relative to preventive maintenance and energy savings can be calculated.
- Savings in energy consumption.

Maintenance

For the OPEX analysis, it is necessary to identify the maintenance frequency and the resources related to each element.

Table 19. Frequency and resources for the maintenance operations

Element	Times/Year	Manpower ID	Duration (h)	Other elements	
				Element	Usage
AxL	1	Team-01	2	Vehicle	2 hours
TC	2	Team-02	2	Vehicle	2 hours

The hourly costs for the professional categories corresponding to the labour required for the different activities were obtained considering the requirements set by ADIF for each activity and the prices available in its price database [03]. The different components of each work team were then aggregated by number and category, resulting in a single price for the entire labour team.

The classification of the work, considering qualifications, regulations, and other aspects such as safety and hygiene, determines the composition of the teams. The following table describes these requirements along with the total cost of the complete team.

Table 20. Individual costs for maintenance activities

Element		Description	Price/hour
Team-01	Manpower	Team of 2 people. Requires a first officer and a specialist laborer.	60,00 €

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Team-02	Manpower	Team of 2 people. Requires a manager and a first officer.	78,00 €
Vehicle	Other	Vehicle for transportation	15,00 €

Energy

Based on information provided by ADIF on different equipment in its infrastructure, the average energy consumption value of each type of element removed from the track is summarized in the following table.

Table 21. Energy consumption

Element	Consumption
Axle Counter	30 W/h
Track Circuit	100 W/h

Savings should be analysed considering a time period, either simply based on the estimated lifespan of the equipment affected or, if it is a business case, until the return on investment is found.

In those cases where new equipment is deployed, energy analysis is a balance between new consumption and savings due to the removal of devices' consumption.

For the migration scenarios, the savings information is provided in five-year periods, up to a total of 30 years, which is the estimated useful life of this type of equipment. The reason for this is that, in the migration scenarios, the equipment that is maintained is not necessarily new.

In all greenfield analysis, the information about the maintenance savings or costs is provided for 30 years.

5.1.4 Certification Process Impact

5.1.4.1 Scope and Capabilities of the Integration and Testing for Certification

The integration and testing strategy for certification shall define system tests that are composed of several types of tests that are used to verify and validate the different categories of requirements:

- Functional tests: these tests shall demonstrate that the test object fulfils the functional requirements and interface specifications assigned to this test object. These tests include ERTMS tests (e.g., Subset 076 [27])
- Safety tests: considering tests with fault injection aimed to verify the expected system behaviour in case of failure.
- Non-functional tests: performance tests, maintainability tests, environmental (climate, EMC) tests, load tests, stress tests, endurance tests.
- User tests: testing by end users who perform specific tasks under real-life conditions.
- Cybersecurity tests: testing the effectiveness of the cyber security strategy against potential attacks.

The integration and testing strategy shall allow system tests to be classified into two categories, depending on where and how they can be performed:

- Factory acceptance tests: validate each subsystem once completed by the supplier against requirements, design intent, and standards. Typically, the subsystem under test is within an environment of simulated interfaces, drivers, and recording devices.

Interne

- Site acceptance tests: validate the system integration on site, considering the real railway environment. Site tests can be performed firstly in test tracks, or in shadow passenger operations, and then in regular tracks.

The integration and testing strategy shall define the different levels of integration, verification, and validation (like system test, subsystem test, component test), described below.

5.1.4.2 CCS+ Integration Verification Validation (IVV) activities

The IVV activities contain technical and non-technical activities.

The technical activities of the IVV steps are the “Testing” activities: tests are needed during each of the IVV steps to prove that the system under test fulfils the objectives of this IVV step. On one hand, tests should confirm the correctness of the tested functions and properties, and on the other hand, possible errors should be detected. The nature and specification of these tests differ depending on the IVV step (Integration, Verification, or Validation for a given life cycle phase) to which they are associated. Checks performed during the tests can be automatic or manual and are the checks associated to the “T” (Test), the “D” (Demonstration) and some of the “I” (Inspection: the ones that require a test scenario) of the IADT classification.

Non-technical activities are related to quality management, review of documentation, process compliance checking, safety activities, proof by analysis (“A” of the IADT classification) or inspection (“I” of the IADT classification that do not require any test scenario)

5.1.4.3 CCS+ Trackside Level activities

The testing activities related to the Integration and Testing strategy that apply to particular testing levels for certification are defined as follows:

- Platform Level:
  - Activity: Qualification (HW/low SW level)
  - Description: The Platform Qualification (in accordance with the associated Qualification plan) shall fully be the responsibility of the Platform supplier.
- Component Level:
  - Activity: SW Testing
  - Description: The Component SW Testing (in accordance with the associated Component SW Test Plan) shall fully be under the responsibility of the Component Supplier
- CCS-TR Constituent Level
  - First Activity: Integration.
  - Description: The Constituent Integration activity shall ensure that the functional interfaces of the Component(s) contained in the Constituent are consistent with their definition and therefore, in case of n>1 Components, that these Components are compatible with each other.
  - Second Activity: Testing.
  - Description: The Constituent Testing activity shall define the tests mentioned in 5.1.4.1, above, which are relevant at the Constituent level: functional tests, safety tests, non-functional tests (including performance tests), cybersecurity tests.

- Group of CCS-TR Constituents Level
  - First Activity: Integration
  - Description: The Factory group of CCS-TR Constituents Integration activity shall ensure that the functional, mechanical and electric interfaces of the Constituents are consistent with their definition and therefore these Constituents are compatible with each other.
  - Second Activity: Testing
  - Description: The Factory CCS-TR Testing activity shall define the tests mentioned in 5.1.4.1, above, which are relevant at the CCS trackside level: functional tests, safety tests, non-functional tests (including performance tests), user tests, cybersecurity tests.
- Trackside Level:
  - First Activity: Integration
  - Description: The Site CCS-TR Integration activity shall ensure that the functional, mechanical and electric interfaces between the CCS-TR and the trackside elements are compatible.
  - Second Activity: Testing
  - Description: The Site CCS-TR Testing activity shall define the tests mentioned in 5.1.4.1, which are relevant at the Trackside level: functional tests, safety tests, non-functional tests (including performance tests), user tests, cybersecurity tests. These tests can be static or dynamic tests, depending on the target of test.
- System Level
  - First Activity: Integration
  - Description: The CCS Integration activity shall ensure that the external interfaces of a group of trackside Constituents (possibly, but not limited to, the whole CCS-TR) and a group of on-board Constituents (possibly, but not limited to, the whole CCS-OB) are compatible from a functional and messaging protocol point of view. The integration tests can be performed with real airgap transmission (mainly in Factory and with a limited number of tests on Site) or simulated airgap transmission (in Factory)
  - Second Activity: Testing
  - Description: The CCS Testing activity shall define the tests mentioned in 5.1.4.1, above, which are relevant at the System level: functional tests, safety tests, non-functional tests (including performance tests), user tests, cybersecurity tests. These tests can be static or dynamic tests and can be performed in Factory and on Site, depending on the target of test (the number of Site tests shall remain as limited as possible)

5.1.4.4 Radio Block Center (RBC) specific testing activities for certification

Since the RBC is the core of the signalling system affected by the migration to the HTD technology, this subsection generally addresses the RBC testing specific activities. These testing activities are the core activities for validating and certifying this constituent, the RBC, with a special focus on a laboratory environment. The impact of introducing HTD technology on System Validation and Acceptance Phases have been generally defined above, in the sub-section 4.1.5. So, the new test

cases for specifically verifying and validating HTD functions will be added to the set of test cases for the standard (i.e., without HTD functionality) RBC.

The RBC is a constituent of the trackside subsystem, according to the description in the chapter 2 of the TSI Subset-026 [12]. Taking into account the ERTMS reference architecture (see the Figure 1 in the Chapter 2 of SS-026), the following constituents and components that an RBC interacts with can be identified:

- The ETCS on-board equipments, also known as the ATPs.
- A variable set of components, depending on the Infrastructure Manager requirements, of the trackside subsystem, namely:
    - The radio communication network: FRMCS or GSM-R (FRMCS FIS-7970 [18], FRMCS FFFIS-7950 [19], SUBSET-037 [20], SUBSET-146 [21])
    - The adjacent, if any, Radio Block Centres (SUBSET-039 [22], SUBSET-098 [23])
    - The Key Management Centre: KMC (SUBSET-114 [24], SUBSET-137 [25], SUBSET-146 [26])
    - The Public Key Infrastructure: PKI (SUBSET-137 [25], SUBSET-146 [26])
- The Interlockings.
- The Control Centres.

The current TSI is the main and well-known set of standards for defining the testing activities. Nevertheless, during the last few years, different initiatives have been taken in order to define the specifications of an RBC focusing on a Building Block approach, so that in the future, a common set of operational rules will allow to standardise all the involved interfaces that are needed for an RBC to work in a real environment. One of these initiatives, which was created by the ERTMS Users Group and EULYNX, is the Reference CCS Architecture (RCA).

The aim of the RCA is generating an architecture description (business and operational requirements, and interface specifications) to be used as a standard reference tender specification for enabling of further specification steps and specific implementations.

In this regard, the RCA describes the Advanced Protection System as follows (see [28]): “APS is a generic form for functions of the future railway system architecture that are today located for example in Interlocking (IxL), Radio Block Centre (RBC) and trackside functions needed for controlling automated train operations. Or in other terms: APS is the trackside Command-Control and Signalling (CCS) subsystem in RCA, excluding Traffic Management System (TMS), Plan Execution (PE) or the switchable field elements including legacy and future train detection systems”.

Hereafter, a brief description of the three testing levels on an RBC that can be performed in a laboratory, in the context of a certification process:

RBC Constituent Level

Testing of the RBC shall start at CCS-TR Constituent Level in factory on host machine or on dedicated hardware. Software, non-functional and functional tests should be possible at this stage. The non-functional tests can be (non-exhaustive list): performance tests, extreme condition tests or fault-event injection tests.

To perform the tests, the test environment used at Constituent Level shall allow to interface the RBC with a single module, or a set of lab modules, that simulates the inputs of the RBC depending on the

test scenario. These lab modules can be one or several of the components listed above (ATP-OB, RBC, Interlocking, etc)

Group of CCS-TR Constituents Level

Some Components, the RBC and others, are integrated together to build a Group of Constituents that can be tested as a whole. This Group of Constituents can be, but it is not limited to, the CCS-TR equipment. Functional tests can also be performed at this level, still in factory and on host machine or with the software of each Component of the group integrated on their hardware.

The main differences with the tests performed at RBC Constituent Level are that the inputs for the group of Constituents are simulated depending on the test scenario. Therefore, the test scenario must consider the expected behaviour of the group of Constituents, and the test scenario might include the correct conditions in other interfaces that make it possible to check the RBC outputs.

The objectives of the functional tests described for the RBC Constituent Level can be included as part of the whole set of objectives for the Group of CCS-TR Constituents Level. It may be easier to simulate only the RBC inputs than these inputs plus the inputs of the group of Constituents. Nevertheless, tests performed at the Group of CCS-TR Constituents Level may be more complete than the ones performed at the RBC Constituent Level.

System Level

Currently, these System level activities are part of the IM testing process to accept the ERTMS contracted system, and they can also be considered as operational test scenarios.

The scenarios are mainly selected according to ERTMS standard operations as well as specifically defined operations (defined by the corresponding IM), which will not be in any case against the TSI requirements. For example, it needs to be ensured that when trains, tracked by the CCS-TR, are running on a specific line, the RBC is able to progressively provide and update different Movement Authorities to the ATP-OBs as soon as they are needed (including the possible requests received from the ATP-OBs), communicate correctly with the adjacent RBCs or exchange the appropriate information with the Interlockings in due time.

At this level, the RBC is integrated in a group of Trackside Components, which may be the whole CCS-TR. Besides, some Building Blocks of the CCS-OB should be also integrated in the lab. In principle, the RBC can be tested together with the CCS-TR Constituents mentioned in the Group of CCS-TR Constituents Level sub-section, before. On the CCS-OB side, at least one ATP-OB should be tested together with the CCS-TR Constituents. On top of this, and depending on the specific project, other on-board BBs can be tested, for example, the Digital Register On-Board (DR-OB) or the Advanced Safe Train Positioning (ASTP).

5.1.5 CAPEX-OPEX Analysis results for Migration scenarios

5.1.5.1 Migration scenarios in Netherlands

The Dutch cases belong to the same line, SAAL Corridor, but two separate analyses are carried out, the first is for the entire corridor, from Schiphol Airport, to Amsterdam Zuid, to Almere and ends in Lelystad; and the second for a section of it which is, Flevo Line, that runs from Weesp (between Amsterdam and Almere) to Lelystad.

Interne

According to the used scenarios in headway analysis, two different levels of axle counters reductions are considered for both, SAAL and Flevo Line. These four scenarios belong to a four-track line, with some minor exceptions where there is a double-track.

SAAL Corridor

SAAL Corridor is the whole length track,

Table 22. CAPEX analysis for SAAL Corridor. Scenario I1-S

ELEMENT	#	Description	TOTAL	€/km
RBC	2	RBC - Specific Application update.	1.140.479,96 €	3.912,25 €
IxL	12	IxL - Retrofit for Interlockings.	8.432.527,68 €	28.926,57 €
AC-R	570	Axle Counter Removal	281.470,12 €	965,54 €
AC-C	515			
		CAPEX for Scenario	9.854.477,76 €	33.804,36 €

Table 23. OPEX analysis for SAAL Corridor. Scenario I1-S

ELEMENT	#	Description	Total/Year	€/km
AC-R	570	Savings in Axle Counters removed	108.105,29 €	370,84 €
AC-R	570	Energy savings	24.461,69 €	83,91 €
		OPEX for Scenario	132.566,98 €	370,84 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	901.709,05 €	1.883.350,88 €	3.136.202,26 €	4.735.193,37 €	6.775.956,24 €	9.380.544,28 €
Rate 2,5 % Savings	846.802,97 €	1.654.895,44 €	2.569.177,89 €	3.603.604,57 €	4.773.963,41 €	6.098.117,01 €

Table 24. CAPEX analysis for SAAL Corridor. Scenario I4-S

ELEMENT	#	Description	TOTAL	€/km
RBC	2	RBC - Specific Application update.	1.140.479,96 €	3.912,25 €
IxL	12	IxL - Retrofit for Interlockings.	8.432.527,68 €	28.926,57 €
AC-R	678	Axle Counter Removal	296.643,14 €	1.017,59 €
AC-C	407			
		CAPEX for Scenario	9.869.650,78 €	33.856,41 €

Table 25. OPEX analysis for SAAL Corridor. Scenario I4-S

ELEMENT	#	Description	Total/Year	€/km
AC-R	678	Savings in Axle Counters removed	128.588,40 €	441,10 €
AC-R	678	Energy savings	29.096,53 €	99,81 €
		OPEX for Scenario	157.684,94 €	540,92 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	1.072.559,18 €	2.240.196,31 €	3.730.430,05 €	5.632.387,90 €	8.059.821,64 €	11.157.910,56 €
Rate 2,5 % Savings	1.007.249,85 €	1.968.454,58 €	3.055.969,49 €	4.286.392,80 €	5.678.503,84 €	7.253.549,71 €

Flevo Line

Flevo Line is a partial zone where the most interlocking and stations are concentrated. As in the SAAL Corridor scenarios, the TTD reduction is analysed in two different scenarios, the first one has

Interne

a 50% reduction, approximately, and the second one is the maximum reduction, limited to operative criteria.

Table 26. CAPEX Analysis for Flevo Line. Scenario I1-F

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	570.239,98 €	8.711,01 €
IxL	7	IxL - Retrofit for Interlockings.	4.918.974,48 €	75.142,44 €
AC-R	139	Axle Counter Removal	60.363,14 €	922,11 €
AC-C	81			
		CAPEX for Scenario	5.549.577,60 €	84.775,56 €

Table 27. OPEX Analysis for Flevo Line. Scenario I1-F

ELEMENT	#	Description	Total/Year	€/km
AC-R	139	Savings in Axle Counters removed	26.362,52 €	402,71 €
AC-R	139	Energy Savings	5.965,22 €	91,12 €
		OPEX for Scenario	32.327,74 €	493,84 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	219.890,45 €	459.273,29 €	764.793,18 €	1.154.722,59 €	1.652.382,31 €	2.287.536,24 €
Rate 2,5 % Savings	206.501,08 €	403.562,22 €	626.518,82 €	878.773,75 €	1.164.177,04 €	1.487.084,67 €

Table 28. CAPEX Analysis for Flevo Line. Scenario I4-F

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	570.239,98 €	8.711,01 €
IxL	7	IxL - Retrofit for Interlockings.	4.918.974,48 €	75.142,6 €
AC-R	163	Axle Counter Removal	63.734,92 €	973,62 €
AC-C	57			
		CAPEX for Scenario	5.552.949,38 €	84.827,07 €

Table 29. OPEX Analysis for Flevo Line. Scenario I4-F

ELEMENT	#	Description	Total/Year	€/km
AC-R	163	Savings in Axle Counters removed	30.914,32 €	472,25 €
AC-R	163	Energy Savings	6.995,18 €	106,86 €
		OPEX for Scenario	37.909,51 €	579,11 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	257.857,15 €	538.572,27 €	896.843,80 €	1.354.099,16 €	1.937.685,73 €	2.682.506,52 €
Rate 2,5 % Savings	242.155,94 €	473.242,03 €	734.694,73 €	1.030.504,46 €	1.365.186,03 €	1.743.847,50 €

5.1.5.2 Migration scenarios in Spain

These scenarios belong to different lines in Spain with very heterogeneous characteristics, those are described for each of them, prior to include the analysis.

Túnel Atocha-Chamartín. Cercanías

This is a case study with high traffic density over a short distance, making it a unique element. According to the analysis in [02] the RBC would handle 48 trains per hour and 10 simultaneously. It should be noted that the unit cost of the RBC serving the section remains the same, but, due to its

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length and traffic volume, this cost should be shared with the simultaneous intervention in the RBC's area of influence. In this case, the estimated price per kilometer for this section is significantly higher compared to other scenarios studied.

In this scenario 71 VSSs are deployed.

Table 30. CAPEX Analysis for Túnel Atocha-Chamartín Scenario A1.4.

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	485.887,50 €	26.406,93 €
IxL	4	IxL - Retrofit for Interlockings.	2.395.050,00 €	130.165,76 €
TC-M	9	Track Circuit retrofit. TC moved (TC-M), TC removed (TC-R), total TC in track and configured (TC-C) New Axle Counters instlalled (AC-N)	52.225,72 €	2838,35 €
TC-R	23			
TC-C	38			
AC-N	2			
LM	31	Location Markers	14.653,68 €	796,40 €
		CAPEX for Scenario	2.947.816,90 €	160.207,44 €

Table 31. OPEX Analysis for Túnel Atocha-Chamartín Scenario A1.4.

ELEMENT	#	Description	Total/Year	€/km
TC-R	23	Savings in Track Circuits removed	8.556,00 €	465,00 €
AC-N	2	Added expenditure for new Axle Counters	- 300,00 €	- 16,30 €
		Savings in maintenance	**8.256,00 €**	**448,70 €**
TC-R	23	Energy savings for Track Circuit dismantling.	2.498,35 €	135,78 €
AC-N	2	Energy for new Axle Counter installed.	- 65,17 €	- 3,54 €
		Energy Savings	**2.433,18 €**	**132,24 €**
		OPEX for Scenario	10.689,18 €	580,93 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	72.706,85 €	151.858,87 €	252.879,13 €	381.809,43 €	546.360,78 €	756.374,65 €
Rate 2,5 % Savings	68.279,65 €	133.437,99 €	207.158,67 €	290.566,84 €	384.935,54 €	491.705,06 €

C5 Madrid. Cercanías

The migration in this double-track line considers the removal of several track circuits, the new location for some of these and the new installation of axle counters due to the increased distance that cannot be managed thorough track circuits.

The OPEX savings from the removal of train detection equipment are offset by the new costs incurred by the new equipment that needs to be installed.

In this Madrid commuter line 225 VSSs are deployed.

Table 32. CAPEX Analysis for Madrid C5. Scenario A2.4

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	485.887,50 €	4.694,57 €
IxL	13	IxL - Retrofit for Interlockings.	7.783.912,50 €	75.206,88 €
TC-M	6	Track Circuit retrofit. TC moved (TC-M), TC removed (TC-R), total TC in track and configured (TC-C) New Axle Counters instlalled (AC-N)	358.201,77 €	3.460,89 €
TC-R	150			
TC-C	71			
AC-N	22			

LM	132	Location Markers.	62.396,33 €	602,86 €
		CAPEX for Scenario	8.690.398,10 €	83.965,20 €

Table 33. OPEX Analysis for Madrid C5. Scenario A2.4

ELEMENT	#	Description	Total/Year	€/km
TC-R	150	Savings in Track Circuits removed	55.800,00 €	539,13 €
AC-N	22	Added expenditure for new Axle Counters	- 3.300,00 €	- 31,88 €
		Savings in maintenance	**52.500,00 €**	**507,25 €**
TC-R	150	Energy savings for Track Circuit dismantling.	16.293,60 €	157,43 €
AC-N	22	Energy for new Axle Counter installed.	- 716,92 €	- 6,93 €
		Energy Savings	**15.576,68 €**	**150,50 €**
		OPEX for Scenario	68.076,68 €	657,75 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	463.051,65 €	967.150,93 €	1.610.523,53 €	2.431.648,13 €	3.479.634,32 €	4.817.159,76 €
Rate 2,5 % Savings	434.855,92 €	849.832,96 €	1.319.341,39 €	1.850.547,09 €	2.451.557,58 €	3.131.545,78 €

HS Madrid-Torrejón de Velasco

This is a section of the high-speed line nearby Madrid, a short track line without stops. As in some previous analyses, here the cost of the RBC is very significant; neither the length of the track nor the number of simultaneous trains justifies a single RBC for this small section, so in a more detailed economic analysis it would be necessary to average it as it is distributed with the area to which this section of infrastructure belongs.

Table 34. CAPEX Analysis for HS Atocha-Torrejón de Velasco. Scenario A3.1

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	487.887,50 €	5.868,21 €
IxL	4	IxL - Retrofit for Interlockings.	2.395.050,00 €	28.925,72 €
TC-M	4	Track Circuit retrofit. TC moved (TC-M), TC removed (TC-R), total TC in track and configured (TC-C) New Axle Counters instlalled (AC-N)	137.453,22 €	1.606,06 €
TC-R	84			
TC-C	25			
AC-N	8			
LM	80	Location Markers	37.815,96 €	456,71 €
		CAPEX for Scenario	3.056.206,68 €	36.910,71 €

Table 35. CAPEX Analysis for HS Atocha-Torrejón de Velasco. Scenario A3.1

ELEMENT	#	Description	Total/Year	€/km
TC-R	84	Savings in Track Circuits removed	31.248,00 €	377,39 €
AC-N	8	Added expenditure for new Axle Counters	- 1.200,00 €	- 14,49 €
		Savings in maintenance	**30.048,00 €**	**362,90 €**
TC-R	84	Energy savings for Track Circuit dismantling.	9.124,42 €	110,20 €
AC-N	8	Energy for new Axle Counter installed.	- 260,70 €	- 3,15 €
		Energy Savings	**8.863,72 €**	**107,05 €**
		OPEX for Scenario	38.911,72 €	469,95 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	264.674,12 €	552.810,50 €	920.553,66 €	1.389.897,47 €	1.988.912,32 €	2.753.423,93 €

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Rate 2,5 % Savings	248.557,81 €	485.753,13 €	754.117,85 €	1.057.747,91 €	1.401.277,44 €	1.789.949,58 €

Barcelona-Figueras

This is a case study in a High-Speed line with no reduction of TTDs. The area is composed between two terminal stations, Sants AV to Figueras-Vilafrant. Because the simulations were carried out with a freight train being pursued by a high-speed train, the track detectors were kept in place so as not to penalize the freight train's journey, assuming no TIM, therefore the reduction of TTD in this section is not considered and the analysis focuses only on an evolution from ETCS-N2 to HTD taking into account the RBCs and the interlockings update. For the same reason there is no analysis for OPEX savings.

Table 36. CAPEX analysis Barcelona-Figueras. Scenario ES A4.1

ELEMENT	#	Description	TOTAL	€/km
RBC	2	RBC - Specific Application update.	971.775,00 €	3119,15 €
IxL	8	IxL - Retrofit for Interlockings.	4.790.100,00 €	15.375,01 €
LM	6	Location Markers	2.836,20	9,10 €
		CAPEX for Scenario	5.764.711,20 €	18.503,27 €

Leon-Guardo. Regional

This is a low density regional one-track line, the area under study runs between La Asunción Universidad (León) and Matallana. This is the most complex section of the line and combines several tracks in some areas. Although a track with these characteristics is not a clear target for HTD deployment, the analysis of changes to the existing infrastructure, including the removal of trackside equipment, and the complexity of deploying a set of independent VSS systems for each direction of traffic on a single track make it particularly interesting to analyse the potential costs of this deployment.

As in other previous analyses, the cost of the RBC to carry out a real business case would have to be weighted; it is not reflected in the tables, since the RBC serves the entire León-Guardo line and we are only considering a small section of the infrastructure.

Table 37. CAPEX analysis for León-Guardo. Scenario ES 5.4

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	485.887,50 €	16.367,01 €
IxL	3	IxL - Retrofit for Interlockings.	1.796.287,50 €	60.507,55 €
AC-R	15	Axle Counter Removal	6.877,69 €	231,67 €
AC-C	17			
LM	85	Location Markers	40.179,46 €	1.353,44 €
		CAPEX for Scenario	2.329.232,15 €	78.459,67 €

Table 38. OPEX analysis for León-Guardo. Scenario ES 5.4

ELEMENT	#	Description	Total/Year	€/km
AC-R	15	Savings in Axle Counters removed	5.580,00 €	187,96 €
AC-R	15	Energy savings	1.629,36 €	54,88 €
		OPEX for Scenario	7.209,37 €	242,85 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	49.037,44 €	102.421,84 €	170.555,37 €	257.512,95 €	368.495,29 €	510.140,01 €

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Rate 2,5 % Savings	46.051,49 €	89.997,80 €	139.719,02 €	195.974,01 €	259.621,37 €	331.632,51 €

Lérida-Reus

This area is a freight regional one-track line, as in the previous scenario, at first glance, it is not a target area for an HTD deployment, but it is interesting for the same reasons as before, with the difference that now the deployment of the new technology is carried out without removing the original track equipment, in this case track circuits.

No OPEX savings are included.

Table 39. CAPEX analysis for Lérida-Reus. Scenario ES 6.2

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	485.887,50 €	4.632,04 €
IxL	15	IxL - Retrofit for Interlockings.	8.981.437,50 €	85.621,49 €
LM	134	Location Markers	63.341,73 €	603,85 €
		CAPEX for Scenario	9.530.666,73 €	90.857,38 €

Cercanías Barcelona

This area is a short section of the Barcelona commuter network, between Granollers and two stations after a bifurcation that allows to reach La Llagosta or Santa Perpetua. Although it is a double-track section, due to various limitations, the analysis has only been carried out in the direction of the bifurcation, not in the direction of the confluence, therefore considering the equipment and characteristics of that same path.

Again, the cost of the RBC should be distributed across the entire service area, and, in a complete economic analysis, the equivalent of the same should be allocated to this section.

There is no TTD reduction, so no OPEX savings are included.

Table 40. CAPEX analysis for Cercanías Barcelona. Scenario ES 7.1

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	485.887,50 €	25.169,00 €
IxL	4	IxL - Retrofit for Interlockings.	2395.050,00 €	124.063,71 €
LM	134	Location Markers	4.727,00 €	244,86 €
		CAPEX for Scenario	2.885.664,50 €	149.477,57 €

5.1.5.3 Migration scenarios in France

Lille

In this French new line between Lille and Henin Beaumont no scenarios with reduced TTD have been simulated. Therefore, to maintain consistency with the work reflected in D37.4 [02], the migration from ETCS-L2 to HTD on the line is estimated without applying calculations for the elimination of track detection devices. Consequently, no analysis of potential savings in maintenance or electricity consumption is performed.

Table 41. CAPEX analysis for Lille. Scenario FR S1.1

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	517.734,86 €	5.283,01 €
IxL	3	IxL - Retrofit for Interlockings.	1.914.024,68 €	19.530,86 €
		CAPEX for Scenario	2.431.759,54 €	24.813,87 €

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Bretagne Pays de Loire

On this line that runs between Cannes and St. Brieuc, a section within LNOBL, the analysis carried out includes the reduction of axle counters when migrating the line from ETCS-N2 to HTD.

Table 42. CAPEX analysis for Bretagne Pays de Loire. Scenario FR S2.1

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	517.734,86 €	2.442,15 €
IxL	6	IxL - Retrofit for Interlockings.	3.828.049,36 €	18.056,84 €
AC-R	54	Axle Counter Removal	50.703,90 €	239,17 €
AC-C	206			
		CAPEX for Scenario	4.396.488,12 €	20.738,15 €

Table 43. OPEX analysis for Bretagne Pays de Loire. Scenario FR S2.1

ELEMENT	#	Description	Total/Year	€/km
AC-R	54	Savings in Axle Counters removed	8.313,62 €	39,22 €
AC-R	54	Energy savings	1.947,03 €	9,18 €
		OPEX for Scenario	10.260,65 €	48,40 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	69.792,04 €	145.770,87 €	242.741,23 €	366.502,73 €	524.457,24 €	726.051,67 €
Rate 2,5 % Savings	65.542,33 €	128.088,47 €	198.853,70 €	278.918,05 €	369.503,52 €	471.992,66 €

Table 44. CAPEX analysis for Bretagne Pays de Loire. Scenario FR S2.2

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	517.734,86 €	2.442,15 €
IxL	6	IxL - Retrofit for Interlockings.	3.828.049,36 €	18.056,84 €
AC-R	78	Axle Counter Removal	53.765,22 €	253,61 €
AC-C	182			
		CAPEX for Scenario	4.399.549,44 €	20.752,59 €

Table 45. OPEX analysis for Bretagne Pays de Loire. Scenario FR S2.2

ELEMENT	#	Description	Total/Year	€/km
AC-R	78	Savings in Axle Counters removed	12.008,56 €	56,64 €
AC-R	78	Energy savings	2.812,38 €	13,27 €
		OPEX for Scenario	14.820,94 €	69,91 €

30 Years Saving Analysis						
Years	**5**	**10**	**15**	**20**	**25**	**30**
Rate 5 % Savings	100.810,73 €	210.557,92 €	350.626,23 €	529.392,83 €	757.549,35 €	1.048.741,31 €
Rate 2,5 % Savings	94.672,25 €	185.016,69 €	287.233,12 €	402.881,63 €	533.727,31 €	681.767,18 €

5.1.5.4 Migration scenarios in Sweden

Stockholm Citybanan

The CAPEX analysis for the migration from ETCS-L2 to HTD on this Swedish line, only the necessary upgrade to the RBC and its single interlocking system were considered. The removal of the trackside detectors was not contemplated, and therefore, the OPEX difference between the two scenarios was not calculated.

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Table 46. CAPEX analysis for Stockholm Citybanan. Scenario SW S1.0

ELEMENT	#	Description	TOTAL	€/km
RBC	1	RBC - Specific Application update.	552.164,45 €	46.013,70 €
IxL	1	IxL - Retrofit for Interlockings.	680.436,04 €	56.703,00 €
		CAPEX for Scenario	1.232.600,49 €	102.716,71 €

Southern Mainline

The analysis of this line focuses on a section that goes from Norrköping to Mjölby. As in the previous Swedish scenario only the CAPEX analysis, for RBCs and interlockings, has been performed.

Table 47. CAPEX analysis for Southern Mainline. Scenario SW S3.0

ELEMENT	#	Description	TOTAL	€/km
RBC	3	RBC - Specific Application update.	1.656.493,35 €	138.041,11 €
IxL	3	IxL - Retrofit for Interlockings.	2.041.308,12 €	170.109,01 €
		CAPEX for Scenario	3.697.801,46 €	308.150,12 €

5.1.6 CAPEX Analysis for Greenfield Scenarios

The scenarios analysed, reflected in the table, have been selected taking into account that they are lines or sections of track significant enough to be able to offer a valid result, discarding those sections that are excessively short or with characteristics that are not suitable to extract a useful result for the objectives of this deliverable.

Since the same train detection system data determined through simulations is being included in the analysis of the deployment between ETCS-L2 and HTD, and coincides with that used for the migration scenarios, the expected OPEX figure, savings of the line with HTD versus the line with ETCS-L2, have already been included in the previous OPEX chapters for the migration scenarios, and are not repeated in this section.

5.1.6.1 Greenfield scenarios in Netherlands

SAAL Corridor

The differences in deployment between ETCS-L2 and HTD on the SAAL Corridor line, assuming it is carried out from Greenfield, focus on the assumptions of the budget differences as well as the different number of axle counters that would be deployed. According to simulations the original ETCS-L2 has 1085 axle counters and for the HTD deployment only 407 axle counters are necessary.

Table 48. CAPEX for Signalling SAAL Corridor Greenfield deployments NL I4-S.

Signalling		ETCS-L2		HTD	
		€/km	estimated	€/km	Estimated
Equipment, cabling, signalling and field works		111.310,95 €	32.448.812,18 €	111.310,95 €	32.448.812,18 €
Engineering		6.386,49 €	1.861.756,96 €	9.579,73 €	2.792.635,44 €
Test & Integration		6.227,02 €	1.815.271,10 €	9.340,54 €	2.722.906,65 €
Estimated HTD Track Circuit Saving					
Axle Counters Difference	62,49 %	Over 32.448.812,18 €			- 4.460.889,24 €
	%	**Subtotal**	36.125.840,24 €	**Subtotal**	33.503.465,03 €
RAMS for Signalling	1,13%		409.176,47 €		379.474,35 €
Signalling Documentation and Courses	1,38%		496.743,63 €		460.685,01 €
Total budget for Signalling			**37.031.760,34 €**		**34.343.624,38 €**

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Table 49. CAPEX for Train Protection System SAAL Corridor Greenfield deployments NL I4-S.

Train Protection System		ETCS-L2		HTD	
		€/RBC	estimated	€/RBC	Estimated
ERTMS & Legacy		6.374.835,24 €	12.749.670,48 €	6.374.835,24 €	12.749.670,48 €
Engineering		953.173,52 €	1.906.347,03 €	1.143.808,22 €	2.287.616,44 €
Test & Integration		372.235,17 €	744.470,35 €	744.470,35 €	1.488.940,69 €
	%	Subtotal	15.400.487,86 €	Subtotal	16.526.227,61 €
RAMS for TPS	1,30%		199.960,62 €		214.577,27 €
TPS Documentation and Courses	0,57%		88.350,41 €		94.808,61 €
Total budget for Train Protection System			**15.688.798,88 €**		**16.835.613,49 €**

Table 50. CAPEX for Centralised Traffic Control SAAL Corridor Greenfield deployments NL I4-S.

Centralised Traffic Control		ETCS-L2		HTD	
		€/km	estimated	€/km	Estimated
CTC		1.351,43 €	393.961,65 €	1.351,43 €	393.961,65 €
Software Engineering		2.305,94 €	672.216,94 €	2.767,13 €	806.660,32 €
Test & Integration		641,67 €	187.057,04 €	641,67 €	187.057,04 €
	%	Subtotal	1.253.235,63 €	Subtotal	1.387.679,02 €
RAMS for CTC	1,03%		12.857,31 €		14.236,60 €
CTC Documentation and Courses	3,30%		41.324,32 €		45.757,47 €
Total budget for Centralised Traffic Control			**1.307.417,25 €**		**1.447.673,09 €**

Table 51. Comparison Summary for SAAL Corridor Greenfield deployments NL I4-S.

ETCS-L2 vs HTD Budget			ETCS-L2	HTD	HTD/L2
Signalling			37.031.760,34 €	34.343.624,38 €	-7,26%
Train Protection System			15.688.798,88 €	16.835.613,49 €	7,31%
Centralized Traffic Control			1.307.417,25 €	1.447.673,09 €	10,73%
Environmental Actions	%	Base	54.027.976,48 €	52.626.910,96 €	
Gen.Documentation, Health & Safety, Project Supervision	3,10%		1.674.867,27 €	1.631.434,24 €	
Total budget for the Scenario			**55.702.843,75 €**	**54.258.345,20 €**	**-2,59%**

5.1.6.2 Greenfield scenarios in Spain

Spain. Commuter C5 Madrid

The following tables summarises the results for this whole commuter line, using the ETCS-L2 optimum design with 221 track circuits and also the HTD deployment that has 71 track circuits and 22 new axle counters due to the increased length of some sections.

Table 52. CAPEX for Signalling Commuter C5 Madrid ES A2.4.

Signalling		ETCS-L2		HTD	
		€/km	Estimated	€/km	Estimated
Equipment, cabling, signalling and field works		94.845,33 €	9.816.491,86 €	94.845,33 €	9.816.491,86 €
Engineering		5.441,77 €	563.223,14 €	8.162,65 €	844.834,72 €
Test & Integration		5.305,89 €	549.160,13 €	7.958,84 €	823.740,20 €
Estimated HTD Track Circuit Saving					
Track Circuits Difference	46,88 %	Over 9.816.491,86 €			-1.465.811,00 €

	%	**Subtotal**	10.928.875,13 €	**Subtotal**	10.019.255,77 €
RAMS for Signalling	1,13%		123.785,04 €		113.482,31 €
Signalling Documentation and Courses	1,38%		150.276,07 €		137.768,46 €
Total budget for Signalling			**11.202.936,24 €**		**10.270.506,54 €**

Table 53. CAPEX for Train Protection System Commuter C5 Madrid ES A2.4.

Train Protection System		**ETCS-L2**		**HTD**	
		€/RBC	**estimated**	**€/RBC**	**Estimated**
ERTMS & Legacy		5.431.840,74 €	5.431.840,74 €	5.431.840,74 €	5.431.840,74 €
Engineering		812.175,77 €	812.175,77 €	974.610,93 €	974.610,93 €
Test & Integration		317.172,46 €	317.172,46 €	634.344,92 €	634.344,92 €
	%	**Subtotal**	6.561.188,98 €	**Subtotal**	7.040.796,59 €
RAMS for TPS	1,30%		85.190,77 €		91.418,01 €
TPS Documentation and Courses	0,57%		37.640,61 €		40.392,05 €
Total budget for Train Protection System			**6.684.020,35 €**		**7.172.606,65 €**

Table 54. CAPEX for Centralised Traffic Control Commuter C5 Madrid ES A2.4.

Centralised Traffic Control		**ETCS-L2**		**HTD**	
		€/km	**estimated**	**€/km**	**Estimated**
CTC		1.151,52 €	119.182,22 €	1.151,52 €	119.182,22 €
Software Engineering		1.964,84 €	203.360,67 €	2.357,80 €	244.032,80 €
Test & Integration		546,75 €	56.588,94 €	546,75 €	56.588,94 €
	%	**Subtotal**	379.131.83 €	**Subtotal**	419.803,96 €
RAMS for CTC	1,03%		3.889,62 €		4.306,89 €
CTC Documentation and Courses	3,30%		12.501,53 €		13.842,66 €
Total budget for Centralised Traffic Control			**395.522,98 €**		**437.953,51 €**

Table 55. Comparison Summary for Commuter C5 Madrid ES A2.4.

ETCS-L2 vs HTD Budget			**ETCS-L2**	**HTD**	**HTD/L2**
Signalling			11.202.936,24 €	10.270.506,54 €	-8,32%
Train Protection System			6.684.020,35 €	7.172.606,65 €	7,31%
Centralized Traffic Control			395.522,98 €	437.953,51 €	10,73%
Environmental Actions	**%**	**Base**	18.282.479,57 €	17.881.066,70 €	
Gen.Documentation, Health & Safety, Project Supervision	3,10%		566.756,87 €	554.313,07 €	
Total budget for the Scenario			**18.849.236,44 €**	**18.435.379,77 €**	-2,20%

Spain. León-Guardo. Regional

On the León-Guardo line, the study has been carried out exclusively on the section between León and Matallana. The rest of the route is not taken into account because the simulations have focused exclusively on this section, therefore not having the details of the necessary changes between both deployments.

For this reason, it should be noted that the cost of the chapter dedicated to ERTMS, if a whole analysis is achieved, would be shared with the rest of the currently excluded section of the line, and the additional costs would have to be considered for the rest of the items.

For the track section under analysis, the ETCS-L2 has 32 axle counters and the HTD deployment only 17.

Interne

Table 56. CAPEX for Signalling León Guardo ES A5.4.

Signalling		ETCS-L2		HTD	
		€/km	Estimated	€/km	Estimated
Equipment, cabling, signalling and field works		94.845,33 €	2.815.673,37 €	94.845,33 €	2.815.673,37 €
Engineering		5.441,77 €	161.549,81 €	8.162,65 €	242.324,72 €
Test & Integration		5.305,89 €	157.516,10 €	7.958,84 €	236.274,16 €
Estimated HTD Track Circuit Saving					
Track Circuits Difference	67,87 %	Over 2.815.673,37 €			-290.366,32 €
	%	**Subtotal**	3.134.739,29 €	**Subtotal**	3.003.905,93 €
RAMS for Signalling	1,13%		35.505,38 €		34.023,50 €
Signalling Documentation and Courses	1,38%		43.103,82 €		
Total budget for Signalling			**3.213.348,48 €**		**3.079.234,25 €**

Table 57. CAPEX for Train Protection System León Guardo ES A5.4.

Train Protection System		ETCS-L2		HTD	
		€/RBC	estimated	€/RBC	Estimated
ERTMS & Legacy		5.431.840,74 €	5.431.840,74 €	5.431.840,74 €	5.431.840,74 €
Engineering		812.175,77 €	812.175,77 €	974.610,93 €	974.610,93 €
Test & Integration		317.172,46 €	317.172,46 €	634.344,92 €	634.344,92 €
	%	**Subtotal**	6.561.188,98 €	**Subtotal**	7.040.796,59 €
RAMS for TPS	1,30%		85.190,77 €		91.418,01 €
TPS Documentation and Courses	0,57%		37.640,61 €		40.392,05 €
Total budget for Train Protection System			**6.684.020,35 €**		**7.172.606,65 €**

Table 58. CAPEX for Centralised Traffic Control León Guardo ES A5.4.

Centralised Traffic Control		ETCS-L2		HTD	
		€/km	estimated	€/km	Estimated
CTC		1.151,52 €	34.185,14 €	1.151,52 €	34.185,14 €
Software Engineering		1.964,84 €	58.330,13 €	2.357,80 €	
Test & Integration		546,75 €	16.231,46 €	546,75 €	16.231,46 €
	%	**Subtotal**	108.746.73 €	**Subtotal**	120.412,75 €
RAMS for CTC	1,03%		1.115,66 €		1.235,35 €
CTC Documentation and Courses	3,30%		3.585,83 €		3.970,50 €
Total budget for Centralised Traffic Control			**113.448,22 €**		**125.618,61 €**

Table 59. Comparison Summary for Commuter León Guardo ES A5.4.

ETCS-L2 vs HTD Budget			ETCS-L2	HTD	HTD/L2
Signalling			3.213.348,48 €	3.079.234,25 €	-4,17%
Train Protection System			6.684.020,35 €	7.172.606,65 €	7,31%
Centralized Traffic Control			113.448,22 €	125.618,61 €	
Environmental Actions Gen.Documentation, Health & Safety, Project Supervision	%	Base	10.010.817,06 €	10.377.459,51 €	
	3,10%		310.335,33 €	321.701,24 €	
Total budget for the Scenario			**10.321.152,38 €**	**10.699.160,75 €**	3,66%

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5.1.6.3 Greenfield scenarios in France

France. Bretagne Pays de Loire

For this line the ETCS-L2 has 260 axle counters and the HTD deployment only reduces the number to 182.

Table 60. CAPEX for Signalling Bretagne Pays de Loire FR S2.2.

Signalling		ETCS-L2		HTD	
		€/km	Estimated	€/km	Estimated
Equipment, cabling, signalling and field works		101.061,94 €	21.425.132,04 €	101.061,94 €	21.425.132,04 €
Engineering		5.798,45 €	1.229.271,15 €	8.697,67 €	1.843.906,72 €
Test & Integration		5.653,67 €	1.198.577,71 €	8.480,50 €	1.797.866,57 €
Estimated HTD Track Circuit Saving					
Track Circuits Difference	17,27 %	Over 21.425.132,04 €			-814.155,02 €
	%	**Subtotal**	23.852.980,91 €	**Subtotal**	24.252.750,32 €
RAMS for Signalling	1,13%		270.168,90 €		274.696,86 €
Signalling Documentation and Courses	1,38%		327.987,29 €		333.484,27 €
Total budget for Signalling			**24.451.137,10 €**		**24.860.931,44 €**

Table 61. CAPEX for Train Protection System Bretagne Pays de Loire FR S2.2.

Train Protection System		ETCS-L2		HTD	
		€/RBC	estimated	€/RBC	Estimated
ERTMS & Legacy		5.787.869,28 €	5.787.869,28 €	5.787.869,28 €	5.787.869,28 €
Engineering		865.409,62 €	865.409,62 €	1.038.491,54 €	1.038.491,54 €
Test & Integration		337.961,44 €	337.961,44 €	675.922,89 €	675.922,89 €
	%	**Subtotal**	6.991.240,34 €	**Subtotal**	7.502.283,70 €
RAMS for TPS	1,30%		90.774,57 €		97.409,98 €
TPS Documentation and Courses	0,57%		40.107,75 €		43.039,53 €
Total budget for Train Protection System			**7.122.122,66 €**		**7.642.733,22 €**

Table 62. CAPEX for Centralised Traffic Control Bretagne Pays de Loire FR S2.2.

Centralised Traffic Control		ETCS-L2		HTD	
		€/km	estimated	€/km	Estimated
CTC		1.227,00 €	260.122,94 €	1.227,00 €	260.122,94 €
Software Engineering		2.093,62 €	443.847,88 €	2.512,35 €	532.617,46 €
Test & Integration		582,59 €	123.509,05 €	582,59 €	123.509,05 €
	%	**Subtotal**	827.479.87 €	**Subtotal**	916.249,45 €
RAMS for CTC	1,03%		8.489,35 €		9.400,07 €
CTC Documentation and Courses	3,30%		27.285,40 €		30.212,50 €
Total budget for Centralised Traffic Control			**863.254,63 €**		**955.862,02 €**

Table 63. Comparison Summary for Bretagne Pays de Loire FR S2.2.

ETCS-L2 vs HTD Budget	ETCS-L2	HTD	HTD/L2
Signalling	24.451.137,10 €	24.860.931,44 €	1,68%
Train Protection System	7.122.122,66 €	7.642.733,22 €	7,31%
Centralized Traffic Control	863.254,63 €	955.862,02 €	10,73%

Environmental Actions Gen.Documentation, Health & Safety, Project Supervision	%	Base	32.436.514,39 €	33.459.526,68 €	
	3,10%		1.005.531,95 €	1.037.245,33 €	
Total budget for the Scenario			**33.442.046,33 €**	**34.496.772,01 €**	3,15%

5.1.6.4 Greenfield scenarios in Sweden

In this comparison between the ETCS-L2 and HTD deployments, no modifications to the track circuits were planned, according to the simulations. The following tables summarize the economic estimates for the items considered.

Table 64. CAPEX for Signalling Stockholm Citybanan SW S1.0.

Signalling		ETCS-L2		HTD	
		€/km	Estimated	€/km	Estimated
Equipment, cabling, signalling and field works		107.782,60 €	1.293.391,26 €	107.782,60 €	1.293.391,26 €
Engineering		6.184,05 €	74.208,58 €	9.276,07 €	111.312,87 €
Test & Integration		6.029,64 €	72.355,68 €	9.044,46 €	108.533,52 €
	%	**Subtotal**	1.439.955,51 €	**Subtotal**	1.513.237,64 €
RAMS for Signalling	1,13%		16.309,54 €		17.139,57 €
Signalling Documentation and Courses	1,38%		19.799,92 €		20.807,58 €
Total budget for Signalling			**1.476.064,97 €**		**1.551.184,78 €**

Table 65. CAPEX for Train Protection System Stockholm Citybanan SW S1.0.

Train Protection System		ETCS-L2		HTD	
		€/RBC	estimated	€/RBC	Estimated
ERTMS & Legacy		6.172.764,99 €	6.172.764,99 €	6.172.764,99 €	6.172.764,99 €
Engineering		922.959,72 €	922.959,72 €	1.107.551,66 €	1.107.551,66 €
Test & Integration		360.436,02 €	360.436,02 €	720.872,04 €	720.872,04 €
	%	**Subtotal**	7.456.160,72 €	**Subtotal**	8.001.189.69 €
RAMS for TPS	1,30%		96.811,12 €		103.887,79 €
TPS Documentation and Courses	0,57%		42.774,93 €		45.901,68 €
Total budget for Train Protection System			**7.595.746,78 €**		**8.150.978,16 €**

Table 66. CAPEX for Centralised Traffic Control Stockholm Citybanan SW S1.0.

Centralised Traffic Control		ETCS-L2		HTD	
		€/km	estimated	€/km	Estimated
CTC		1.308,59 €	15.703,09 €	1.308,59 €	15.703,09 €
Software Engineering		2.232,85 €	26.794,19 €	2.679,42 €	32.153,02 €
Test & Integration		621,33 €	7.455,99 €	621,33 €	7.455,99 €
	%	**Subtotal**	49.953,26 €	**Subtotal**	55.312,10 €
RAMS for CTC	1,03%		512,48 €		567,46 €
CTC Documentation and Courses	3,30%		1.647,16 €		1.823,87 €
Total budget for Centralised Traffic Control			**52.112,91 €**		**57.703,43 €**

Table 67. Comparison Sumary for Stockholm Citybanan SW S1.0.

ETCS-L2 vs HTD Budget	ETCS-L2	HTD	HTD/L2
Signalling	1.476.064,97 €	1.551.184,78 €	5,09 %
Train Protection System	7.595.746,78 €	8.150.978,16 €	7,31 %

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Centralized Traffic Control			52.112,91 €	57.703,43 €	10,73 %
Environmental Actions Gen.Documentation, Health & Safety, Project Supervision	%	Base	9.123.924,66 €	9.759.866,37 €	
	3,10%		282.841,66 €	302.555,86 €	
Total budget for the Scenario			**9.406.766,33 €**	**10.062.422,22 €**	6,97 %

5.2 ANALYSIS RELATED ROLLING STOCK

This section examines the costs related to the adaptation of rolling stock to meet the minimum requirements for operation with an HL3/HTD system, considering both CAPEX (initial investment) and OPEX (recurring operational costs)

The main cost for the rolling-stock CAPEX is the installation of TIMS in all the units. Having this system is mandatory to be able to take full advantage of the new HTD technology; without it, or without its full deployment, some benefits could be perceived, but only with its full implementation could the new capacity of the network be exploited to the fullest.

5.2.1 Fleet under analysis

The first considered information is the fleet affected for this modification, the number of rolling-stock units to be modified is a sensible parameter because the final project cost is strongly linked to the size of the deployment.

According to assumption A-17, some of the fleets have been estimated using the round-trip duration and the maximum headway of the line, adding to this a percentage of reserve units.

Only some scenarios are included in this part of the analysis, discarding those that, because they are small sections of line with interest mainly from the point of view of the infrastructure, do not justify analysing the costs of the entire fleet that uses them.

The following table summarizes the number of elements considering in every single selected line. Where Total Evo is the number of trains that has evolved to TIMS for each case study, when the fleet size is an estimate based on a previously established criterion, it is reflected as the sum of the maximum number of trains plus the reserve trains.

Table 68. Number of trains for retrofit per line.

Line	Country	High Speed	Commuter	Other	Total Evo
SAAL Corridor	Neederlands	86	102	-	188
Flevo Line	Neederlands				
Cercanías C5 Madrid	Spain	-	41+5	-	46
Barcelona-Figueras	Spain	6+1	-	-	7
León-Guardo	Spain	-	-	11+2	13
Lille	France	-	13+2	-	15
LNOBPL	France	4	4	5	13+4
Citybanan	Sweden	-	6+1	-	7

5.2.2 CAPEX Analysis for Rolling Stock

Different sources offer different costs for the TIM installation on a train:

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- "Cost–Benefit Analysis for the Track Occupancy Concept", EUG and EULYNX partners. 31/01/2023 [10]: 10.000,00 €.
- Aoun, J., Quaglietta, E., Goverde, R. M. P., Jack, A., Blumenfeld, M., Redfern, B., Bosse, G., Pelster, L., Scheidt, M., & Söser, S. (2020). Cost-Effectiveness Analysis for Virtual Coupling. European Commission. [11]: 24.000,00 €.

For this analysis a cost of 20.000,00 € for each TIM equipment totally installed and tested for every unit of the fleet is used.

As TIMS offers a new functionality, the EVC needs to be updated. Based on the information provided by [08], *D15.1 – HL3 System Specification with Identification of Use Cases and Related Engineering Rules,* the following requirements have been identified for onboard equipment to operate with HL3/HTD systems. In this context, the reference is always to new equipment compliant with the requirements set out in ETI CMS 2023/1695, i.e., Baseline 4 equipment:

- System Version 2.1 is expected to cover all functionalities of System Version 3.0, except for Supervised Manoeuvre, FRMCS usage, ATO operation, and other enhancements.
- System Version 2.2 is expected to cover all functionalities of System Version 3.0, except for Supervised Manoeuvre, FRMCS usage, and other enhancements.

Additionally, based on the technical documents Principles: ERTMS/ETCS Hybrid Train Detection and Engineering Guideline: ERTMS/ETCS Hybrid Train Detection Engineering published by the EEIG ERTMS Users Group, the following requirements apply to equipment that is not Baseline 4:

- For Baseline 3 R2 (3.6.0) equipment, System Version 2.1 is compatible if Change Requests (CR) 940 and 1304 are implemented.
- For Baseline 3 MR1 (3.4.0) equipment, System Version 2.0 is not compatible due to non-compliance with HL3/HTD safety requirements.
- For Baseline 2 equipment, System Version 1.x is considered obsolete and not analysed for HL3/HTD usage.

Based on this information, the following ETCS equipment migration scenarios are considered:

- Vehicles without ETCS: require full installation of new equipment compliant with ETI CMS 2023/1695, at least Baseline 4 Version 2.1.
- Vehicles with ETCS Baseline 2, System Version 1.x: require full installation of new equipment compliant with ETI CMS 2023/1695, at least Baseline 4 Version 2.1.
- Vehicles with ETCS Baseline 3 MR1 (3.4.0), System Version 2.0: require analysis of two options:
    - Software and hardware upgrade to Baseline 4 Version 2.1 or alternatively to B3 R2 Version 2.1 with CR 940 and CR 1304.
    - If a version upgrade is not feasible, full installation of new equipment compliant with ETI CMS 2023/1695, at least Baseline 4 Version 2.1.

As observed, the available options involve assessing the feasibility of software or hardware upgrades or the complete installation of new equipment that meets at least the Baseline 4 Version 2.1 requirements.

Nevertheless, and for simplicity since it is expected that this type of improvement will not come independently, a single cost of 60.000,00 € for the EVC update is considered.

The information obtained from Renfe retrofitting rolling stock projects gives us an average of 40.000,00 € for project and engineering and for a fleet of 100 units.

As in the infrastructure analysis, some general items that increase the final cost are added. The next table offers these figures.

Table 69. CAPEX for the Rolling Stock

Element	Unit	Cost/Unit	Total per train
TIM	1 per train	20.000,00 €	20.000,00 €
EVC update	1 per train	60.000,00 €	60.000,00 €
Engineering Project	100 trains project	40.000,00 €	400,00 €
Environmental, Courses, documentation, Project Supervision, Safety & Health	Previous items (5%)	80.400,00 €	4020,00 €
Total cost for a single rolling stock			**84.420,00 €**

5.2.3 CAPEX Analysis results for Rolling-Stock retrofitting

In accordance with the adjustments made in the case of infrastructure, the same price corrections are applied to rolling stock between different countries (see Table 1. EUROSTAT information index according to [04] and [05]), so the following table indicates the unit cost for each line and the total depending on the size of its fleet for its retrofitting.

Table 70. Total Rolling Stock retrofitting Budget

Line	Fleet	Unit	Total for Rolling Stock
SAAL Corridor	188	99.075,73 €	18.626.237,38 €
Flevo Line			
Cercanías C5 Madrid	46	84.420,00 €	3.883.320,00 €
Barcelona-Figueras	7	84.420,00 €	590.940,00 €
León-Guardo	13	84.420,00 €	1.097.460,00 €
Lille	15	89.953,29 €	1.349.299,29 €
LNOBPL	17	89.953,29 €	1.529.205,86 €
Stockholm Citybanan	7	95.935,22 €	671.546,52 €

6 COMPENDIUM OF RESULTS

6.1 COMPENDIUM OF RESULTS FOR INFRASTRUCTURE CAPEX OPEX ANALYSIS

In summary, it can be observed that a high percentage of the cost of ERTMS deployment is directly related to the number of RBCs put into service, even though these have a direct relationship with the number of trains to be managed and the length of track served. Optimizing the area of these elements is very important to optimize the investment.

The savings options, as observed in all scenarios where track circuit reductions have been implemented, are few from the perspective of maintenance or energy consumption reduction by the removed components. Remember, that the maintenance analysis has not considered reactive maintenance, because its characteristics make it difficult to reduce its cost. Generally, response time constraints, especially in large areas, prevent reducing the equipment used for maintenance, and

logistical issues related to obtaining spare parts for the various crews also hinder the anticipated significant savings.

In greenfield scenarios, and due to the deployment cost of the different train detection elements, and to a greater extent in the case of track circuits which have a higher cost than axle counters, it is possible that the estimated increases for HTD in the specific application, engineering and testing work and commissioning, may be offset. Price variations of HTD deployment compared to ETCS-L2 are observed from -2.6% to 7%, the former being where the greatest difference between detection systems is implemented between both technologies.

6.1.1 Estimation of cost per Kilometre. ETCS L2 to HTD Migration

This part of the study aims to identify the cost per kilometer for an ETCS L2 migration to HTD. To do this, a weighted average of all the previous analyses in this document is calculated. Unlike the economic calculations for each scenario, which applied the estimated cost based on the Spanish base price and adjusted by the Eurostat indices, this section uses Spanish reference prices for all scenarios, thus obtaining a normalized average per kilometer. To obtain the data for each country, the Eurostat index is then applied to this average.

It is important to note that, mainly due to the sector's lack of experience in projects of this type, the calculation of this value has the assumptions and limitations detailed in the section 2.2.1 Assumptions and limitations and that, given the heterogeneity of the lines and their characteristics and having a small sample, it has a low likelihood.

The next table shows the results from the different scenarios including the track kilometres and the CAPEX for the migration; remember that those prices are based on reference Spanish costs. This weighted average gives us a result of **36.774,38 €/km**.

Table 71. Weighted average CAPEX per km (Spanish prices reference)

ID	Line	Track km	CAPEX
NL I1-S	SAAL Corridor	291,515	8.396.758,78 €
NL I4-S			8.409.687,34 €
NL I1-F	Flevo Line	65,462	4.728.658,95 €
NL I4-F			4.731.531,96 €
ES A1.4	Túnel Atocha-Chamartín	16,1	2.947.816,90 €
ES A2.4	Madrid C5 Cercanías	103,5	8.651.307,83 €
ES A3.2	HS Atocha-Torrejón Velasco	82,8	3.026.420,59 €
ES A4.1	Barcelona-Figueras	311,551	5.764.711,20 €
ES A5.4	León-Guardo	29,687	2.329.232,15 €
ES A6.2	Lérida-Reus	104,897	9.530.666,73 €
ES A7.1	Cercanías Barcelona	19,305	2.885.664,50 €
FR S1.1	Lille	98	2.282.175,00 €
FR S2.1	Bretagne Pays de Loire	212	4.126.047,45 €
FR S2.2			4.128.920,47 €
SW S1.0	Stockholm Citybanan	12	1.084.650,00 €
SW S3.0	Southern Mainline	158	3.253.950,00 €
Weighted average per km (2.076,094)			**36.774,38 €**

The OPEX savings due to the TTD retrofit is showed in the next table, and, as in the CAPEX per Kilometre, a weighted average is calculated (estimated for a year), the results are, for the preventive maintenance 254,08 €/km, and due to energy consumption 60,71 €/km.

Table 72. Weighted average OPEX per km (Spanish prices reference)

ID	Line	Track km	Maintenance	Energy
NL I1-S	SAAL Corridor	291,515	85.500,00 €	18.574,70 €
NL I4-S			101.700,00 €	22.094,12 €
NL I1-F	Flevo Line	65,462	20.850,00 €	4.529,62 €
NL I4-F			24.450,00 €	5.311,71 €
ES A1.4	Túnel Atocha-Chamartín	16,1	8.256,00 €	2.433,18 €
ES A2.4	Madrid C5 Cernanías	103,5	52.500,00 €	15.576,68 €
ES A3.2	HS Atocha-Torrejón Velasco	82,8	30.048,00 €	8.663,72 €
ES A5.4	León-Guardo	29,687	5.580,00 €	1.629,36 €
FR S2.1	Bretagne Pays de Loire	212	8.100,00 €	1.759,71 €
FR S2.2			11.700,00 €	2.541,60 €
		Weighted average per km	**254,08 €**	**60,71 €**

According to the EUROSTATS indexes used along these documents, for domestic industrial activities [04], labour costs [05] and electricity prices for non-household consumers [09], the following table provides the result for each country based on the average data obtained above.

Table 73. Average estimation for CAPEX and OPEX per km (Countries under analysis).

Country/Zone	CAPEX/km	Maintenance/km	Energy/km
Euro area	39.785,72 €	276,69 €	79,02 €
European Union	39.451,10 €	283,35 €	76,38 €
France	40.254,18 €	258,29 €	67,17 €
Netherlands	44.336,48 €	327,02 €	79,95 €
Spain	37.778,03 €	254,08 €	60,71 €
Sweden	42.931,10 €	272,26 €	46,90 €

6.2 Economic Value of the Benefits

From an economic point of view, and in order to develop a business case with a return on investment that justifies the investment, it is not possible to consider only the factors applied in these partial analyses, both in the case of migrations and greenfield scenarios.

The following graph shows an example of the NL I4-2 scenario, SAAL Corridor with maximum TTD reduction in the Netherlands. It can be seen that for three inflation indices applied to maintenance and energy savings, only the most economically unfavourable scenario could offer a 30-year ROI. The remaining scenarios analysed in this document present more unfavourable figures.

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Figure 4. Return of Investment for SAAL Corridor with maximum TTD reduction.



Therefore, other measurable aspects must be established, such as the improvement of line capacity by reducing the headway and the possibility of increasing the slots available to the infrastructure manager to offer services to railway operators, and these the theoretical increase in passengers and goods in their operations.

Other non-economic benefits must be considered, which will need to be given an economic value in order to realize the return on investment, probably indirect benefits in other sectors and in the areas affected by the new infrastructure or the improvement of the existing one.

Beyond financial returns, rail projects strengthen environmental protection, social inclusion (cultural exchange, educational opportunities, etc.), and territorial balance, all of which are strategic priorities for Europe.

7 CONCLUSIONS

This deliverable has assessed the deployment of **ETCS Hybrid Train Detection / Hybrid Level 3 (HTD/HL3)** through a combined **qualitative** and **quantitative** life-cycle analysis, building on the methodologies, scenarios, and simulation results developed within WP37 of the FP2-R2DATO project. The assessment confirms that HTD/HL3 represents a **technically feasible and strategically relevant evolution** of ETCS Level 2, capable of delivering measurable benefits in terms of capacity, operational flexibility, and long-term efficiency, while also introducing significant challenges that must be carefully managed.

The results demonstrate that HTD/HL3 deployment is not a simple incremental upgrade, but a **system-level transformation** affecting signalling design, safety justification, operational rules, cost structures, and organisational processes. Consequently, its successful implementation requires a holistic and well-governed approach.

This chapter includes de summary of the conclusion of the qualitative analysis, qunatitative analysis and an overall conclusions outlook.

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7.1 Summary of Qualitative Findings

The qualitative product life-cycle analysis highlights that HTD/HL3 impacts **all system life-cycle phases**, from concept and requirements definition to validation, operation, maintenance, and decommissioning.

7.1.1 Key Functional and Lifecycle Challenges

TIMS fleet retrofitting: This is the most significant logistical and economic challenge. It involves taking rolling stock out of service for installation, which has a considerable operational impact and cost.

RBC software modification: This represents the greatest technical challenge, as it involves the large-scale redesign, development, and validation of safety-critical software.

Development and approval of the new Safety Case: This is the main regulatory and project challenge. It requires an immense documentation and engineering effort and is a critical milestone on which the authorization for entry into service depends.

7.1.2 Critical Success Factors for the Migration

Phased approach: A "big bang" migration is extremely risky. A gradual approach, implementing HTD in pilot areas and expanding progressively, allows for learning and correcting issues in a controlled manner.

Early stakeholder engagement: Close collaboration from the outset among the infrastructure manager, railway undertakings, technology suppliers, and the safety authority is essential to align expectations, requirements, and plans.

Robust training program: The ultimate operational success depends on all personnel (drivers, controllers, maintainers) understanding and trusting the new technology. Investment in training and change management is therefore indispensable. The Virtual Subsection (VSS), as a component of Trackside Train Detection systems, has a threefold impact on the ETCS-TS specific application design and development:

Management of VSS as a new topologic entity: The new entity should be incorporated into the topologic data modelling tool either manually or automatically:

- **Manually**: The user is required to characterize the VSS in terms of its length, limits, and placement according to a pre-established methodology, e.g., FP2-R2DATO D37.2 Methodology for optimised placement of (virtual) blocks [01]. This approach means that a functional upgrade of the modelling tool is necessary.
- **Automatically**:
    - Specific modelling rules to identify when the length of the VSS equals that of the TTD (VSS=TTD)
    - Specific modelling rules that define the breakdown of TTD into a certain number of VSS in compliance with a pre-established methodology, e.g., FP2-R2DATO D37.2 Methodology for optimised placement of (virtual) blocks [01]. These rules can be configured by the user.

Likewise, this approach means that a functional upgrade of the modelling tool is necessary.

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Compilation of ETCS-TS configuration files, which need adapting to new binary blocks (code) or to the evolution of predefined ones.

Additional laboratory and on-site tests to validate operational rules and check the coherency of data across the whole system.

7.2 Main Quantitative Results

The quantitative analysis confirms that HTD/HL3 deployment requires **significant initial investment**, particularly in signalling system upgrades and rolling-stock retrofitting. However, these costs may be offset in the medium to long term by **reduced OPEX**, improved capacity utilisation, and lower energy consumption.

The economic outcome is **strongly context-dependent**, with high-density and capacity-constrained lines showing the most favourable return profiles. Conversely, low-traffic lines may require broader strategic justification beyond direct cost savings. Next table summarises the principal quantitative results derived from the scenarios analysed in this deliverable.

Table 74. Summary of main quantitative results for ETCS L2 to HTD/HL3 deployment

Aspect	Result / Order of Magnitude	Scope / Notes
CAPEX for HTD/HL3 migration (infrastructure)	**36.774,38 €/km**	Weighted average across analysed migration scenarios (Spanish reference prices, Eurostat adjustment applied)
CAPEX for HTD/HL3 greenfield deployment (increment vs L2)	**Range between ≈ - 3% to 7%**	Difference between HTD/HL3 and ETCS L2 CCS elements only
OPEX savings – preventive maintenance	**254,08 €/km**	Mainly driven by reduction of TTD (axle counters, track circuits)
OPEX savings – energy consumption	**60,71 €/km**	Due to dismantling of powered trackside detection equipment
Typical payback horizon (infrastructure OPEX only)	**≈ [10–20] years**	Highly dependent on traffic density and reduction level of TTD
Rolling-stock CAPEX (TIMS + EVC update)	**≈ [80–100] k€ per vehicle**	Average value including engineering and ancillary costs
Share of rolling-stock CAPEX in total system investment	**≈ [30–50] %**	Strongly dependent on fleet size and infrastructure length
Highest benefit scenarios	**High-density commuter and mixed-traffic lines**	Capacity-constrained corridors show best cost-benefit profile
Lowest benefit scenarios	**Low-density regional/main lines**	Benefits mainly strategic rather than purely economic

7.3 Overall Conclusions and Outlook

The assessment confirms that **ETCS HTD/HL3 is a viable and valuable evolution path** for the European railway signalling system, offering clear benefits when deployed under suitable operational and organisational conditions. Its implementation should be treated as a **strategic transformation programme**, addressing technical, economic, regulatory, and human-factor dimensions in a coordinated manner.

Future work should prioritise:

- Validation through real-world pilot deployments.
- Further harmonisation of safety and operational rules at European level.
- Progressive consolidation of cost benchmarks.
- Continued alignment with HL3 standardisation and specification activities.

Overall, HTD/HL3 emerges as a **key enabler for future railway**, supporting higher capacity and improved efficiency.

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