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1 Executive Summary

The objective of X2Rail-3 (Grant Agreement No. 826141) Task 7.5 is an analysis of the business model for the Virtually Coupled Train Sets (VCTS) concept. The VCTS concept was developed in X2Rail-3 Work Packages 6 and 7. The MOVINGRAIL project, which was the only project funded under the IP2 open call S2R-OC-IP2-01-2018, provided inputs concerning the cost effectiveness, application roadmap as well as business risks and overall market potential of VCTS. This deliverable (D7.5) is the outcome of Task 7.5. First, it provides an analysis of the inputs provided by MOVINGRAIL, putting them in context with previous X2Rail-3 work. Then, taking the conclusions of the analysis into account, two different application cases for VCTS are presented. Strategies to implement the application cases are detailed, including a vision for implementing VCTS within the RCA and OCORA reference architectures. Finally, the business case of VCTS is compared against business objectives identified within the LinX4Rail project.

The application cases for VCTS presented in this deliverable are *standalone VCTS and ETCS-based VCTS*. Standalone VCTS is an application of VCTS that focuses on low-traffic lines that are today using Class B signalling systems that cannot be upgraded to ETCS in a cost-effective way. In summary, it is a low-cost onboard train protection system which has the objectives of providing an economically interesting upgrade path for Class B systems and raising the maturity of the underlying technology required for VCTS, thus, fostering the wide-scale introduction. ETCS-based VCTS is an application of VCTS that focuses on high-traffic lines and bases on ETCS Level 2 or Level 3. ETCS-based VCTS is the actual goal of the VCTS concept and has the main objectives of reducing headway and improving flexibility of operation in order to increase line capacity and provide the technical basis for innovative business models.

For each application case, a migration strategy is presented, detailing the non-technical and technical steps required for implementing and on-site testing a first complete demonstrator within a period of three to five years. The migration strategies provide details for train protection, traffic management, automatic train operation, on-board train integrity, communication and VCTS (on-board and trackside, if applicable) sub-systems. As detailed in Deliverable 7.4 “Impact Analysis” which was prepared in parallel to this deliverable, the introduction of VCTS does not change the fundamental principles of any of the existing sub-systems, i.e., a full rework is not required.

Beyond the migration strategies, the vision of implementing ETCS-based VCTS within the RCA and OCORA reference architectures is presented, which would imply software changes only and, thus, simplify the migration considerably. Finally, the impact of VCTS is compared against the business objectives identified in the LinX4Rail project. Taking the presented migration strategies and MOVINGRAIL input into account, it is shown that VCTS is in line with the RUs’, IMs’ and suppliers’ business objectives.

Ultimately, VCTS is an innovative concept that can raise scepticism by operators and the general public. Its safety can be achieved within the near future, but this needs to be communicated clearly to foster the acceptance of VCTS. Only then, VCTS cannot only improve current railway operation with increased capacity, reliability and lower operational costs, but even provide the basis for novel business models that benefit from the increased flexibility.

2 Table of Contents

2.1 Summary of Chapters

2.2 Index of Figures

3 Abbreviations and Acronyms

Abbreviation / Acronyms	Description
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CBTC	Communication-Based Train Control
CCS	Control Command and Signalling
DMI	Driver Machine Interface
EoA	End of Authority
ERA	European Railway Agency
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EUG	ERTMS Users Group
EVC	European Vital Computer
FRCMS	Future Rail Communication Management System
GA	Grant Agreement
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
GPS	Global Positioning System
GSM-R	Global System for Mobile Communications – Rail(way)
IM	Infrastructure Manager
IP	Innovation Program
IXL	Interlocking
I2I	Infrastructure to Infrastructure
JRU	Juridical Recording Unit
LTE	Long Term Evolution
MA	Movement Authority
MC	Mechanical Coupling
MCTS	Mechanically Coupled Train Set
OB	On Board
OTI	On Board Train Integrity
RAMS	Reliability, Availability, Maintainability, Safety
RBC	Radio Block Centre
RU	Railway Undertaking
S2R	Shift2Rail
SIL	Safety Integrity Level
SRS	System Requirements Specification
STM	Specific Transmission Module
SW	Software
T2G	Train to Ground
T2T	Train to Train
TCMS	Train Control and Monitoring System
TD	Technical Demonstrator
TI	Train Integrity

TMS	Traffic Management System
TRL	Technology Readiness Level
TS	Trackside
TSI	Technical Specifications for Interoperability
UNISIG	Union Industry of Signalling
VCTS	Virtually Coupled Train Sets
WP	Work Package

4 Background

The present document constitutes the first issue of Deliverable D7.5 “Business Model” in the framework of the Project titled “Advanced Signalling, Automation and Communication System (IP2 and IP5) – Prototyping the future by means of capacity increase, autonomy and flexible communication” (Project Acronym: X2Rail-3; Grant Agreement No 826141 [1]).

4.1 Aim of this document

This document was prepared to provide an insight into the business model of Virtually Coupled Train Sets (VCTS), covering the introduction and operation of this innovative concept. The concept itself was developed in work packages 6 and 7 of the Shift2Rail project X2Rail-3. More specifically, deliverables 6.1 “VCTS Concept and Application condition analysis” [2] and 6.2 “Performance and Safety Analysis” defined the functions of VCTS, identified operational scenarios and hazards. The resulting VCTS concept was further analysed and specified in the subsequent deliverables 7.1 “Feasibility Analysis” [3], 7.2 “System Functional Architecture Specification” [4] and 7.3 “System Functional and non-Functional Requirements Specification” [5].

This document consists of two main parts: First, the evaluation of the results of the Shift2Rail open call S2R-OC-IP2-01-2018 “Analysis for Moving Block and implementation of Virtual Coupling concept” under which the business case of VCTS was analysed. The second part presents the strategy and vision for the implementation of VCTS. Two application cases are presented that have different objectives: Standalone VCTS and ETCS-based VCTS. Standalone VCTS aims to provide an economically interesting upgrade path for Class B systems that at the same time fosters the widescale introduction of VCTS by raising the maturity of the underlying technologies. The ETCS-based application case has the objectives to increase the capacity of the railway network and provide improved flexibility of service, it describes the application case of VCTS that the concept was designed for.

4.2 Further project information

The “Advanced Traffic Management & Control Systems” pillar (IP2) focuses on control, command and communication systems and tackles the Shift2Rail (S2R) objectives. These include evolving requirements for new functionalities and expanding the level of standardization in an increasingly challenging economic climate.

The IP2 challenge is to increase functionalities of the existing signalling and automation systems as well as related design and validation processes, thus, providing a more competitive, flexible, real-time, intelligent traffic control management and decision support system. This is to be achieved whilst addressing all four market segments (High speed, Regional, Metro and Freight) and maintaining backward compatibility to the existing European Rail Traffic Management System (ERTMS) and especially its European Train Control System component (ETCS).

Within this program, the S2R-project X2Rail-3 aims to continue the research and development of key technologies to foster innovations in the field of railway signalling, telecommunication, testing methodologies and cyber security, as part of the longer term Shift2Rail IP2 strategy mentioned above.

X2Rail-3 targets a number of different innovation streams (Technical Demonstrators – TD), focussing on different aspects of the signalling and automation systems. Within these, two dedicated work packages (WP6 and WP7) aim to investigate an innovative concept of Virtual Train Coupling, capable of operating physical traction units at distances below absolute braking distance and providing the basic functionalities to dynamically modify their own composition on the move.

4.3 VCTS Concept of X2Rail-3

This section summarized the virtually couples train sets (VCTS) concept as defined in WP6 and WP7 of X2Rail-3.

4.3.1 Concept Overview

In today's operation, typical implementations of train signalling- and protection-systems are based on the absolute braking distance of the trains, utilizing either a **fixed blocks** approach or planning to utilize the **moving blocks** approach. These are the two most common philosophies currently applied in worldwide railway operation:

- With **fixed blocks** (e.g., ETCS Level 1 / Level 2), the track is divided into several sections and train movements are authorized up to the entry point of the next occupied section. Trains set their target for stopping, also called End of Authority (EoA) at the beginning of the next occupied section. This solution does not maximize the railway capacity, as a whole section is blocked even if the trains is about to leave the block.

- The **moving blocks** approach (e.g., ETCS Level 3) tries to overcome some limitations of fixed blocks by setting the EoA directly at the rear end of the next train on the track. In this concept, trains must be able to 1) safely determine their own rear end position and 2) update their position to the signalling system continuously. Therefore, reliable, precise and continuous train integrity validation, vehicle location and communication are necessary.

Although current systems have been optimized for line capacity, both cases leave room for improvements due to the absolute braking distance approach. Even for moving block, while setting the EoA at the rear end of the front train, it is considered that the following train must be able to brake assuming that the first train stops instantaneously, regardless of its current speed and braking curve.

Utilizing that potential, the next step is the virtual coupling, where trains exchange its braking capabilities to follow cooperative (and ideally regularly updated) braking curves, which allows trains to move much closer to each other and even couple and decouple dynamically (detailed below).

In common signalling and train protection systems, trains are never allowed to drive closer than their absolute braking distance. To allow backward compatibility, a group of trains that are virtually coupled with each other (a *virtually coupled train set*, VCTS) must be seen as one single train by the current signalling system, analogous to a mechanically coupled train.

4.3.2 Train Sets

4.3.2.1 Mechanically Coupled Train Sets

A mechanically coupled train set, or MCTS (see Figure 4-1), is a set formed of two or more trains that can also drive independently. The MCTS is based on the mechanical coupler, the device that connects the trains mechanically and serves as a bridge to transfer force, information and often also pressure for the pneumatic brakes.

Traditionally, in mechanically coupled trains the coupler performs two basic functions. **Keeping the relative position between the coupled units fixed** as well as **transmission of information** for braking the train co-ordinately. Most modern mechanical coupling systems are combined with additional functions, such as transfer of additional information electrically or pneumatically as well as collision mitigation systems.

The coupling and decoupling procedures of mechanically coupled trains are well-established in the railway system. The definition, where and when trains are joined and separated, is based on their compatibility, destinations and schedules. Coupling is done with one train in standstill and the other one approaching at low speed (driving on sight) until the mechanical connection between the trains is established. This can be done by manual interlocking of the mechanical connection by an operator or, in modern systems, by automatic coupling. The same is true for the connection of the air pressure pipe and additional data interfaces. Finally, the train integrity is checked and the train set can be baptized to be recognized as one single train by the signalling system. For decoupling, the steps are performed in the opposed order.

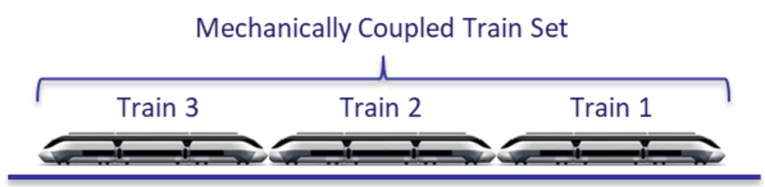


Figure 4-1 – Example of a mechanically coupled train set (train graphic by DLR, NGT Project)

4.3.2.2 Virtually Coupled Train Sets

The concept of virtually coupled train sets aims to replace the mechanical coupling established by conventional railway operation by a virtual link. It is based on the permanent, reliable and safe exchange of relevant information between the consists (trains) of a platoon and additionally with the TMS, signalling and interlocking system. Therefore, the moving units are aware of themselves and of their environment at all times. The concept is visualized in Figure 4-2.

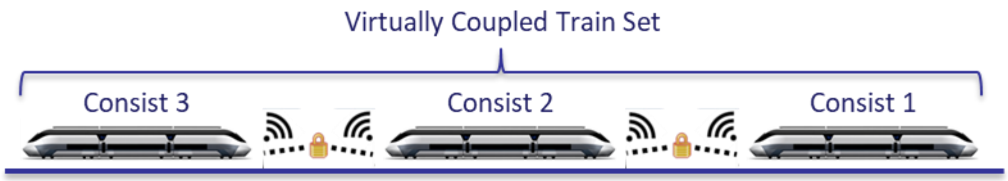


Figure 4-2 – Example of a virtually coupled train set

The shift to a virtual link means that trains within the platoon may have, at any time, different kinematic behaviours since no physical connection is implemented. The core of virtual coupling thus becomes the capability of maintaining a safe distance between trains which are not physically (mechanically, electrically and pneumatically) linked and, at the same time, to allow movements of trains as close as possible.

This distinction highlights that VCTS is not simply a mechanism to transfer controls and feedbacks from a master train to the slaves, but also a whole set of functions to supervise trains headway control, which needs to be implemented by means of a specific cooperation strategy between the trains of a virtually coupled platoon. Within the VCTS concept, the coupling procedures can be distinguished between the extremes of “pure static coupling” (analogous to mechanical coupling process at standstill) and dynamic coupling “on the fly” during the ride.

4.3.3 Goals and Benefits of VCTS

Considering the abovementioned remarks, several major benefits of the VCTS approach over the traditional railway operation scenario can be derived. Those advantages are listed below:

- Increase **line capacity** by reducing the headway
- Enhance **line efficiency and operational flexibility** by reduced coupling time and new consist building procedures
    - Consists can be established or dissolved while in operation
    - Faster consist building procedures
- Increased **robustness of schedule**
- Gaining **interoperability** between different vehicle:
    - Types
    - Models
    - Manufacturers
- Enabling vehicles to **operate in different signalling systems**
- Maximized **utilization of platforms** and **passenger comfort**
- Reduce global **investment-, maintenance- and operational costs**
    - Adding on-board and trackside signalling/electronic systems, instead of tracks or heavy changes of the infrastructure
    - Reduction of materials (cables, etc.) and therefore mitigation of weight- and design-constraints of rolling stock
    - Omission of manual coupling procedures or sidetracks

- Increase **competitiveness** in railway freight and passenger transportation against road transportation
- General support of the global Shift2Rail goal to address climate change

The available and utilized technology is the key driver regarding the achievable performance by VCTS in terms of network capacity, reliability, safety, etc. Depending on the selected technology, VCTS will be allowed to achieve different levels of performance. However, the minimum goal is to increase the line capacity to at least the ETCS Level 3 specification, while reaching an equal or better safety performance. Whichever the technical solution applied to implement VCTS is, it must comply in any case with the safety targets of the VCTS functions and the safety requirements of local authorities and the operating signalling system.

4.4 Shift2Rail Open Call S2R-OC-IP2-01-2018

One of the main aims of T7.5 is the evaluation of outcomes from the Shift2Rail Open Call S2R-OC-IP2-01-2018 that was part of the Shift2Rail Work Plan 2018[1] and closed for submissions in April of the same year. The topic of the call was “Analysis for Moving Block and implementation of Virtual Coupling concept”. Projects funded under this call were expected to define approaches for testing of Moving Block signalling systems, provide feedback on Moving Block Operational and Engineering rules and analyse the business case, communications structures and input from automated car driving for VCTS. Concerning the business case of VCTS, i.e., the relevant aspect for this deliverable, the activities of the funded projects were expected to cover (summarized, details can be found in the Shift2Rail Work Plan 2018):

- Identification of potential markets (as defined by the Multi Annual Action Plan) which can be interested to introduce VCTS.
- Cost/effective analysis assessing the potential benefits of VCTS application, from the point of view of an operator, highlighting pros/cons in terms of performances compared with the traditional train separation system (Fixed and Moving Block).
- For each market segment, provide the expected roadmap for the introduction of VCTS focusing the main business and market actions, necessary to foster the application of VCTS.
- For each market segment, identify the potential risks in terms of business due to the introduction of VCTS. Also providing actions, suggestions, mitigations in order to overcome the potential obstacles.

The only project funded under S2R-OC-IP2-01-2018 was MOVINGRAIL[2] “MOving block and VIrtual coupling New Generations of RAIL signalling” (Grant agreement ID: 826347). The project

[1] https://ec.europa.eu/research/participants/data/ref/h2020/other/wp/jtis/h2020-wp18-shift2rail_en.pdf

[2] https://movingrail.eu/

was funded from 1st of December 2018 until 31st of December 2020. The deliverables produced under Work Package 4 “Business Analysis of Virtual Coupling” are a main input of this deliverable and evaluated in Section 6.

4.5 Structure of the deliverable

The remainder of this document is structured as follows: Chapter 5 summarizes the objective as defined by Grant Agreement 826141. Chapter 6 evaluates the analyses of the business case of VCTS that were performed within the Shift2Rail open call S2R-OC-IP2-01-2018 and discusses the results in the context of X2Rail-3 WP7. Chapter 7 identifies two alternative application opportunities for VCTS based on the discussions of Chapter 6. Chapter 8 focuses on the first application case: *Standalone VCTS*, which is a limited application of VCTS targeting low-traffic lines that can even be seen as an intermediate step fostering *ETCS-based VCTS* that is analysed in Chapter 9. Finally, Chapter 10 concludes our findings.

5 Objective

The objective of D7.5, which is the result of T7.5, was defined by Grant Agreement 826141 as follows (full quote, highlights are ours):

- **T7.5 – Analysis of the Business Model**
  Together with a tight cooperation with the S2R-OC-IP2-01-2018 (Analysis for Moving Block and implementation of Virtual Coupling concept) the task aims:
    - to **check the outcomes** (Business Case) produced by the Open Call
    - to **analyse the best options and the strategic vision** to be adopted by the RU/IM and the Suppliers for fostering and introducing the VCTS.
- **D7.5 – Business Model**
  Output of Task 7.5. Document providing the **analysis of the application of VCTS in some selected markets including the best strategy and vision** which might foster the introduction of such innovative system.

The time duration of T7.5 was defined as month 30 to month 36 of X2Rail-3, i.e., May to November 2021, where D7.5 was due in month 35 (October 2021). This is the same duration as T7.4 / D7.4 “System Impact Analysis” which ran in parallel of T7.5 / D7.5. Due to the short amount of time and the parallelism of the tasks, inputs were shared between them but presented with different foci.

6 Business Case Evaluation of S2R-OC-IP2-01-2018

As detailed in Section 4.3.1, the MOVINGRAIL project, which is the only project funded under the open call S2R-OC-IP2-01-2018, is a main input of for this deliverable. This chapter evaluates the results of deliverables D4.1 to D4.4 of MOVINGRAIL, which were the output of WP4 “Business Analysis of Virtual Coupling”. The evaluation is done in comparison to the results of WP6 and WP7 of X2Rail-3, i.e., D6.1, D6.2 and D7.1, which are another main input of this deliverable.

Specifically, the deliverables from MOVINGRAIL reviewed in this chapter are:

- D4.1 “Market Potential and Operational Scenarios for Virtual Coupling” [6]
- D4.2 “Cost Effective Analysis for Virtual Coupling” [7]
- D4.3 “Application Roadmap for the Introduction of Virtual Coupling” [8]
- D4.4 “Business Risk Analysis of Virtual Coupling” [9]

The following Sections 6.1 to 6.5 provide a summary of the main definitions and results concerning the business case analysis of VCTS presented in D4.1 to D4.4 of MOVINGRAIL. Section 6.6 provides a discussion of these results in the context of X2Rail-3 WP6 and WP7.

6.1 VCTS Concept of MOVINGRAIL

VCTS in MOVINGRAIL (MR) is defined as a concept based on moving blocks, i.e., its aim is to further increase the capacity of ETCS Level 3. VCTS has two main objectives (MR D4.1, p. 20ff.):

- **Objective 1: reduce headway.** Increase capacity by grouping trains such that they can be treated as one train in interlocking areas (e.g., to resolve occupation conflicts when multiple trains approach a merging junction).
- **Objective 2: improved flexibility of operation.** Coupling/decoupling on the fly can enable to more frequent, shorter trains.

That ETCS Level 3 is seen as the basis of VCTS has certain **implications** on the implementation (see Figure 6-1, further discussion in Section 6.6):

- ETCS Level 3 can be used as the fallback, e.g., in case T2T communication fails.
- A leading train is controlled as in ETCS Level 3 whilst the following train receives speed and brake command data from the leader.
- The lack of Train Integrity Monitoring (TIM) technologies, especially for freight, is hindering ETCS Level 3 implementation and will thus hinder VCTS implementation.

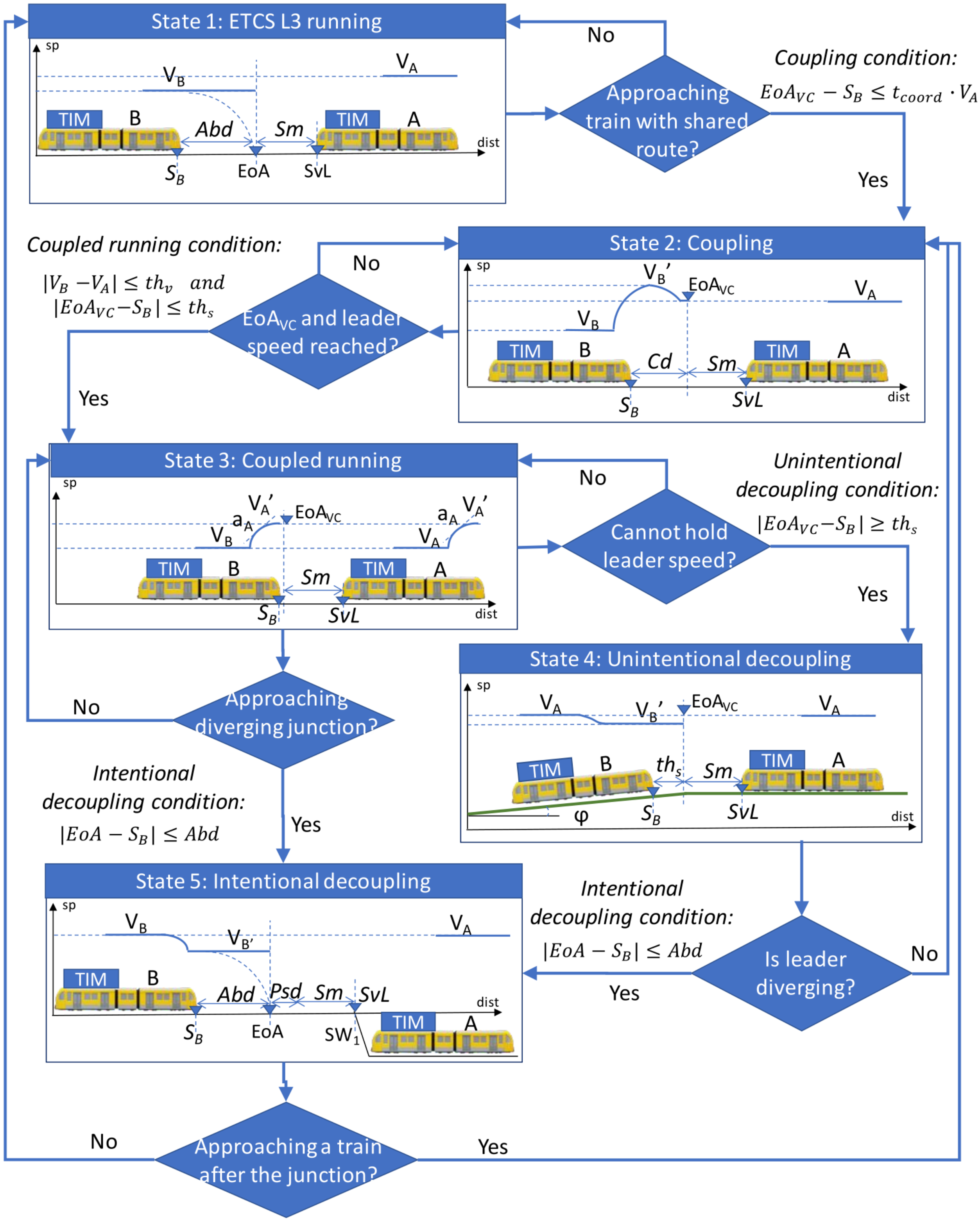


Figure 6-1 VCTS states as presented by MOVINGRAIL D4.1

6.1.1 Requirements

Within MOVINGRAIL, the following requirements for an implementation of VCTS are formulated:

- As mentioned, ETCS Level 3 needs to be implemented and available as a fallback.
- Train position reporting is performed via radio communication with the RBC.
- MA is broadcasted to trains by the RBC.
- Automatic Train Operation (ATO) shall be equipped to all trains for automated driving.
- Trains need to exchange speed, acceleration and position information and a Vehicle to Vehicle (V2V) communication architecture is therefore required.
- Switches need to be upgraded to support diverging junctions with lower than braking distance.
- Cooperative management of railway traffic is required to optimise the composition/decomposition of based on their origin/destination pairs, their service category, and the congestion level at neighbouring bottlenecks.

These are basic requirements that enable the implementation of VCTS. Drawing conclusions from analysing the impact on capacity of VCTS, two **additional requirements** for an optimised operation of VCTS is formulated in MR D4.2 (p.87):

- "An advanced traffic management system is required to optimise the formation of virtually coupled platoons based on multiple factors such as track speeds and interstation distances."
- "Also, the real potential of VC would be unleashed when redesigning switch technologies since the capacity analysis here performed assumed current switches where diverging virtually coupled trains in a convoy will need to be separated by an absolute braking distance as it occurs for MB."

These requirements point at the research necessary for advanced planning algorithms that can handle the changes to operational procedures by VCTS as well as shortcomings in switch technology that are targeted by projects like Repoint[3], which is close to commercialization.

6.1.2 Challenges

The following main challenges in fulfilling the requirements stated in the previous section and that need to be solved for an implementation of VCTS are identified. Each challenge is presented together with a mitigation recommended by the MOVINGRAIL consortium, if available.

6.1.2.1 Safety challenges

- Distance at diverging junctions
    - Switches might not have enough time to be moved and locked in between consecutive trains with potential risks of train derailments.
      Recommendation: apply absolute braking distance in this case.

[3] https://www.lboro.ac.uk/enterprise/repoint/

- Communication frequency
  - Risk for collisions when braking information is not broadcasted timely.
    Recommendation: select a communication technology that ensures sufficiently frequent information exchange.
- Platooning trains with different characteristics
  - In the case that trains have different braking characteristics, the following train might overshoot its MA.
    Recommendation: exchange information about breaking capabilities and adjust braking rates accordingly.

6.1.2.2 Technological challenges

- Communication architecture
  - A V2V communication layer which complements RBC to train communication for communication position, speed, acceleration reliably at high frequency needs to be deployed.
- Interface with TMS and IXL
  - The main challenge is to understand whether trains can still be controlled by central TMS or individually. Interlocking areas controlled by on-board system using train to IXL interface thinkable, could improve safety at level crossings (e.g., when train detection is removed with moving block).
- ATO Interface
  - Generally, a problem that already exists. Requires VCTS-specific functions for keeping relative distance and considering individual braking performance.

6.1.2.3 Infrastructure and operational challenges

- Platform length for platoons
  - Longer platforms might be required to allow platoons of multiple trains to stop at the same track. Segregation of a platform might be required to avoid confusion when trains of a platoon have different destinations.
- Train planning rules
  - The running time of a train in a platoon depends on the characteristics of the platoon (thus, the other trains).
- Engineering and operational rules
  - “On the fly” coupling/decoupling would allow more flexible service but is only suitable for market segments where the distance to stations/junctions is sufficiently high.
  - Switches might not have enough time to be safely moved and locked at diverging junctions, thus absolute braking distance should be imposed at the switch to tolerate switch failures.
  - Cooperative management of railway traffic is required.
  - Protocols for traffic management and train-to-trackside communication might be modified.

The challenges identified by MOVINGRAIL are very much in line with the ones identified within X2Rail-3 WP7, this is further discussed in Section 6.6.2.

The results for the cost effectiveness analysis of MR D4.2, summarized in the next section, are based on preliminary operational procedures of VCTS that define characteristics like planned service headway, train composition, the crew required, etc. for each market segment. Only the results are summarized in the following, details on the operational procedures including detailed explanations how they were defined by surveying experts with the aim of introducing VCTS in an economically attractive way can be found in MR D4.1, Section 5.

6.2 Cost Effectiveness

MOVINGRAIL D4.2 “Cost-Effectiveness Analysis for Virtual Coupling” presents an analysis of cost effectiveness of Moving Blocks, and VCTS in comparison to Moving Blocks. Quantitative criteria (infrastructure capacity, costs, system stability, travel demand, and energy consumption) are evaluated using analytical and simulative modelling. Qualitative criteria (safety, public acceptance, and regulatory approval) are evaluated by surveying selected experts. The results for the different criteria are summarized below. Finally, a multi-criteria analysis (MCA) is performed that assigns a score to the different signalling alternatives and market segments (see summary in Section 6.2.7).

6.2.1 Infrastructure Capacity

A capacity index is defined specifically for the MCA of MR D4.2. A minimum train headway for each signalling alternative is calculated and normalised with respect to the baseline (ETCS L2 for high-speed, 3-Aspect for the other market segments), it is then averaged across several different manoeuvres (see details in Section 5.1.1. of MR D4.2). The lower the minimum train headway, the higher the capacity index gets, representing a capacity increase. For a given combination of signalling system and market segment, minimum train headways are computed based on the compression method and an extension of it is applied to Moving Block and Virtual Coupling. The main parameters are shown in Figure 6-2, the results in Figure 6-3.

	High speed	Main line	Regional	Urban	Freight
Switching time [s]	9	8	7	5	7
Safety margin for VC [m]	200	120	100	80	100
Max. speed [km/h]	300	160	120	80	100
Turnout speed [km/h]	130	80	60	80	60
Turnout length [m]	140	76	63	76	63
Block length baseline [m]	1500	1000	700	400	1000
Dwell time [s]	240	60	60	30	120
Gradient	0	0	0	0	0

Figure 6-2 Parameter values used to compute minimum train headways for the market segments, from MOVINGRAIL D4.2, p.37

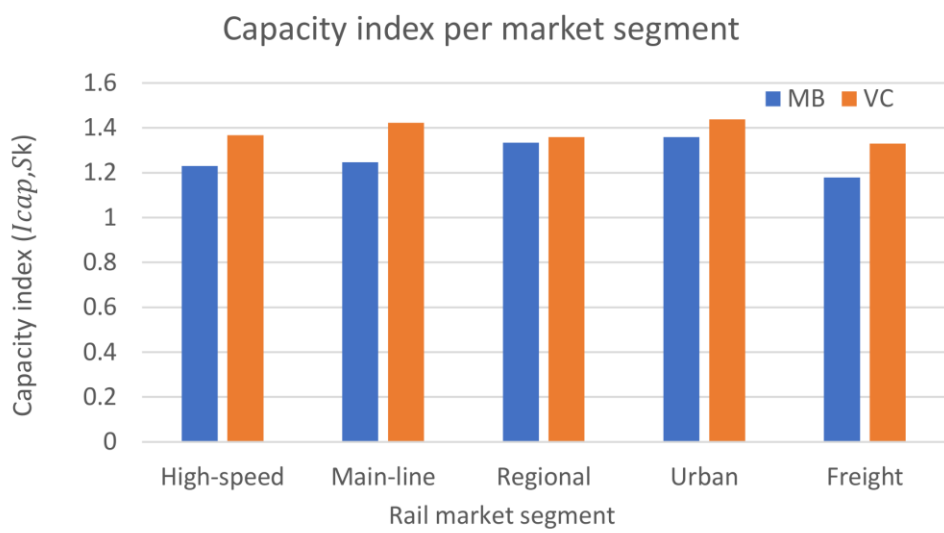


Figure 6-3 Capacity Index of ETCS Level 3 “Moving Blocks” (MB) and VCTS (VC) per market segment as reported by MOVINGRAIL D4.2, p.41 (analytical results).

The results show that Moving Blocks (MB) and VCTS (VC) provide capacity improvements in every market segment. Furthermore, VCTS provides capacity improvements over Moving Blocks. It is stated that “significant capacity gains are observed for Virtual Coupling over ETCS Level 3 under the condition that cooperative train control algorithms can efficiently coordinate the composition/decomposition of virtually coupled platoons. […] Such algorithms are still in development, so the simulation results reported here can be further improved by considering more advanced algorithms in the future.” (MR D4.2, p. 51)

6.2.2 Total Costs

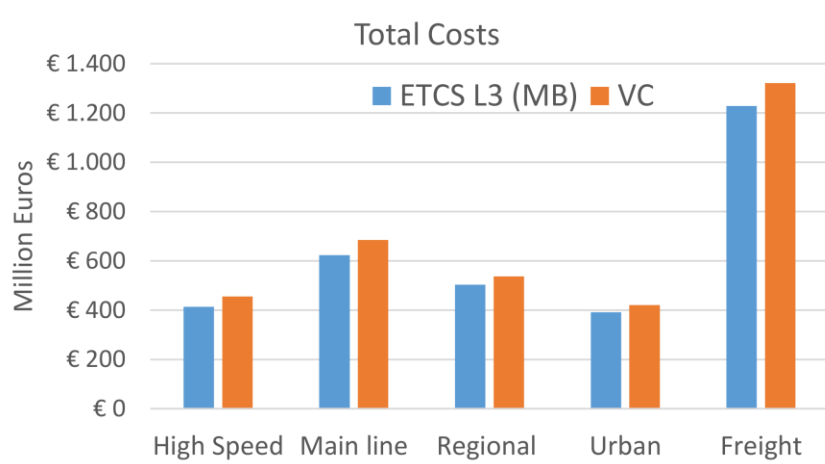


Figure 6-4 Total cost of introducing ETCS L3 and VCTS reported by D4.2 of MOVINGRAIL

Total costs are reported in terms of capital expenditure (CAPEX) and operational expenditure (OPEX). The total results are shown in Figure 6-4 and Figure 6-5. The results for each market segment are calculated based on case studies that are defined in D4.1 of MOVINGRAIL. Further details can be found in Section 5.1.2 of MR D4.2. Note that the assumption that ETCS L3 is the base for VCTS results in the costs of introducing VCTS being higher than ECTS L3 in every case.

More details on how the CAPEX and OPEX values are obtained for each market segment and signalling alternative are presented in the following two sections.

		Market Segment	Total CAPEX	Total OPEX	Total Costs
Alternatives	ETCS L3	**High-Speed**	€369,232,000	€44,227,260	**€413,459,260**
		Main line	€579,608,000	€43,635,784	**€623,243,784**
		Regional	€481,827,000	€21,474,732	**€503,301,732**
		Urban	€388,820,000	€3,172,601	**€391,992,601**
		Freight	€1,182,190,000	€46,313,378	**€1,228,503,378**
	VC	**High-Speed**	€411,712,000	€44,212,040	**€455,924,040**
		Main line	€641,528,000	€43,630,503	**€685,158,503**
		Regional	€515,307,000	€21,471,293	**€536,778,293**
		Urban	€417,620,000	€3,172,215	**€420,792,215**
		Freight	€1,275,670,000	€46,290,368	**€1,321,960,368**

Figure 6-5 Total cost, total CAPEX and total OPEX of introducing ETCS L3 and VCTS reported by D4.2 of MOVINGRAIL

6.2.2.1 Capital Expenditure (CAPEX)

Capital expenditure, i.e., the investment costs for the migration from baseline signalling to ECTS Level 3 Moving Block, for the migration from ECTS Level 3 to VCTS and from baseline to VCTS (as the sum of the two previous results) are reported for each market segment. For high-speed railways the baseline is ETCS L2, the results are shown in Figure 6-7. For all other market segments the baseline is conventional fixed-block three-aspect or ETCS Level 2, these results are shown in Figure 6-6. The costs are estimated based on field knowledge and literature research. CAPEX results are also reported for the case studies defined in MR D4.1 for each of the market segments in the total costs shown in Figure 6-5. It can be noted that the CAPEX for the different use cases is dominated by the railway authority deployment costs.

CAPEX	Signalling System		
	3-Aspect to L3	L3 to VC	3-Aspect to VC
Trackside (scheme design, equipment, installation and test)	€1,100,000/km	-	€1,100,000/km
Train equipment	€425,000/MU	-	€425,000/MU
Train equipment engineering First in class	€150,000/MU	-	€150,000/MU
Train equipment installation	€40,000/MU	-	€40,000/MU
TIM equipment	€24,000/MU	-	€24,000/MU
EVC software upgrade	-	€50,000/MU	€50,000/MU
ATO equipment	-	€100,000/MU	€100,000/MU
ATO engineering First in class	-	€150,000/MU	€150,000/MU
ATO installation	-	€40,000/MU	€40,000/MU
V2V communication equipment	-	€20,000/MU	€20,000/MU
Railway Authority deployment costs	€330,000,000	€330,000,000	€330,000,000

Figure 6-6 CAPEX per signalling system transition with baseline three-aspect signalling reported by MOVINGRAIL D4.2 (MU – Multiple Unit)

CAPEX	Signalling System		
	L2 to L3	L3 to VC	L2 to VC
TIM equipment	€24,000/MU	-	€24,000/MU
Recovery of unwanted train detection and signage	€100,000/km	-	€100,000/km
EVC software upgrade	€50,000/MU	€50,000/MU	€100,000/MU
ATO equipment	-	€100,000/MU	€100,000/MU
ATO engineering First in class	-	€150,000/MU	€150,000/MU
ATO installation	-	€40,000/MU	€40,000/MU
V2V communication equipment	-	€20,000/MU	€20,000/MU
Railway Authority deployment costs	€330,000,000	€330,000,000	€330,000,000

Figure 6-7 CAPEX per signalling system transition with baseline ETCS L2 reported by MOVINGRAIL D4.2 (MU – Multiple Unit)

6.2.2.2 Operational Expenditure (OPEX)

The operational expenditures (OPEX) presented by MOVINGRAIL are computed based on four components: average infrastructure maintenance, average rolling stock maintenance, energy provision and personnel wages. The results are shown in Figure 6-8 and reported for an estimated lifetime of the signalling system of 30 years, discounting the operational costs with a rate of 5% each year. It can be noted that the OPEX is estimated lower for VCTS because of smaller crew sized due to Automatic Train Operation (ATO). It is reported that ATO on top of Moving Block would have similar OPEX. Details on the underlying parameters used for the estimates can be found in Section 5.1.2 of MR D4.2.

OPEX item	Market Segment	Signalling System			
		3-Aspect	ETCS L2	ETCS L3	VC
Average infrastructure maintenance	High-speed	-	€8,988,476	€8,489,116	€8,489,116
	Main line	€4,158,603	-	€3,534,812	€3,534,812
	Regional	€2,750,572	-	€2,337,986	€2,337,986
	Urban	€229,214	-	€194,832	€194,832
	Freight	€16,470,686	-	€14,000,083	€14,000,083
Average rolling stock maintenance	High-speed	-	€21,864,785.72	€33,174,157.65	€33,174,157.65
	Main line	€29,534,728.08	-	€39,379,637.43	€39,379,637.43
	Regional	€12,050,517.89	-	€17,947,579.84	€17,947,579.84
	Urban	€2,930,217.12	-	€2,930,217.12	€2,930,217.12
	Freight	€22,034,565.73	-	€26,441,478.87	€26,441,478.87
Energy provision	High-speed	-	€1,767,089.36	€2,524,413.38	€2,524,413.38
	Main line	€530,702.15	-	€707,602.86	€707,602.86
	Regional	€786,817.56	-	€1,180,226.34	€1,180,226.34
	Urban	€46,547.72	-	€46,547.72	€46,547.72
	Freight	€4,874,005.32	-	€5,848,806.39	€5,848,806.39
Personnel	High-speed	-	€39,573.26	€39,573.26	€24,352.78
	Main line	€13,731.71	-	€13,731.71	€8,450.28
	Regional	€8,939.36	-	€8,939.36	€5,501.14
	Urban	€1,004.19	-	€1,004.19	€617.96
	Freight	€23,009.55	-	€23,009.55	€0.00

Figure 6-8 Summary of OPEX results for the different case studies defined in D4.1 of MOVINGRAIL, table from D4.2 of MOVINGRAIL

6.2.3 System Stability

As stated in D4.2, p. 60 of MOVINGRAIL, “System stability is defined as the capability of a railway system to mitigate delay propagation across the network. Stability depends on the timetable structure (train frequency and traffic heterogeneity), as well as the infrastructure layout and signalling system. It can be measured in terms of the total buffer time available per time unit and is thus related to infrastructure occupation.”. However, a more general stability index is defined that is based on an average minimum headway over various operational scenarios and a given typical train frequency per hour. Thus, this index is independent of specific infrastructure layouts or timetable structures and allows comparison across the different markets segment using an abstract railway system model that is parameterized for each market segment and different manoeuvres to calculate the index for each market segment and signalling system alternative.

The final stability index results are shown in Figure 6-9. The more detailed results of MR D4.2 Section 5.1.3 show that system stability gains for VCTS over Moving Blocks are much higher when considering only following movements in a platoon of virtually coupled trains, where the corresponding headway is given by the manoeuvre of non-stopping trains following on a plain line without junctions. Generally, the results are affected by the assumption that absolute braking distance is required at junctions, because current switch technology is too slow.

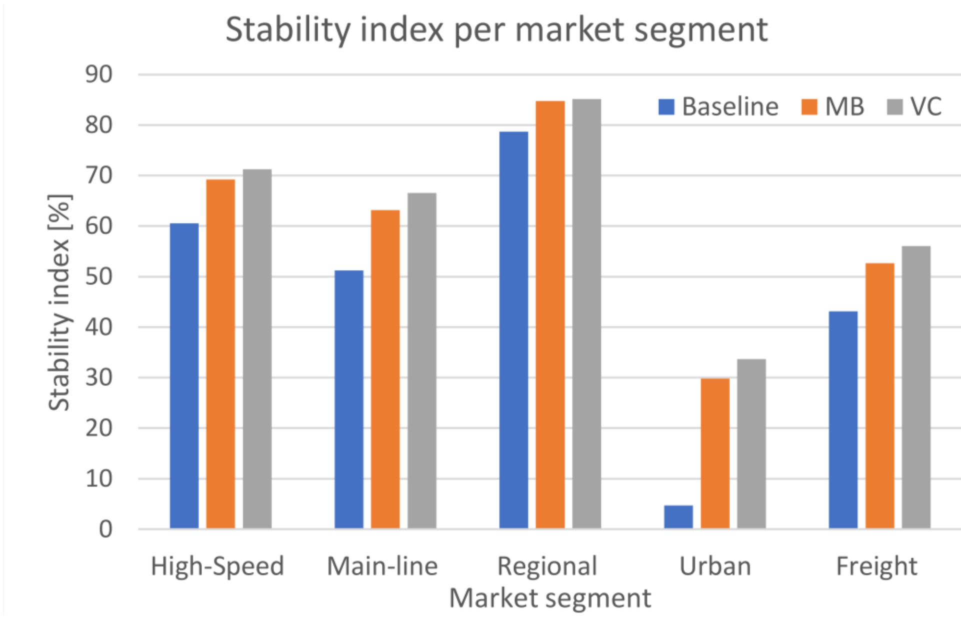


Figure 6-9 Moving Block (MB) and VCTS (VC) influence on the stability Index reported by MOVINGRAIL D4.2

6.2.4 Travel Demand

Travel demand is analysed based on survey results from MOVINGRAIL D4.1 to understand the modal shift, i.e., the question whether travellers will prefer or reject the railway compared to other modes of transport (e.g., car, bus) when ECTS Level 3 or VCTS are introduced. It is assumed that ECTS Level 3 and VCTS will increase ticket prices by 10% and 20%, respectively, while train service is improved by giving customers more flexibility by increased service frequency. Costs are expected to increase due to decrease train lengths while service frequency is increased as a result of estimated headway reductions of 50% for ETCS Level 3 and 61 to 63% for VCTS.

Results with an assumed ticket price increase are shown in Figure 6-10. In the results of Figure 6-11, no ticket price increase is assumed. It can be seen that ticket prices have a strong impact on the perceived attractiveness of ECTS Level 3 and VCTS for travellers.

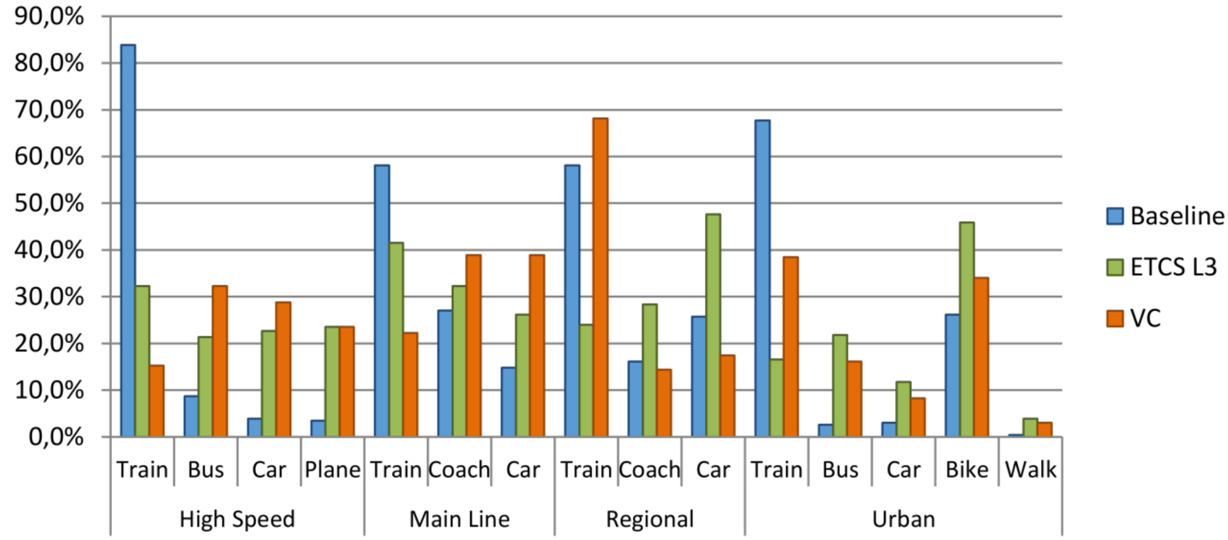


Figure 6-10 Impact of ETCS L3 and VCTS (VC) on modal share, with an estimated ticket price increase (10% for ETCS L3, 20% for VCTS) as reported by MOVRINGRAIL D4.2

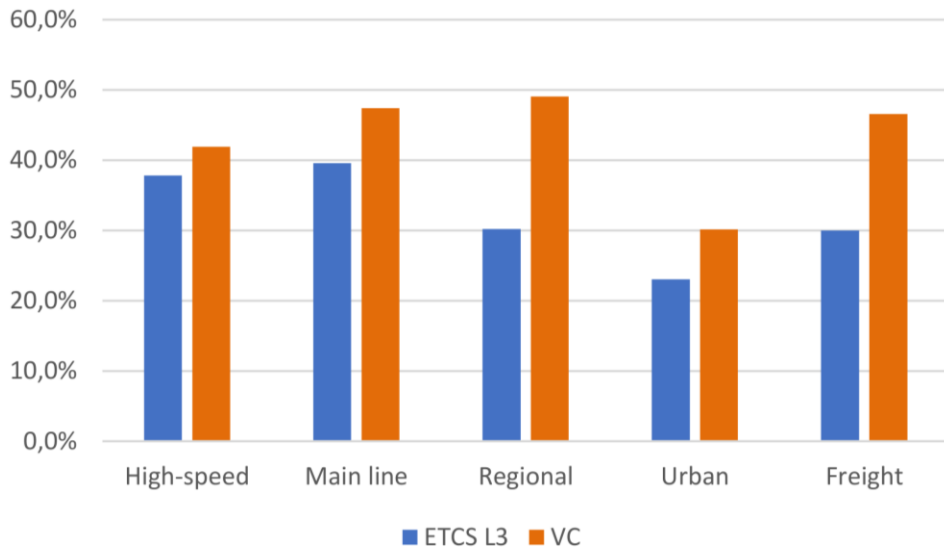


Figure 6-11 Impact of ETCS L3 and VCTS (VC) on modal share, without a ticket price increase as reported by MOVRINGRAIL D4.2

6.2.5 Energy Consumption

Energy consumption has been estimated using an energy consumption index that represents the average energy consumption of a signalling alternative over different operational scenarios relative to the respective baseline (3-Aspect or ECTS L2). The energy consumptions per scenario were obtained using simulation of two trains following each other. For VCTS, no energy optimizing control algorithms where applied, but the slave train simply follows the speed and braking/acceleration from the master.

The results show some energy reductions of ECTS L3 compared to the baseline (ca. 1% energy index reduction for high-speed trains, ca. 2% for other segments) and slightly higher energy reductions of VCTS compared to the baseline (ca. 1.5% energy index reduction for high-speed trains, ca. 3% for other segments).

6.2.5.1 CO_2 Emissions

Given the modal shift in travel demand summarized in Section 6.2.4 and publicly available data on CO_2 emissions for each transportation mode as a baseline, changes in CO_2 emissions by introducing ECTS L3 and VCTS, respectively, were estimated as shown in Figure 6-12.

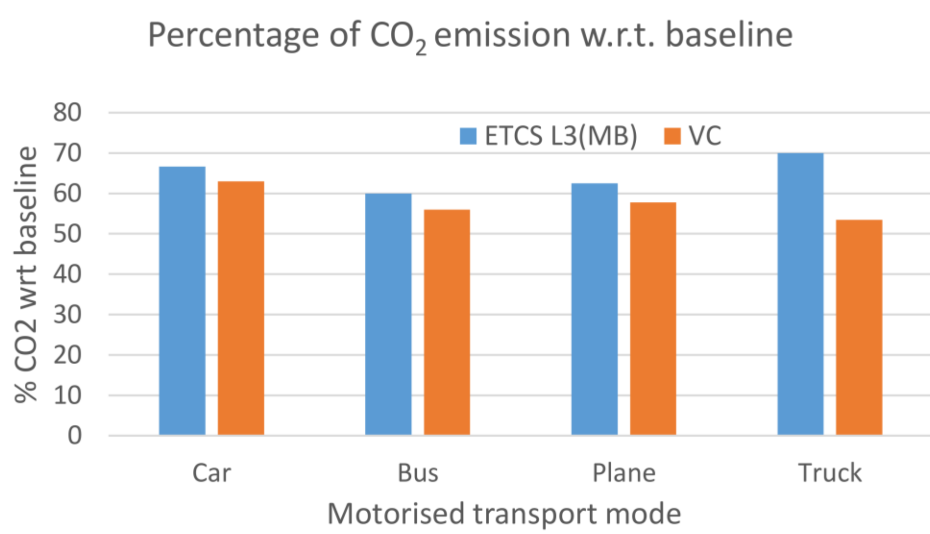


Figure 6-12 Estimated reduction of CO_2 emissions as reported by MOVRINGRAIL D4.2

6.2.6 Qualitative Criteria

The qualitative criteria, i.e., safety, public acceptance and regulatory approval were obtained by surveying experts and non-experts using the so-called *Delphi Technique* that aims to reach a consensus between participants. Participants were asked to raise and rate potential issues as well as steps necessary for regulatory approval.

Two rating questions were asked for the issues raised, where participants should rate the importance (from 1 = definitely unnecessary to 5 = essential) and likelihood that a given issue or step is solved within 5 years (1 = low, 5 = high). For each issue or step an index is computed by dividing the score for solving it within 5 years by the priority score.

6.2.6.1 Safety

As a result of surveying, the level of safety and the perception of safety are evaluated to be the highest level of significance and risk. The mentioned issues and their scores are shown in Figure 6-13. The authors comment (in 2020): “A notable finding from the stakeholder reviews was that for all of the safety issues, no stakeholder expects them to be fully resolved in the next 5 years”.

System	Aspects for safe and reliable operations	Score Priority	Score 5 years
ETCS L3 MB	Harmonised non-functional requirements on train integrity (safety and performance)	4	3
	Trains are able to stop within their MA	5	5
	MAs are exclusively issued for a given section of track for only one train at a time	5	5
	Routes are held until the train has passed	5	5
	Reliability of communications system	3	5
	Have a full view over the performance railway network in software and see what the safety levels are	5	5
	Have a full view over the performance railway network in software and see where the remaining capacity is (or where bottlenecks are)	4	4
	Have a full view over the energy consumption of the railway network in software	3	3
	Central co-ordination of the switching system in software to find the appropriate balance between capacity utilisation, safety and energy consumption dynamically	2	2
	Spacing	5	5
	Capacity gain	5	3
	Costs	5	3
	Arithmetic Mean of assessments	**4.33**	**3.61**
	Standard Deviations	**0.88**	**1.16**
VC	Standardised communication to following vehicles	4	3
	System behaviour and operations defined for degraded situations	4	3
	Trains are able to stop within their MA	4	5
	MAs are exclusively issued for a given section of track for only one train at a time	4	5
	Routes are held until the train has passed	4	5
	Formations virtually coupled in rear will not crash into formations in front without causing any more Fatality Weighted Injuries (FWIs)	5	1
	Reliability of communications system	5	2
	Have a full view over the performance railways network in software and see what the safety levels of individual convoys, consists and units are	5	5
	Have a full view over the performance railways network in software and see where the remaining capacity is (or bottlenecks are)	4	4
	Spacing	5	3
	Capacity	5	1
	Costs	5	2
	Arithmetic Mean of assessments	**4.5**	**3.25**
	Standard Deviations	**0.5**	**1.48**

Figure 6-13 Scored safety issues raised during expert interviews as reported by MOVINGRAIL D4.2

6.2.6.2 Public Acceptance

Public acceptance is seen as closely linked to safety, as perceived safety issues might influence the public's tolerance for technical failures. Furthermore, it is stated that "regulators are unlikely to take risks upon themselves by approving technologies that the public have concerns about". The risks are shown in Figure 6-14, some issues were mentioned but not scored.

Issue	Score Priority	Score 5 years
Culture that expects transportation delivered by organisations (rather than personally) to be 100% safe	5	1
Safety	5	1
Safety incident causes public concern	5	2
Populist politicians oppose new technology	3	2
Interoperable solution (working cross-border and cross-supplier)	5	3
Convincing politicians that if they allow VC and a VC train crashes, that there is not going to be a massive backlash	5	3
Reliability	5	3
Costs	5	3
Railway press analysis raises concerns	4	3
Passenger pressure groups raise concerns	4	3
Difficult explaining link MovingRail and capacity	3	3
Non realisation of capacity benefits - public apathy	2	3
Technical delays/issues raise concerns over safety	5	4
Mainstream media raising fears	4	4
Opacity	5	5
Fear of collision – passengers	3	5
People are safe	5	
Rail is reliable	4	
Rail is a flexible (as much as realistically possible) in the transport / journey chain	3	
People feel safe (perception)	2	
View of maturity vs road sector - expectation for similar capability		
Expectation of almost guaranteed no train on train collision lost		
Expectation to work unnoticed to traveller		
Unwillingness to pay more		
Arithmetic Mean of numerical assessments	4.1	3.0
Standard Deviation	1.01	1.12

Figure 6-14 Scored public acceptance issues raised during expert interviews as reported by MOVINGRAIL D4.2

6.2.6.3 Regulatory Approval

In order understand steps and risks concerning regulatory approval, stakeholders were asked to identify the issues as well as barriers, and then the potential mitigations. The following is stated in MR D4.2 concerning the process and discussions with stakeholders:

"Given that railways have always been controlled through mechanisms that are designed around maintaining safe absolute braking distances between trains, it is non-trivial to be asking regulators to accept that this fundamental signalling principle can be modified. However, the thinking that has gone into the development of Virtual Coupling is recognised as an innovation that could achieve benefits for the railway and its users". The results are shown in Figure 6-15 and Figure 6-16.

In summary, it is stated that safety is a major issue for all market segments that contains risks for public and regulatory acceptance. Therefore, early clarification of the regulatory process as well as early involvement of regulators is seen critical in achieving a successful implementation of VCTS.

Regulatory approval		
Issue	**Score Priority**	**Score 5 years**
Clear articulation of the new system	4	3
Route through the Common Safety Method	5	5
Multiple NSA's or European Agency approval	5	5
Public concerns put pressure on regulators	3	2
Technical complexity makes demonstration of safety for Movingrail challenging	5	3
Any safety incident has potential to set back approval	5	1
Approval through ERA will make ERA careful and slow	5	3
BREXIT creates confusion over approvals for use in UK	3	5
Demonstrate at least same safety level as today	5	2
Safety must always be improved	5	2
Overcoming 2 centuries of the principle of no closer than the absolute braking distance	5	1
Time (as the inverse of speed difference) between two consists or units	5	5
Maximum length of a convoy	4	4
Safety	5	1
Reliability	5	3
Costs	5	3
Proper ability to evaluate risk needed		
Arithmetic Mean of assessments **Standard Deviation**	**4.63** **0.70**	**3.0** **1.41**

Figure 6-15 Scored regulatory approval issues raised during expert interviews as reported by MOVINGRAIL D4.2

Regulatory approval		
Steps towards regulatory approval of VC	**Score Priority**	**Score 5 Years**
Early engagement with Regulator/s	5	5
Decision to seek approval from EUAR (not NSA's)	5	5
Clarify with EU Commission that EUAR can approve	5	4
Creation of clear system definition and draft specifications	5	3
Set up simulation and test track for testing system	5	3
Sponsorship of specifications/standards through EU Processes	5	3
Description of operations and system	3	4
Hazard analysis	4	3
Prototype on test track	4	2
Pilot in regular operation	4	1
Talk to the regulators as soon as possible	5	5
Build evidence that VC is at least as safe as whatever it will replace	5	1
Demonstrate that the benefits of VC cannot be delivered by any other safer means	5	1
Build a safety case based on the previous two points	5	1
Safety	5	1
Reliability	5	3
Costs	5	3
Conspicuity of a convoy (see e.g. military pelotons on the road using flags to explain what the beginning and end of the peloton is)	5	
Software centric approach including continuous integration and continuous delivery	4	
Software centric approach including non-deterministic artificial intelligence (AI)	3	
Demonstrable step change improvement in capacity		
Communication of safety principles to necessary stakeholders		
Demonstration of potential public acceptance		
Arithmetic mean of assessments	**4.6**	**2.82**
Standard Deviation	**0.66**	**1.42**

Figure 6-16 Scored regulatory approval issues raised during expert interviews as reported by MOVINGRAIL D4.2 (continued from Figure 6-15)

6.2.7 Multi-Criteria Analysis

Given all the performance scores, summarized in the previous sections, a multi-criteria analysis was performed. Figure 6-17 summarizes the scores for all market segments in a single table. Figure 6-18 shows how each score was weighted in order to obtain the final overall score shown in Figure 6-19. Section 5.1 of MOVINGRAIL D4.2 provides details on how the weights were obtained in iterative survey rounds (so-called *hybrid Delphi-AHP method*).

		Market Segment	Criteria							
			Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	High-Speed	€413,459,260	1.230	69.19	0.378	0.992	0.834	0.732	0.648
		Main line	€623,243,784	1.247	63.16	0.396	0.979	0.834	0.732	0.648
		Regional	€503,301,732	1.334	84.76	0.302	0.979	0.834	0.732	0.648
		Urban	€391,992,601	1.359	29.83	0.231	0.979	0.834	0.732	0.648
		Freight	€1,228,503,378	1.178	52.64	0.300	0.979	0.834	0.732	0.648
	VC	High-Speed	€455,924,040	1.367	71.22	0.419	0.985	0.722	0.732	0.648
		Main line	€685,158,503	1.423	66.54	0.474	0.973	0.722	0.732	0.648
		Regional	€536,778,293	1.358	85.12	0.491	0.973	0.722	0.732	0.648
		Urban	€420,792,215	1.437	33.67	0.302	0.973	0.722	0.732	0.648
		Freight	€1,321,960,368	1.330	56.06	0.466	0.973	0.722	0.732	0.648

Figure 6-17 Summary of all performance scores for each market segment as presented by MOVINGRAIL D4.2

		Market Segment	Criteria							
			Total costs	Infra capacity	System stability	Travel demand	Energy consumption	Safety	Public acceptance	Regulatory approval
Alternatives	ETCS L3	High-Speed	0.062	0.052	0.032	0.026	0.015	0.456	0.039	0.309
		Main line	0.062	0.050	0.031	0.024	0.015	0.456	0.039	0.309
		Regional	0.062	0.056	0.032	0.018	0.015	0.456	0.039	0.309
		Urban	0.062	0.054	0.029	0.022	0.015	0.456	0.039	0.309
		Freight	0.062	0.051	0.031	0.019	0.015	0.456	0.039	0.309
	VC	High-Speed	0.056	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Main line	0.056	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Regional	0.058	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Urban	0.057	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Freight	0.057	0.057	0.033	0.029	0.015	0.395	0.039	0.309

Figure 6-18 Summary of all weights for each performance score and market segment used to summarize the scores into a single final score, table from MOVINGRAIL D4.2

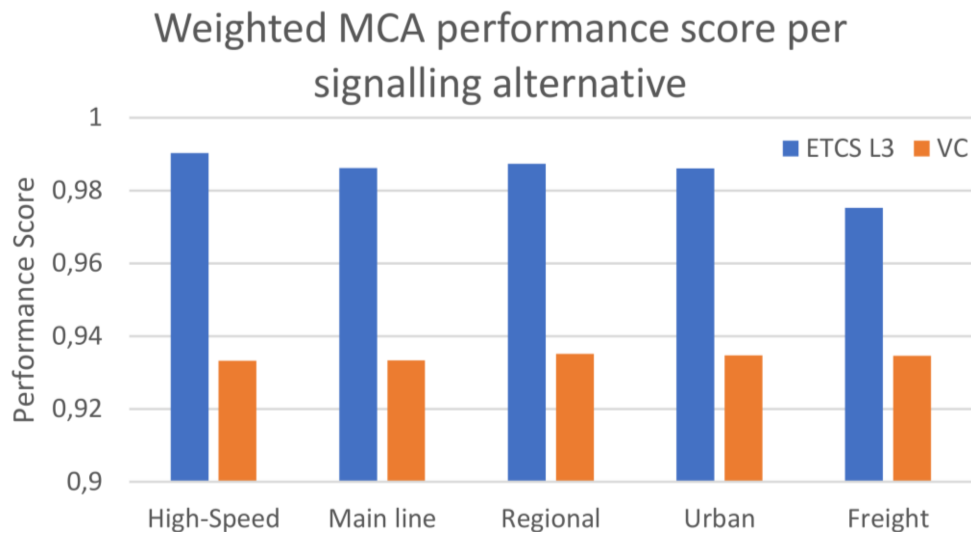


Figure 6-19 Final multi-criteria analysis results presented by MOVINGRAIL D4.2

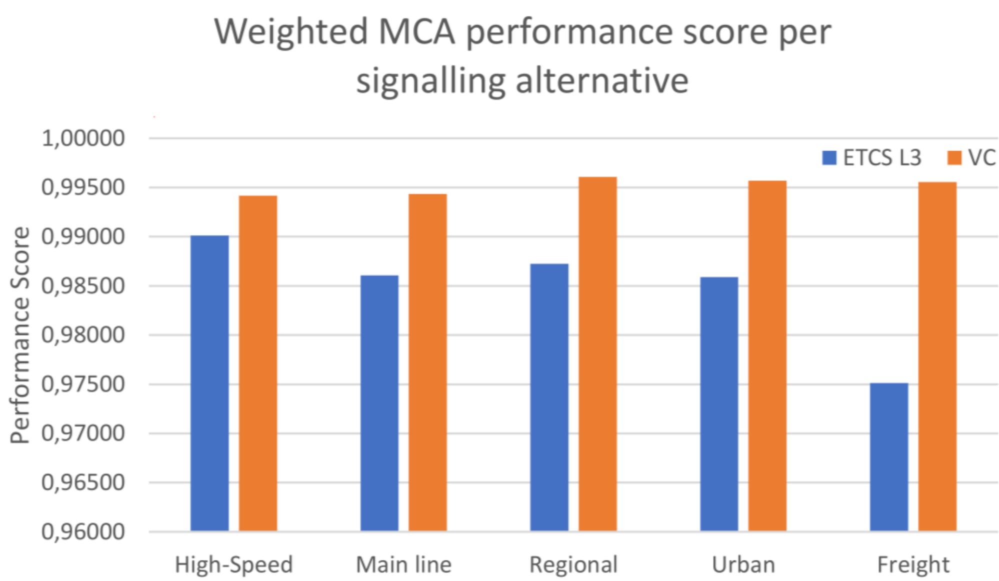


Figure 6-20 Final multi-criteria analysis results under the assumption of equal safety scores as presented by MOVINGRAIL D4.2

The authors of MOVINGRAIL D4.2 note that a very high weight (46%) was assigned to the safety score (see Figure 6-17). Under the assumption that both signalling alternatives have the same safety score, VCTS gets a higher overall score than ETCS Level 3, see Figure 6-20. Generally, note that the graphs go from 90 to 100% and 96 to 100%, respectively. The difference in overall score lies in few percentage points in every case.

6.3 Application Roadmap

6.3.1 SWOT Analysis

Based on surveying experts, MOVINGRAIL D4.1 presents a strengths, weaknesses, opportunities and threats (SWOT) analysis of VCTS for each market segment. The overall results are shown in Figure 6-21, the additional results for each market segment in Figure 6-22.

Strengths	Weaknesses
• Line capacity ↗ • Delay propagation ↘ • Latency in comm with RBC in MB ↘ • Service flexibility ↗ • OPEX ↘ • Potential accidents impact ↘	• Full ABD at diverging junctions • Safety risks for heterogeneous braking rates • Investments needed to install the V2V • Infra upgrades to the OLS, platforms and possibly switch technologies • Potential ticket fees ↗
Opportunities	**Threats**
• Railway customers ↗ • Potential profit ↗ of IMs and RUs • Deregulation of the railway market with opening to smaller transport operators • Restructuring of railway market from a competitive to a more cost-effective cooperative consortium model • Migration of current CCS to more future-proof and efficient digital railway architectures • Capacity ↗$^{+}$ and maintenance costs ↘$_{-}$ by installing advanced switch technologies.	• Ticket costs ↗ for railway customers • Possible train control complexity ↗ with respect to MB • Costs of stakeholders ↗$^{+}$ to address safety issues due to RBD • Policies, processes and engineering rules.

Figure 6-21 MOVINGRAIL SWOT Analysis of Virtual Coupling to all Market Segments (Table 1 from D4.2)

Several strengths like increased line capacity, reduction of delay propagation and reduced OPEX are identified, but also weaknesses that relate to safety and increased investment costs for stakeholders and increased ticket fees. A more detailed analysis of the results can be found in Section 6 of MR D4.1.

Market Segment	Strengths	Weaknesses
High Speed	• Significant headway ↘ • Platooning efficiency ↗ • Coupling/Decoupling feasible on-the-run	• High safety risks in case of V2V signal loss • Substantial stress of overhead catenary
Main Line	• Capacity ↗+ • Potential amount of level crossing closures ↘ • Coupling/Decoupling feasible on-the-run	• High complexity and uncertainty in managing heterogeneous rolling stock in one convoy
Regional	• Potential amount of level crossing closures ↘	• Potential longer closure of level crossing to road users • Coupling/Decoupling only allowed at standstill
Urban	• Platooning efficiency ↗	• Only marginal capacity improvements
Freight	• Flexibility ↗+ and capacity ↗+ of freight delivery • Handling operations at marshalling yards ↘ • Coupling/Decoupling feasible on-the-run	• Complexity in platoon sequencing due to different rolling stock characteristics
Market Segment	**Opportunities**	**Threats**
High Speed	• None additional to Table 1	• None additional to Table 1
Main Line	• Migration to advanced systems for ATC	• None additional to Table 1
Regional	• Customers ↗+	• None additional to Table 1
Urban	• None additional to Table 1	• Investments for VC deployment might not be compensated by a sufficient customer increase
Freight	• Attracting relevant market share from other modes • Shorter trains with fixed composition overcome limitations of TIM while reducing brake build-up times • Collection and distribution of goods over the last mile can be optimized and automated.	• Legislative rules in terms of weight and length platooning.

Figure 6-22 MOVINGRAIL Additional Strengths, Weaknesses, Opportunities and Threats of Virtual Coupling to each Market Segment (from D4.2)

6.3.2 Roadmap

In D4.3 of MOVINGRAIL, roadmaps for the migration to VCTS are developed based on MR D4.1, MR D4.2 and additional surveys. Optimistic and pessimistic scenarios are presented for each market segment based on the SWOT analysis of D4.1 (see previous section), highlighting strength and opportunities in the optimistic case as well as threats and weaknesses in the pessimistic case.

The aim of the roadmaps is to implement “the EU vision of having VC deployed by year 2050, and thus reducing CO_2 emissions by 60% and increasing railway demand by 30% for passengers and 50% for freight by year 2050” (MR D4.2, p. 42). The authors further state that the “time estimates of all step changes must be viewed as rough expert opinions based on experience with past technology whereas governmental policy may change the speed of developments” (MR D4.3., p. 56). Some technologies that are required for the introduction for the introduction of VCTS are not considered, because they are targeted by other projects of Shift2Rail. This includes train integrity and train positioning.

The individual steps identified are shown in Figure 6-23 with their respective priority and time order. These are mapped to optimistic and pessimistic scenarios per market segment as shown in Figure 6-24, where the optimistic scenario assumes a decrease in CO_2 emissions by 60% and CAPEX as well as OPEX by 40% compared to the baseline presented in MOVINGRAIL D4.2 (see Section 6.2.2). The pessimistic case assumes a decrease in CO_2 emissions by 50% and CAPEX as well as OPEX by 20%. Details per market segment can be found in MOVINGRAIL D4.2 Section 5.3.

Steps	Category	Priority	Time order
R&I			
Research on longitudinal motion control systems within train convoys, including convoy stability and relations to ATO	Operation	Very High	1.0
Research on operational procedures (convoy formation on-the-run, platooning, cooperative merging, cooperative departing)	Operation	Very High	1.1
Research on integrated traffic management and train control for train convoy management	Operation	Very High	2.0
Innovation in high-precision train positioning (if assumed critical for VC)	Technology	Medium	3.0
Innovation in switch technology (removing the need for absolute braking distance in rear of moving switches) (if assumed critical for VC)	Technology	Medium	3.1
Concept of Operations	Operation	High	3.2
Requirements			
System Requirements Specification of Virtual Coupling	Technology	High	4.0
Initial RAMS analysis of Virtual Coupling	Technology	High	4.1
Initial Risk Assessment of Virtual Coupling according to Common Safety Method	Technology	High	4.2
Operational and Engineering rules for Virtual Coupling (operational configurations and scheme design)	Operation	Medium	8.0
Specifications			
Specifications of operational procedures in interlocking areas	Operation	Medium	5.0
Specifications of operational procedures for coupling, coupled running and decoupling	Operation	Medium	5.1
Specifications of systems architectures for Virtual Coupling (integrated communication and control architecture intra & inter convoys)	Technology	High	6.0
Specifications of communication protocols including safety and security aspects	Technology	Medium	7.0
Specifications of communication models for VC: train-to-train and RBC-train	Technology	Medium	7.1
Standardization (e.g. within ERTMS)	Technology	Medium	9.0
Design, Develop and Build			
Develop communications system for VC	Technology	Medium	10.0
Upgrade RBC and EVC software for VC	Technology	Medium	10.1
Develop ATO for VC	Technology	Medium	10.2
Development of testing methods for VC	Technology	Medium	10.3
Early deployment and trial of VC	Technology	Medium	11.0
Final Risk Assessment of Virtual Coupling according to Common Safety Method	Technology	Low	12.0
Final RAMS analysis of Virtual Coupling	Technology	Low	12.1
Safety case	Technology	Medium	12.2
Deploy			
Safety approval	Technology	Medium	13.0
Regulatory approval process (inclusion in TSI)	Technology	Low	13.1
Deployment of ETCS Level 3 Moving Block (assumed ready for deployment when required for VC)	Technology	Very Low	14.0
Deployment of Virtual Coupling in the real-world	Technology	Very Low	15.0

Figure 6-23 Steps, priority, and time order for the introduction of VCTS as presented by MOVINGRAIL D4.3

	Short title of step	Step No.	Optimistic Scenario (months)					Pessimistic Scenario (months)				
			HS	ML	Rgn	Urb	Frt	HS	ML	Rgn	Urb	Frt
Feasibility Study	VC, scope and boundaries	1.1	2					5				
	Operational scenarios	1.2	2					5				
	Market analysis & use cases	1.3	3					6				
	CEA incl. capacity analysis	1.4	5					8				
	Technology roadmap	1.5	2					4				
	Business risk analysis	1.6	2					4				
	COM solutions	1.7	5					8				
	VC COM structures	1.8	4					8				
R & I	Long. motion control systems in convoys	2.1	24	30	24	18	24	36	40	36	30	36
	Operational procedures	2.2	6	12	6	6	6	12	18	12	12	12
	Integrated traffic mngmt & train operation	2.3	24	30	24	18	24	36	40	36	30	36
	Train positioning	2.4	24	24	12	12	12	36	36	24	24	24
	Switch technology	2.5	24	24	12	12	12	36	36	24	24	24
	Concept of Operations	2.6	6	12	6	6	6	18	24	18	18	18
Requiremen	System Requirements Specs	3.1	12	18	12	12	12	18	24	18	18	18
	Initial RAMS analysis	3.2	3	6	3	3	3	6	10	6	6	6
	Initial CSM-RA	3.3	3	6	3	3	3	6	10	6	6	6
	Operational & Engineering rules	3.4	10	12	10	10	10	20	24	20	20	20
Specifications	Operational procedures in IXL	4.1	6	10	6	6	6	12	20	12	12	12
	Operational procedures for cplg, cpled & decplg	4.2	8	10	8	8	8	18	24	18	18	18
	Systems architectures	4.3	8	12	8	8	8	18	24	18	18	18
	COM protocols incl. safety and security	4.4	12	18	12	12	12	18	24	18	18	18
	COM models: V2V & V2I	4.5	8	12	8	8	8	18	24	18	18	18
	Standardization (e.g. ERTMS)	4.6	12	18	12	12	12	24	30	24	24	24
Design, Develop & Build	Develop COM system	5.1	8	12	8	8	8	12	18	12	12	12
	Upgrade RBC & EVC software	5.2	6	10	6	6	6	18	24	18	18	18
	Develop ATO	5.3	12	18	6	3	6	24	30	12	6	12
	Develop testing methods	5.4	12	12	12	12	12	20	20	20	20	20
	Early deployment & trial	5.5	6	10	6	4	6	12	18	12	10	12
	Final CSM-RA	5.6	6	8	6	4	6	12	18	12	10	12
	Final RAMS analysis	5.7	6	8	6	4	6	12	18	12	10	12
	Safety case	5.8	4	6	4	4	4	8	10	8	8	8
Deploy	Safety approval	6.1	6					18				
	Regulatory approval process (inclusion in TSI)	6.2	18					30				
	Deployment of ETCS Level 3 MB	6.3	18	24	18	12	18	24	30	24	24	24
	Deployment of VC in the real-world	6.4	12	18	12	8	12	18	24	18	16	18

Priority scale

- Very high
- High
- Medium
- Low
- Very low

Legend

HS	High-Speed
ML	Mainline
Rgn	Regional
Urb	Urban
Frt	Freight

Figure 6-24 Roadmaps with optimistic and pessimistic scenarios for each market segment from MOVINGRAIL D4.3

Finally, the times until deployment of VCTS are shown in Figure 6-25. It can be seen that, according to MOVINGRAIL, the EU goal of introducing VCTS by 2050 can be reached in all market segments and scenarios but for the pessimistic scenario for mainline.

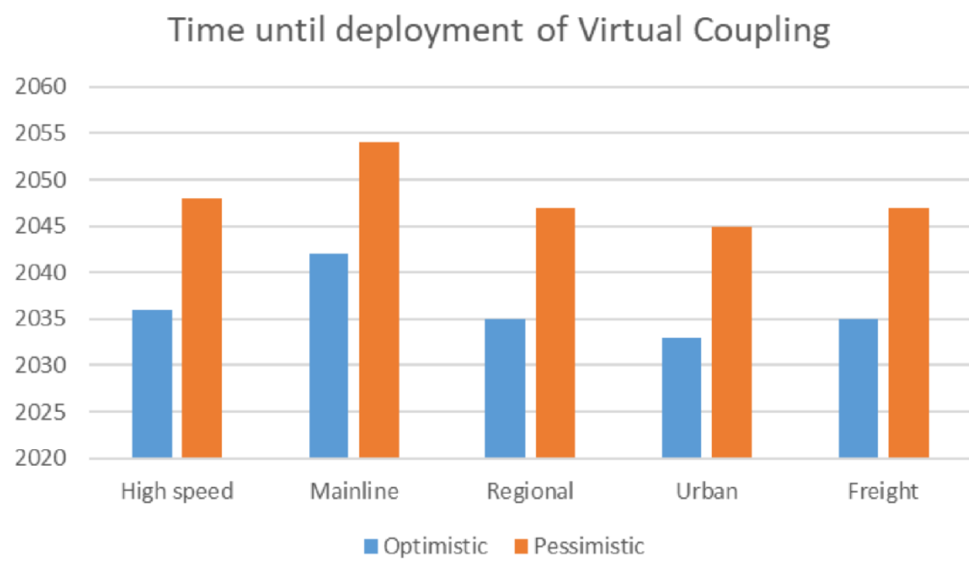


Figure 6-25 Estimated times until deployment starting December 2019 reported by MOVINGRAIL D4.3

6.4 Business Risks

D4.4 of MOVINGRAIL reports on business risks associated with the potential introduction of VCTS. With input from stakeholders, industry, academia and regulators, an online survey was designed and applied for identifying and ranking business risks. Results were validated and extended in a workshop with stakeholders. VCTS is, as in the other deliverables of MOVINGRAIL, understood as a technological extension of ETCS Level 3. This is reflected in the list of risks identified, the main risks are shown in Figure 6-26. The authors comment: “It was also observed that business risks cannot be entirely decoupled from technical risks, as the uptake of Virtual Coupling depends on the confidence in the technology itself. Most of the risks that were emphasised by participants relate to the technical hurdles being overcome so that the benefits would demonstrably exceed the costs.” (MR D4.4, p 34).

An example is given by the risk for a rear end collision of high-speed trains in the event of the leading train rapidly decelerating at an immovable object (e.g., embankment slip). Three ways of overcoming this risk are suggested:

- Configuring dedicated infrastructure that ensures virtually no possibility of the risk arising
- Technical specification of VCTS where the distance between trains in a platoon is always greater than the emergency safety distance plus safety margin
- Regulators and Governments accepting and legislating to operate VCTS with a certain risk

While this is not a business risk itself, it highlights the risks that investors have to face.

RISK		Overall score	Median impact score
3.1	No take up from operators due to business/safety concerns	69.8	10
6.4	Migration to ETCS Level 3 with Moving Block may take a very long time	58.6	7
7.1	Costs exceed the benefits	57.6	8
4.8	Need to upgrade existing on-board systems and adaptation of logical ICT systems	52.3	6
7.8	Elapsed time between now and implementation may change business cases	51.4	7
2.2	Different suppliers develop slightly different solutions	48.1	7
4.7	The added complexity of cooperative train control technologies needed to maximise benefits of Virtual Coupling creates unexpected system risks	48.0	7
2.1	Proof of concept works, but no suppliers want to invest in it	47.5	9
1.2	Excessive time elapses from proof of concept to defining actual specifications	46.8	7
4.10	Trains can run closer on plain line but not in junction/station/complex layouts - thus limiting the benefit	46.6	7

Figure 6-26 Top overall business risk scores and impact scores (out of 55 business risks identified) as reported by MOVINGRAIL D4.4

6.5 Conclusions of MOVINGRAIL

MOVINGRAIL performed extensive surveying of experts with detailed analyses of the results. Modelling as well as simulation were performed and provided quantitative results for the market segment-specific use cases.

In general, VCTS was determined to make railway transport more attractive to customers due to the increase flexibility by higher service frequencies when ticket cost increases are limited. This could especially be seen in mainline, regional and freight market segments. The freight market can benefit from a completely new operational setup that allows shorter trains, higher frequency and thus increased flexibility. For market segments where customers are already satisfied, e.g., urban/suburban lines, increase in attractiveness was seen negligible. However, VCTS can still be interesting in this case for railway managers and operators because it helps to reduce traffic instability and delay propagation. Furthermore, a deregulation of the railway market is expected that allows new business opportunities for smaller transport operators and railway owners.

The multi-criteria analysis of single quantitative criteria like capacity, system stability and energy consumption, showed that VCTS outperforms ETCS Level 3 in all market segments. VCTS scored lower, however, in the qualitative criteria safety, where stakeholders expressed concern for the maturity of technologies required for VCTS that can be reached within five years. As safety was weighted with 46% in the final score, VCTS performs worse than ETCS Level 3 in the final multi-criteria analysis result. Under the assumption that both signalling systems had the same safety score, VCTS performed better than ETCS Level 3.

The SWOT analysis highlighted that VCTS provides clear benefits over ETCS Level 3, because of its higher network capacity and lower operational costs due to smaller crew sizes and removal of track-side equipment. Weaknesses mentioned were the increased investment costs (over an already deployed ETCS Level 3), especially for the communication infrastructure and modernizing the current switch technology, which would otherwise limit the capacity benefits of VCTS.

Based on the SWOT analysis, optimistic and pessimistic scenarios for the deployment of VCTS were presented for every market segment. The essential system components identified that need to undergo changes were interlocking, communication structures, automatic and cooperative train protection, automatic and cooperative train operation, railway traffic planning, and railway traffic management. All scenarios, but the pessimistic mainline scenario, fulfilled the target of deploying Virtual Coupling by 2050. The pessimistic mainline scenario resulted in a deployment of VCTS until 2054, due to the complexity of operating freight, regional and IC trains on the same line.

Considering potential markets for early adoption of VCTS, the authors suggest that rural routes and routes that have significantly mixed traffic (i.e., freight and mainline passenger) are not suitable, because costs might outweigh the benefits. Instead, routes with the following characteristics are advised for early adoption: "Captive rolling stock fleets, homogenous train services with similar or identical service speeds, low numbers of junctions, few intermediate stations, existing technical barriers to running more and longer trains, coupled with robust forecasts of growing demand which cannot be met with existing technology and operations.” (MR D4.4, p. 36).

6.6 Discussion in X2Rail-3 Context

The findings of MOVINGRAIL are very much compatible with the findings of X2Rail-3 (as presented in D6.1, D6.2 and D7.1). This is not surprising, given that MOVINGRAIL and X2Rail-3 cooperated (e.g., X2RAIL-3 D6.1 “Virtual Train Coupling System Concept and Application Conditions” was an input to MR D4.3 “Application Roadmap for the Introduction of Virtual Coupling”). However, there are some differences in the assumptions and requirements for VCTS, which will influence the applicability of VCTS. Similarities and differences are discussed in the following.

6.6.1 Assumptions

The main difference is that MOVINGRAIL assumes ETCS Level 3 (Moving Blocks) as the basis for the VCTS implementation. This is reasonable as VCTS can conceptually be seen as the next logical step following ETCS Level 3, however, X2Rail-3 takes a more independent point of view and does not consider a completed ETCS Level 3 rollout a requirement. Both approaches have advantages and disadvantages:

6.6.1.1 Advantages of Assuming ETCS Level 3 as a Basis for VCTS

- ETCS Level 3 will implement some technology that is also required by VCTS and will make the migration from ETCS Level 3 to VCTS less difficult (in terms of regulation and migration paths) than a migration from ETCS Level 2 (or Level 1 and Class B signalling systems). This includes, e.g., train integrity and train location.
- Should problems arise during operation, e.g., in the communication link, will it always be possible to switch to ETCS Level 3 operation as a fallback. This is especially important considering that safety concerns were seen as one of the biggest business risks for VCTS in MOVINGRAIL (see Figure 6-26).

6.6.1.2 Disadvantages of Assuming ETCS Level 3 as a Basis for VCTS

- Conceptually, VCTS is not bound to any specific signalling system and can thus be utilized as a complementary system to any existing or future signalling and train protection system. According to X2Rail-internal experts, any ERTMS level can technically support VCTS operation, as long as train integrity detection is provided and guaranteed. VCTS can avoid significant business risks (see Section 6.4) when interference with the ERTMS implementation roadmap is avoided. An independent, complementary implementation of VCTS would increase acceptance of RUs and IMs, provide backward compatibility, ease standardization, and make the investment costs more predictable and manageable.
- Quoting the second-highest ranked business risk for VCTS from MOVINGRAIL D4.4: “Migration to ETCS Level 3 with Moving Block may take a very long time”.
    - Migrating from ETCS Level 3 to VCTS might be less difficult than migrating from other, less-capable signalling systems, but waiting for ETCS Level 3 before migrating to VCTS might render VCTS an upgrade of limited interest as perceived by stakeholders and operators. This is especially true when authorisation costs (that dominated CAPEX, see Section 26) would add up.
    - Considering that the deployment of ETCS might not be cost-effective in the short term for low-density lines but Class B systems are inevitably becoming obsolete and unmaintainable, a more independent definition of VCTS can become a viable cost-effective option. This would additionally provide a way to improve the maturity of VCTS and lower the hurdle to upgrade ETCS lines to VCTS in the long term. This application of VCTS is detailed in Section 7.1.

6.6.2 Challenges

The following critical challenges have been identified in X2Rail-3 D7.1 (feasibility analysis, where a full list of challenges and mitigations can be found):

- Brake system: the performance of current SIL4 braking systems is insufficient for safe VCTS headway management
- Communication: the headway between high-speed trains requires long communication ranges. Additionally, there is a limited availability of spectrum bands.
- Field elements: Fast change of switch position and immediate status notification are required for de-/coupling manoeuvres via switch.

- Signalling system: VCTS is a new actor with new actions in an existing system, variable platoon lengths need to be considered by the external signalling system.
- Positioning: Highly accurate measurements of distance, relative speed and relative acceleration as needed for VCTS are not yet available.
- Train integrity: The Shift2Rail aim for the delay of on-board train integrity loss detection is 5 s. This time would need to be considered in the safety margins of the headway between consists of the platoon if not improved.

In general, MOVINGRAIL and X2Rail-3 agree about these critical issues (see Sections 6.1.2 and 6.3.2). A difference that can be noted is the recommendation made by MOVINGRAIL of applying absolute braking distance when a consist should join or leave a platoon over a switch ("on-the-fly de-/coupling"). This impacts the benefits of this manoeuvre for increased capacity considerably. Within X2Rail-3 WP7, the introduction of fast switches with instant status notification is seen as realistic. If so, the benefits of on-the-fly de-/coupling would be higher than presented in the results of MOVINGRAIL. Otherwise, the same restrictions apply.

6.6.3 Conclusions

In summary, it can be stated that the understanding of VCTS and the results obtained within MOVINGRAIL and X2Rail-3 are very much compatible, which is the outcome of discussions between the two projects while MOVINGRAIL was still active. Some differences remain, however, which affect the alternatives for deploying VCTS and the attractiveness of the concept. Most notably, MOVINGRAIL assumes ETCS Level 3 as a basis for VCTS, whereas X2Rail-3 defines a more independent system that is seen complementary to existing signalling systems in order to avoid interfering with the ERTMS roadmap and make the benefits of VCTS available before a widespread rollout of ETCS Level 3 can be achieved.

Pursuing the idea of a more independent and complementary design of VCTS, we present two applications of VCTS in the following: *standalone VCTS* and *ETCS-based VCTS.* The two applications comprise a stepwise strategy starting with a limited implementation of VCTS that fosters the required technology until a widely applicable implementation can be achieved. More specifically, Chapter 8 presents a strategy for the application of VCTS as a standalone system that does not rely on any ETCS level. This approach is seen as a viable option to modernize Class B systems on low-traffic lines, where ETCS would require too high investments in order to be cost effective. Chapter 9 presents the strategy and vision of implementing VCTS on top of ETCS. The rationale why these two cases were selected, and a detailed description are provided in the following chapter.

7 Selected Markets for the Application of VCTS

Following the analyses performed in WP6 and WP7 of X2Rail-3, and the evaluation of the input obtained from MOVINGRAIL (see previous chapter), two main application cases have been identified for the introduction of VCTS:

1. **Standalone VCTS**: an application of VCTS that focuses on low-traffic lines that are today using Class B signalling systems that cannot be upgraded to ETCS in a cost-effective way. Standalone VCTS has two objectives: (i) providing an economically interesting upgrade path for Class B systems and (ii) raising the maturity of VCTS, thus, fostering the wide-scale introduction of such an innovative system.
2. **ETCS-based VCTS**: an application of VCTS that focuses on high-traffic lines and bases on ETCS Level 2 or Level 3. ETCS-based VCTS is the actual goal of this project and has the two objectives of: (i) reduced headway and (ii) improved flexibility of operation in order to increase line capacity and provide the technical basis for innovative business models.

The following sections provide details on the reasoning behind these two approaches. Chapter 8 provides a strategy for the introduction of standalone VCTS on low-traffic lines. Chapter 9 provides a strategy and vision for the introduction of ETCS-based VCTS.

7.1 Standalone VCTS

7.1.1 Motivation

Modernizing and digitalizing the railway infrastructure by migrating to ETCS is a challenging and costly undertaking for infrastructure managers (IM) and railway undertakings (RU). In order for this migration to be successful, clear regulations and mature technology are required. These requirements stand in contrast to the introduction of innovative technologies like VCTS. Conceptually, VCTS is the natural step after ETCS Level 3 “Moving Blocks”, as presented by MOVINGRAIL (see Section 6.1 and 6.6). When considering that, e.g., in Germany only 340 km of ca. 8000 km planned railway network have been migrated to ETCS Level 1 or higher until July 2021 [10], however, it becomes clear that we cannot wait for a full ETCS Level 3 rollout as the basis for fostering further innovation, when this means missing out on capacity improvements, improved flexibility of operation and, ultimately, considerable reductions of CO_2 emissions in the transport sector. At the same time, migrating from legacy basic or Class B systems to ETCS on low-traffic regional lines is not considered today, because costs outweigh the benefits. This poses a threat for RUs and IMs because it means that these lines will become irreparable and unmaintainable due to obsolescence.

Thus, a low-cost standalone implementation of VCTS will allow fostering this innovative technology without risking or depending on ETCS migration (note that technological maturity / safety was seen as the biggest business risk in Section 6.4). Simultaneously, this implementation will provide a cost-effective solution for modernizing low-traffic lines and keeping them maintainable.

7.1.2 Background

While “low-traffic” does not have a universal definition, a typical low-traffic line could be understood as a regional or segregated line, many times not electrified and possibly including single track sections. So far, a basic ATP was sufficient as only few services are operated (e.g., two trains per hour and direction), commonly regional or local traffic services. The deployed vehicles are usually small diesel multiple units (e.g., with two cars). Freight trains are not part of the basic scenario as the lines in question do not belong to the main corridors. However, they should not generally be excluded (e.g., the application case may in future lead to viable last mile transportation scenarios). Also, locomotive-hauled passenger trains may be utilized. In this scenario, trains are usually far away from each other. However, situations can occur in which trains are in the vicinity of each other. Either due to the regularly scheduled operation including services with a different amount of stops and thus different mean speeds or entering a single-track section from opposing directions or in degraded situations, for example due to delays.

Currently, the general functionality, including the ATP, is very basic. This includes a wide range of scenarios: In remote places, TMS may not be present and the traffic is controlled by the stations, where the movement authority is given by the station dispatcher. Even phone blockage and manual (wired) interlocking in stations may still be in place. In many cases, no speed supervision is given. In best cases, a Class B ATP electronically protects the track blocks through balises, including the capability to apply automatic safety measures to stop the trains to prevent collision based on the signals, but only rarely continuous speed supervision is deployed.

Many of these legacy or Class B signalling systems will most probably need to be replaced due to obsolescence. Following a detailed case-by-case analysis, most trackside equipment will be dismantled or deactivated, this includes for example block signalling and balises. Then, a new layer of protection is required, which replicates and complements the safety functions of the dismantled system.

7.1.3 Application

Standalone VCTS is a simplified variant of VCTS that provides a new safety layer for low traffic lines at low cost by implementing vehicle-centric ATP functionality using two key technologies:

1. Absolute and safe train positioning without infrastructural inputs (e.g., balises) in combination with a basic digital map (track layout)
2. Safe communication through public networks

For locomotive-hauled trains, additionally, a safe on-board train integrity function is required. While the general, layered architecture of VCTS remains the same as in the ETCS-based implementation, VCTS becomes a more passive role: it acts as a safety layer that only intervenes when necessary. The trains drive independently, do not form platoons, but are mutually aware of each other in order to determine MAs. This keeps the complexity low but provides the basis for a “full” implementation of VCTS in case more performance is desired and fosters the development of this technology.

As it is not the objective of standalone VCTS to increase the capacity of the network, the performance requirements of the underlying technologies are lower. To reduce the complexity of the system, driving below absolute braking distance is not supported and distances between trains become much bigger. This way, this implementation can tolerate uncertainties in train positioning and communication delays, which means that it does not need additional sensors or direct T2T communication as well as less complexity in the onboard units using public cellular networks instead of FRMCS (it is generally not required but could be integrated). Still, the maturity of the key technologies is raised, which is an important steppingstone for the introduction of ETCS-based VCTS.

The objective of a low-cost implementation is achieved through limited infrastructure requirements that result from the vehicle-centric implementation:

- No need for costly trackside equipment like balises
- The existing interlocking can be reused and upgraded later for improved performance
- No complex TMS required
- Public cellular networks are sufficient for communication

Achieving high levels of safety and availability through public cellular networks can be challenging, however, 4G and 5G networks support Quality of Service levels that can prioritise railway communication without needing specialised technology (see, e.g., D1.1 of the Shift2Rail project EMULRADIO4RAIL [6]). Furthermore, realising cost-effective absolute positioning is another challenge that can, however, benefit from developments in the automobile industry where safety critical positioning is crucial for autonomous driving functions (see, e.g., the PRoPART EU project[4]).

To summarize, standalone VCTS behaves like a moving block system (e.g., CBTC, ETCS Level 3) but with much lower performance that enables reduced complexity. Low-traffic regional lines as a first deployment of VCTS for this purpose is conceivable due to lower risks and complexity. VCTS could eventually be deployed in any type of line as a kind of cost-effective ATP, based on mutual awareness of rail vehicles. Any deployed solution shall follow the new reference architecture[5] to facilitate future upgradability. Therefore, this solution fosters the utilization of ETCS technologies and components for VCTS systems. From a technical, economical, and operational standpoint this is seen as advantageous (even an integration into ETCS later on if desired), but it is not a pre-requisite.

The technical details and impact of standalone VCTS are described in D7.4 “Impact Analysis”. A strategy on how to deploy standalone VCTS effectively is described in Chapter 8.

[4] https://cordis.europa.eu/project/id/776307

[5] RCA, see https://ertms.be/workgroups/ccs_architecture

7.2 ETCS-Based VCTS

7.2.1 Motivation

While standalone VCTS provides an interesting upgrade path for Class B systems and helps raising the maturity of technology required by VCTS, the main target of VCTS are highly trafficked lines with the goals of increasing capacity and flexibility of service. Even when ETCS is not deployed on the majority of lines today, it is the standard for new or upgraded lines within the European Union (and even beyond). Therefore, it is clear that the ultimate application of VCTS will be ETCS-based. In contrast to the concept presented by MOVINGRAIL (see Section 6.1), however, the VCTS concept of X2Rail-3 WP6 and WP7 does not require ETCS Level 3, but also considers ETCS Level 2 as a viable basis.

While the technical impact of migrating to VCTS is analysed in D7.4 of this work stream, a strategy for such a migration is presented in Chapter 9. In the following, the background of ETCS and the ETCS-based application of VCTS are presented.

7.2.2 Background

7.2.2.1 The Main Concept

The European Train Control System (ETCS), as part of the European Radio Train Management System (ERTMS) provides a standardized and interoperable paradigm of signalling principles, aimed to support safety of operations of railway networks equipped with the relevant sub-systems aligned to this standard.

The core principle of ETCS is the possibility to update the information related to the track to all trains communicating with a core central sub-system, the Radio Block Center (RBC). The RBC itself interacts with the Interlocking (IXL) to determine the status of the routing, track occupancy and other information regarding wayside elements like level crossings, working area, etc.

The RBC therefore is capable of gathering information from and distribute the information to all trains connected, so that trains equipped with ETCS on Board (ETCS-OB) can compute its own speed profile and braking curves.

The ETCS overcomes thus the limitations of other legacy signalling system by:

- Providing much more information regarding the status of the track ahead
- Distributing the data in a semi-continuous way through a GSM-R channel to all trains
- Utilizing a package of information that is sent to trains and covers much longer distances ahead of the train

ETCS is defined by the European Railway Agency (ERA) and the subsets defining its functions are baselined by the Agency, so that all countries can refer to the same set of requirements. In this way, the ERTMS can be deployed in a seamless way through all countries without the hurdles that are typically involved in having each country its legacy signalling infrastructure.

7.2.2.2 ETCS Levels

ETCS is designed to operate in 5 main incremental levels:

- Level 0 is an ETCS level kept to support operations of ETCS trains in non-ETCS equipped lines. In this level, the system keeps only very few functions of supervision like ceiling speed monitoring.
- Level STM is kept to allow operations of ETCS systems within certain sections of the track where the Legacy signalling system is still in charge of train supervision.
- Level 1 introduces the full operational concept of ETCS, with trains receiving track conditions and Movement Authority from the wayside infrastructure, but with discontinuous delivery. Mostly, the information for the trains is gathered by Eurobalises along the track, which notify the ATP about new track conditions but only in correspondence of Eurobalise crossing.
- Level 2 introduces full ETCS functionality with the information related to Movement Authority and Track Conditions sent to the ATPs by a semi-continuous GSM-R interface. Trains are localised along the track by the RBC through:
  - the position reports sent by the ATPs to the RBC. The position is always referred to a Latest Relevant Balise Group, that is the identifier of the last balise group crossed by the ATP.
  - the track occupancy information, determined by the IXL. The track is therefore split into sections, that become occupied when a train enters the section itself. The detection of the train in the section is implemented by different means, e.g. axle counters, track circuits.
- Level 3 corresponds to the full ETCS functions and its most optimised implementation. Level 3 includes all functions of Level 2, but the line capacity is optimised since trains are capable to localize their own minim safe rear end, relying on the train integrity function. In this way, RBC does not need any additional track occupancy information to determine the End of Authority of each train (in Level 2, the entrance point of an occupied section) and Movement Authorities can be extended up to the rear end of the train in front.

7.2.3 Application

7.2.3.1 State of the Art

The ETCS system has gone through an intense process of deployment across the entire European railway network and also beyond its boundaries (e.g. Asia, Oceania, Africa). The current baseline of the standard is version 3.6.0 [11]. Moreover, new releases of the same baseline are expected in the short-term to include ‘technical opinions’ of the different European operators that therefore will introduce a further refinement of the ETCS functions and architecture.

In general, the ETCS Level 1 and 2 lines are part of the railway infrastructure of actually all EU countries as of today. Whilst undergoing a period of deployment of approximately 20 years, nowadays ETCS is largely the solution adopted by railway operators to upgrade an existing line or to equip a new one.

On the other hand, the deployment of ETCS Level 3 is proceeding more slowly, with mostly test tracks currently operating in few EU countries. The main issues in deploying L3 are related to the evolution of the operational normatives determining how revenue service shall be carried out on L3 lines, especially under the perspective of a signalling system completely free from any train detection system that is not based on train position reports.

Current evolutions of the ETCS subsets are also targeting the standardisation of ATO interfaces and functions, in order to introduce the concept of driverless operations into the ERTMS baseline. At the date of today, trial testing is ongoing by different EU operators. Current Baseline 3.6.0 does not yet include any subset related to ATO but the inclusion of this set of new requirements is foreseen in next baseline (2022).

7.2.3.2 Introducing VCTS

A detailed description of the operational scenarios in which the VCTS impacts the current paradigm of ETCS is developed throughout Deliverable 6.1 [2] of this workstream.

The document especially strengthens the evidence of how the ETCS implementation as of today is limited by the concept of 'absolute braking distance', that VTCS aims to overcome.

Moreover, the following deliverables of WP7 target the practical investigation of what has to be changed in the interfaces and architecture of the ETCS implementation. For instance, Virtual Coupling application in ETCS L2/L3 has been analysed at functional and architectural level in D7.2 Section 13 [4]. Functional implications for on-board and trackside sub-systems have been evaluated in terms of use cases, implications at functional interface level and high-level implications at architectural level.

In general, VCTS implies changes in existing ETCS systems. Proposed system architecture (see Figure 7-1) has the aim to limit the overall effort to introduce VCTS by limiting the changes in involved on-board and trackside sub-systems. The aim is also to be able to address first implementation and on-site testing within few years. As a brief summary of the changes required:

- At the level of the interfaces:
    - the VCTS necessarily requires to interact with the ETCS-OB especially at the level of the status and activation functions.
    - The TMS shall develop an interface to the VCTS on board equipment to interact from a mission monitoring perspective.
- At functional level:
    - The RBC functions shall include the concept of platoon instead of a trainset, for which modification shall foresee dedicated changes to the way the platoon is considered by the whole RBC-IXL assembly as a single train and the way Movement Authorities are assigned (to platoons, instead of trainsets);
    - TMS shall evolve in order to develop the functions like platoon composition establishment and overall monitoring.

At on-board level, the additional VCTS equipment will interact with ATP and ATO. T2T and T2G communications will be managed according to FRMCS with a multi-bearer radio equipment (ACS

Gateway) and WLTB. VCTS visualization can be shown on the ETCS DMI. At trackside level, RBC and TMS will also need an ACS Gateway to manage T2G communication with FRMCS approach.

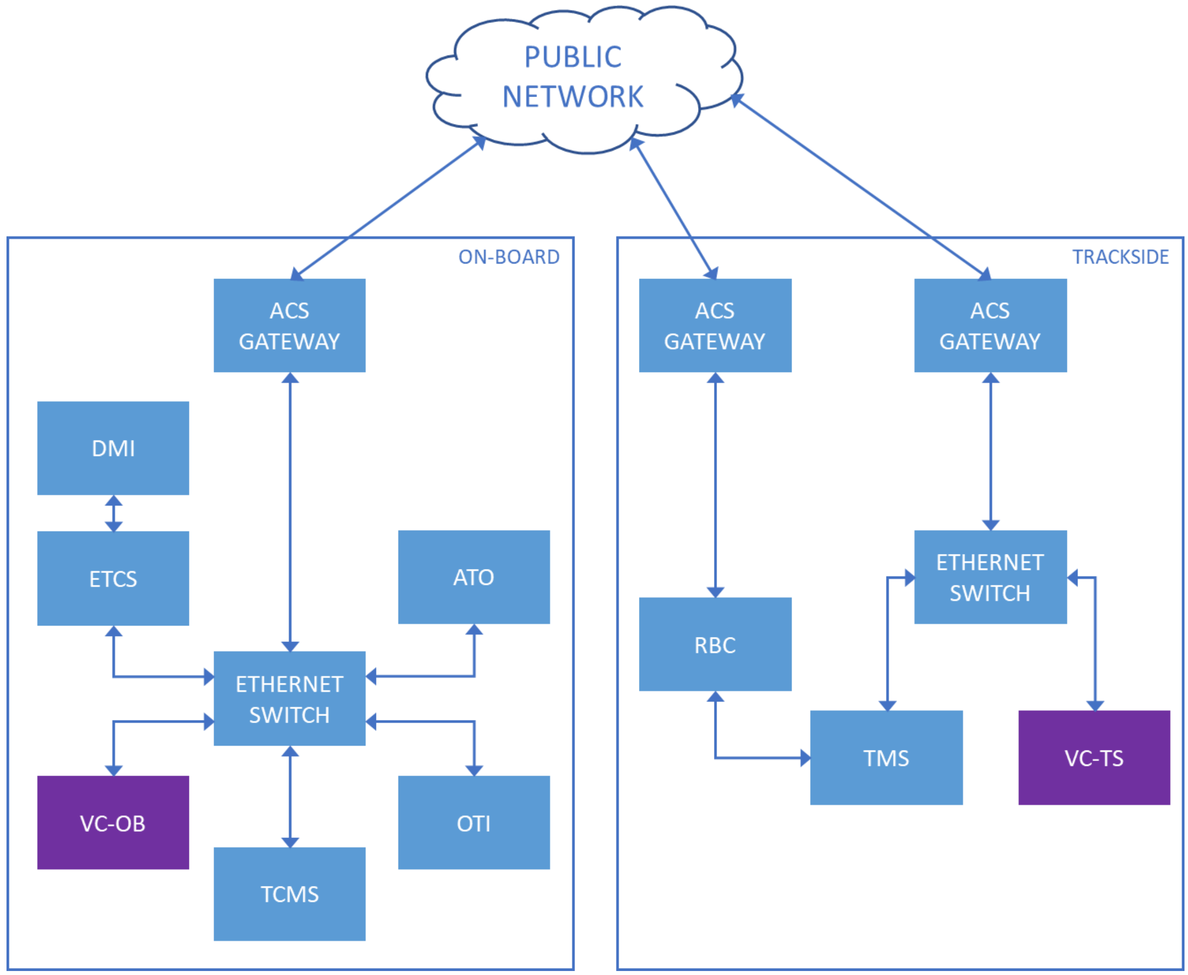


Figure 7-1 Architecture for ETCS L2/L3 application case

Note that the FRMCS approach is proposed because already identified as future solution for railway communications. Therefore, impacts related to this aspect should be addressed anyway within ETCS evolution.

General changes are needed in ATP, RBC, ATO, TMS logic and in related interfaces to manage virtual coupling procedures (e.g. set-up and termination). Also, implications at OTI sub-system level are expected at least in relation to safety target and potentially at performances level.

The impact analysis of ETCS-based VCTS is performed in D7.4 “Impact Analysis”. The strategy and vision for deploying VCTS effectively is described in Chapter 9.

8 Strategy for Standalone VCTS

As detailed in Section 7.1, the strategy for this application is focused on the use of VCTS as a kind of economic ATP for those railway lines where the improvement of the capacity is not the main issue, but the need of evolving the segregated or legacy systems that are about to be obsoleted or not maintained. Thus, the economically interesting upgrade path for Class B systems is the main objective. Furthermore, at the same time, it fosters the introduction of VCTS in a wide scale, where several of the main functionalities of VCTS will be validated as a first step to deploy the overall VCTS system on main lines and high-speed lines, where applicable. This fact, in conjunction with the use of the public communication networks (4G/5G) and the improvements in safety will be facilitated, besides, the improvement of the line capacity.

Following systems are involved in the analysis for the integration of virtual coupling: VCTS, ATP and RBC, TMS, OTI and communication. In this chapter, the migration plan for standalone VCTS applied to low-traffic lines is introduced.

The migration plan proposed in Figure 8-1 is intended to give an overview over migration plan process for all the different systems involved with the VCTS standalone functionalities.

Activity	Duration	Year 1 / Year 2 / Year 3 (Q1–Q4)
Validation and deployment of VCTS standalone	21 months	Delivery of VCTS system
Validation and deployment of TMS	21 months	Delivery of TMS system
Validation and deployment of ATO	21 months	Delivery of ATO system
Validation and deployment of Trains (OTI+APS)	21 months	Delivery of OTI&APS systems
Validation and deployment of Comms	24 months	Delivery of Comms System
Laboratory integration with other systems and functional tests	3 months	
Site testing	3 months	
Deployment and Commissioning	**12 months**	
Procurement	3 months	
Deployment	6 months	
Validation	6 months	
Commissioning	3 months	
Dismantling of ATP system	**9 months**	

Figure 8-1 General migration plan

The analysis of requirements, the specification and design of HW and SW parts, the implementation and the deployment of all the systems are coordinated and harmonized. This harmonization from the beginning brings the opportunity of deliver all the different unitary systems and prepare them to the final implementation at the end of the third quarter of the second year. In the fourth quarter of the year two, the laboratory integration tests for all the unitary systems can be performed. After finishing this laboratory testing in the first quarter of year three, the site testing is performed for all the involved systems in order to validate the final integration. During the third year, the deployment and commissioning for all the systems can be carried out in a coordinated way.

Optionally, after all the site testing is successful, with all the required guarantees to ensure all the systems are validated and integrated, the involved IMs and RUs could decide to perform the dismantling of the previous ATP system, taking into consideration the specific operation conditions of the affected rail lines.

8.1 VCTS Sub-system

8.1.1 Technical Steps

This analysis and migration plan is based on the VCTS standalone concept and specification, within the framework of the X2Rail-3 project and based on the information extracted from the analysis performed within the Deliverable D7.4 Impact Analysis [12]. Specifically, the strategy for the application of standalone VCTS is based on the Chapter 6 Baseline: Application Cases, where the standalone application case is explained in detail, from the background and possible solutions to the operational scenarios. A summary can be found in Section 7.1.

The high-level migration plan tackles the ambition of enabling an additional safety layer by new (mostly on-board) protection functionalities at a relatively low-cost. The VCTS standalone solution relies on the continuous supervision of absolute and safe train positioning without infrastructural inputs (e.g., balises) in combination with a basic digital map (track layout), train integrity supervision as well as establishing safe communication through public networks (e.g., 4G/5G).

Then, in order to introduce the VCTS within the legacy lines, it is required to elaborate the specification, design, development, integration, commissioning and testing activities for the VCTS-OB system. Furthermore, the same activities have to be performed with other required modules that facilitate the VCTS system functions: The adaptable communication systems (ACS) is based on 4G/5G communication technology for VCTS standalone. ACS is in charge of establishing V2I/I2V communications in order to create a T2T channel; besides, the VCTS has to ensure the safety of the train by the use of a positioning module that provides the precise position of the train and by the use of a train integrity module.

This process also has to take into account the communication with the different underlying train control systems and with the VCTS-TS sub-system, understood as the infrastructure module, which will be integrated with the TMS in order to exchange the required information used for planning and control.

Thus, the following tasks are extracted for the migration plan process. In order to achieve the implementation, the most important tasks in the process are:

- Technical analysis for hardware and software requirements in order to comply with underlying systems and with the integration with signalling sub-systems.
- Specification and design of hardware parts.
- Specification and design of software parts.
- Development, implementation and unitary test of HW.
- Development, implementation and unitary test of SW.

The next step consists of the laboratory integration and testing:

- Integration of HW and SW developments.

- Validation of deployments and performance tests.
- Laboratory integration with other systems and functional tests.
- Site testing.

The last step consists of performing the deployment and commissioning. Taking into account that it is necessary to adapt the previous mechanical and electrical design to host a VCTS cabinet and the related wiring toward the underlying sub-systems:

- Procurement.
- Deployment.
- Validation.
- Commissioning.

8.1.2 Non-Technical Steps

After the process and based on the results of the technical steps aforementioned, the following steps are required in order to insert VCTS standalone in the selected railway environment:

- Creation of a standard with new specifications.
- Certification process.
- Training activities and public education project.

8.1.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan has been developed taking into account also the design performed along this X2Rail-3 project, which results are in the deliverables from D7.1 to D7.4. Based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side, as well as our experience in the design, specification and deployment of control centres, the following plan has been determined:

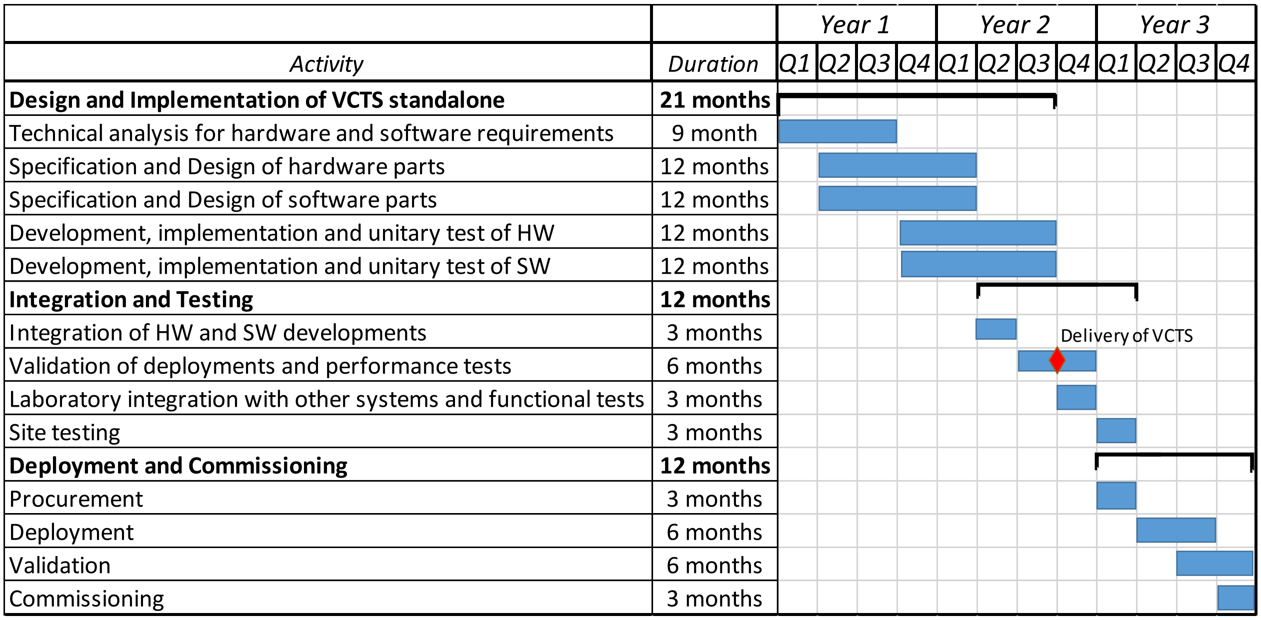


Figure 8-2 VCTS sub-system migration plan

8.2 Train Protection On-board and Trackside (ATP and RBC)

8.2.1 Technical Steps

Based on the definition and specification for VCTS standalone system defined in previous phases of the project, due to the obsolescence and lack of maintenance, the previously installed ATP systems have to be dismantled in order to be replaced by the VCTS system.

Nevertheless, this dismantling process will have to be decided by the IMs and Rus, taking into consideration the specific operation conditions of the affected rail lines.

In order to ensure this process, the following steps need to be performed:

- Dismantling of ATP previous system:
    - Uninstalling of devices (both on board and on track).
    - Removal of electrical and mechanical parts.

8.2.2 Non-Technical Steps

Based on the VCTS standalone definition, understood as a cost efficiently ATP solution, the non-technical steps are included in the list of non-technical steps in the Section 8.1.2.

8.2.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan is developed:

Activity	Duration	Year 1			
		Q1	Q2	Q3	Q4
Dismantling of ATP previous system	**9 months**				
Uninstalling of devices (on track)	6 months				
Uninstalling of devices (on board)	1 month				
Electrical and mechanical parts removal	2 months				

Figure 8-3 ATP and RBC migration plan

8.3 Traffic Management System

8.3.1 Technical Steps

Considering the legacy and Class B systems scenario, different specific changes can be applied to the existing systems. Applicable railway networks can differ regarding the equipped systems. In those cases where TMS is available, it is usually limited in functionality, supporting only basic functions.

In order to facilitate the implementation while saving costs, minimum changes to fulfil VCTS standalone needs are targeted. At the same time, these changes should be compatible with future upgrading. The determined changes are:

- Software development in relation to traffic management for trains, including the different zones where virtual coupling is available.
- Modification of current tools in order to allow new virtual coupling mode along the routes.
- Laboratory testing.
- Hardware upgrade to host VCTS-TS system, interface with TMS through the Integration Layer, ACS Gateway for 4G/5G communication towards VCTS-OB entities.

Thus, the following list of tasks has been defined in order to achieve the required changes. In a first phase, the new specifications, design and development shall be specified:

- Functional requirements specification.
- Functional architecture specification.
- Functional interface specification.
- System requirements specification.
- Operation procedures definition.
- Specification and Design of software parts.
- Development, implementation and unitary test of SW

After this phase, an integration phase is needed and which includes:

- Integration of SW developments
- Validation of deployments and performance tests
- Laboratory integration with other systems and functional tests
- Site testing

Finally, the last step consists of the deployment and commissioning:

- Procurement.
- Deployment.
- Validation.
- Commissioning.

8.3.2 Non-Technical Steps

After the process and based on the results of the aforementioned technical steps, the following steps are required:

- Creation of a standard with new specifications.
- Certification process.
- Training activities and public education project.

8.3.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan has been developed taking into account also the design performed along this X2Rail3 project, which results are in the deliverables from D7.1 to D7.4. Based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side, as well as our experience in the design, specification and deployment of control centres, the following plan has been determined:

		Year 1				*Year 2*				*Year 3*			
Activity	*Duration*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
Design and Implementation of TMS	**21 months**												
Functional requirements specification	6 months												
Functional architecture specification	3 months												
Functional interface specification	3 months												
System requirements specification	3 months												
Operation procedures definition	3 months												
Specification and Design of software parts	12 months												
Development, implementation and unitary test of SW	12 months												
Integration and Testing	**12 months**												
Integration of SW developments	3 months								Delivery of TMS system				
Validation of deployments and performance tests	6 months												
Laboratory integration with other systems and functional tests	3 months												
Site testing	3 months												
Deployment and Commissioning	**12 months**												
Procurement	3 months												
Deployment	6 months												
Validation	6 months												
Commissioning	3 months												

Figure 8-4 TMS migration plan

8.4 Automatic Train Operation

8.4.1 Technical Steps

Although for the lines with low traffic density evaluated in the VCTS standalone solution, ATO is not a necessary requirement, its integration can enable operational benefits. To consider its application, a low-cost solution is required. However, it should provide enough information to ensure adequate situational awareness to drivers during critical phases.

In order to apply the ATO to the VCTS standalone solution, following steps shall be carried out.

- Software development to comply with continuous communication with VCTS-OB and dynamic control of speed and distance.
- Laboratory testing.
- Software upgrade and configuration with new version.
- On board testing.

In a first phase the new specifications, design and development shall be specified:

- Functional requirements specification.
- Functional architecture specification.
- Functional interface specification.
- System requirements specification.
- Operation procedures definition.
- Specification and Design of software parts
- Development, implementation and unitary test of SW

After this phase, an integration and testing phase is needed and would include:

- Integration of SW developments
- Validation of deployments and performance tests
- Laboratory integration with other systems and functional tests
- On board testing

Finally, last step consists of the deployment and commissioning:

- Procurement.
- Deployment.
- Validation.
- Commissioning.

8.4.2 Non-Technical Steps

After the process and based on the results of the aforementioned technical steps, the following steps are required:

- Creation of a standard with new specifications.
- Certification process.

- Training activities and public education project.

8.4.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan has been developed taking into account also the design performed along this X2Rail3 project, which results are in the deliverables from D7.1 to D7.4. Based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side, as well as our experience in the design, specification and deployment of control centres, the following plan has been determined:

		Year 1				*Year 2*				*Year 3*			
Activity	*Duration*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
Design and Implementation of ATO	**21 months**												
Functional requirements specification	4.5 months												
Functional architecture specification	3 months												
Functional interface specification	3 months												
System requirements specification	3 months												
Operation procedures definition	3 months												
Specification and Design of software parts	12 months												
Development, implementation and unitary test of SW	12 months												
Integration and Testing	**12 months**												
Integration of SW developments	3 months								Delivery of ATO system				
Validation of deployments and performance tests	6 months												
Laboratory integration with other systems and functional tests	3 months												
On board testing	3 months												
Deployment and Commissioning	**12 months**												
Procurement	3 months												
Deployment	6 months												
Validation	6 months												
Commissioning	3 month												

Figure 8-5 ATO migration plan

8.5 Trains

8.5.1 Technical Steps

Without the need for high performances, the requirements are reduced to mainly the installation of the different systems: communication, control, on board train integrity and positioning. In order to adapt the trains to the VCTS system, following technologies have to be developed and integrated if not already present:

- SIL4 on-board absolute positioning system.
- SIL4 OTI.

In order to apply both technologies to the VCTS standalone solution, following steps shall be carried out.

- Hardware development to comply with both integrity and positioning services.

- Software development to comply with continuous communication with VCTS-OB.
- Laboratory testing.
- Hardware installation.
- Software upgrade and configuration with new version.
- On board testing.

In a first phase the new specifications, design and development shall be specified:

- Functional requirements specification.
- Functional architecture specification.
- Functional interface specification.
- System requirements specification.
- Operation procedures definition.
- Specification and Design of hardware parts
- Specification and Design of software parts
- Development, implementation and unitary test of HW
- Development, implementation and unitary test of SW

Next step consists of the integration and testing:

- Integration of HW and SW developments
- Validation of deployments and performance tests
- Laboratory integration with other systems and functional tests
- On board testing

Finally, last step consists of the deployment and commissioning:

- Procurement.
- Deployment.
- Validation.
- Commissioning.

8.5.2 Non-Technical Steps

After the process and based on the results of the aforementioned technical steps, the following steps are required:

- Creation of a standard with new specifications.
- Certification process.
- Training activities and public education project.

8.5.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan has been developed taking into account also the design performed along this X2Rail3 project, which results are in the deliverables from D7.1 to D7.4. Based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side, as well as our experience in the design, specification and deployment of control centres, the following plan has been determined:

Activity	Duration
Positioning + Train Integrity	
Design and Implementation	**21 months**
Functional requirements specification	6 months
Functional architecture specification	3 months
Functional interface specification	3 months
System requirements specification	3 months
Operation procedures definition	3 months
Specification and Design of hardware parts	12 months
Specification and Design of software parts	12 months
Development, implementation and unitary test of HW	12 months
Development, implementation and unitary test of SW	12 months
Integration and Testing	**12 months**
Integration of HW and SW developments	3 months
Validation of deployments and performance tests	6 months
Laboratory integration with other systems and functional tests	3 months
On board testing	3 months
Deployment and Commissioning	**12 months**
Procurement	3 months
Deployment	6 months
Validation	6 months
Commissioning	3 months

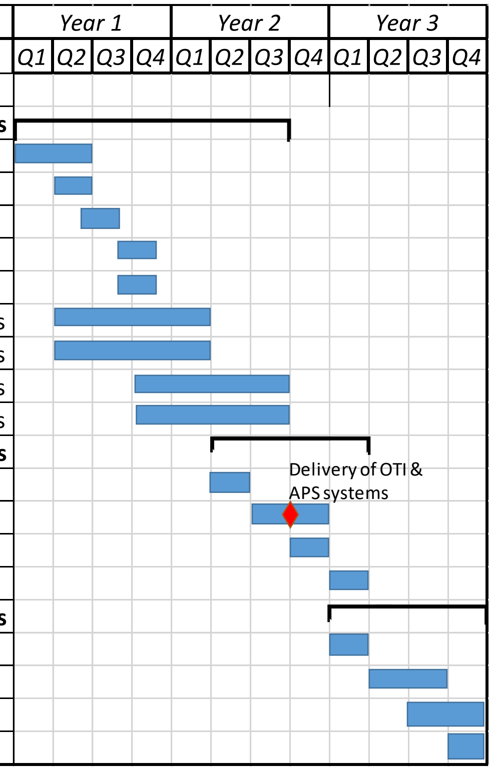


Figure 8-6 Train migration plan

8.6 Communications (T2T and T2G)

8.6.1 Technical Steps

From the impact analysis, different possibilities in terms of the communications deployment can be extracted, taking into account if previous T2G communications system (e.g. GSM-R) is already implemented. In the case that these systems were previously installed, based on the definition of VCTS as a low-cost solution in low traffic lines, we can assume that the GSM-R system can be sufficient for this version of VCTS standalone. Then, no actions are required in order to integrate it within the railway environment for lines with legacy/class B technologies. However, it will be required to implement FRMCS in the future in order to bring more flexibility and enable the complete VCTS solution as well as other safety-critical train applications.

On the other hand, on lines where there is not any T2G communications system, the use of the conventional networks (4G/5G) can enable sufficient performance to this VCTS standalone case. For these cases, the following steps have to be performed in order to achieve a complete integration between VCTS and the conventional mobile networks:

- Hardware development and integration to ensure communications with conventional networks.
- Software development to comply with VCTS connections.
- Laboratory testing.
- Hardware installation.
- Software upgrade and configuration with new version.
- Functional testing.

In a first phase the new specifications, design and development shall be specified:

- Functional requirements specification.
- Functional architecture specification.
- Functional interface specification.
- System requirements specification.
- Operation procedures definition.
- Specification and Design of hardware parts.
- Specification and Design of software parts.
- Development, implementation and unitary test of HW.
- Development, implementation and unitary test of SW.

Next step consists of the integration and testing:

- Integration of HW and SW developments
- Validation of deployments and performance tests
- Laboratory integration with other systems and functional tests
- Functional testing

Finally, last step consists of the deployment and commissioning:

- Procurement.
- Deployment.
- Validation.
- Commissioning.

Due to the low performance requirements, direct T2T communication is not generally required due to the reduction of costs for the standalone solution. In those cases where it is required, continuous T2T communications system have to be implemented and integrated in the train backbone network. In order to perform these tasks, the same migration plan is developed for T2T and T2G.

In general, all the communications T2G/T2T are completely linked to the ACS security requirements. Thus, the standalone VCTS application for segregated lines, where generally the communication through public networks is crucial to lower the costs, requires the adaptation of the ACS system to the integration with them, i.e., the migration plan has to take into account measures to ensure secure communications through public networks.

8.6.2 Non-Technical Steps

After the process and based on the results of the aforementioned technical steps, the following steps are required:

- Creation of a standard with new specifications.
- Certification process.
- Training activities and public education project.

8.6.3 Migration Plan

From the analysis performed in the previous sections a high-level migration plan has been developed taking into account also the design performed along this X2Rail3 project, which results are in the deliverables from D7.1 to D7.4. Based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side, as well as our experience in the design, specification and deployment of control centres, the following plan has been determined:

		Year 1				*Year 2*				*Year 3*			
Activity	*Duration*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
Design and Implementation	**24 months**												
Functional requirements specification	6 months												
Functional architecture specification	4.5 months												
Functional interface specification	4.5 months												
System requirements specification	3 months												
Operation procedures definition	3 months												
Specification and Design of hardware parts	12 months												
Specification and Design of software parts	12 months												
Development, implementation and unitary test of HW	12 months												
Development, implementation and unitary test of SW	12 months												
Integration and Testing	**12 months**												
Integration of HW and SW developments	3 months							Delivery of Comms system					
Validation of deployments and performance tests	6 months												
Laboratory integration with other systems and functional tests	3 months												
On board testing	3 months												
Deployment and Commissioning	**12 months**												
Procurement	3 months												
Deployment	6 months												
Validation	6 months												
Commissioning	3 months												

Figure 8-7 T2T and T2G migration plan

8.7 Summary and Conclusion

Within this chapter of strategy for standalone VCTS, different involved systems have been analysed in order to define the procedure and the duration of the migration process of VCTS in the standalone case. These systems are: VCTS sub-system, Train Protection, TMS, ATO, Trains

(Train integrity and Positioning) and Communications. After this analysis, the following conclusions are extracted for each system:

- VCTS Sub-system:
  - The strategy for the implementation of the VCTS sub-system within the standalone application requires to elaborate the specification, design, development, integration and testing, concluding with the commissioning activities of the VCTS Sub-system itself and the interaction/integration with the other related sub-systems that provides different services to the VCTS (e.g. ACS, Train interface).
  - All these required technical tasks are shown in the migration plan of Section 8.1.3 of this document.
  - These tasks have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 3 years:
    - First 21 months in order to elaborate the specification, design, development and implementation of the HW and SW parts.
    - From the second quarter of the year two to the first quarter of the year three in order to perform the integration and testing.
    - During the third year, the deployment and commissioning tasks will be performed in order to finish the migration process.

- Train Protection (ATP and RBC):
  - The strategy for the implementation of the VCTS sub-system within the standalone application as an ATP system requires to dismantle the previous ATP system.
  - These tasks are shown in the migration plan of Section 8.2.3 of this document and have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 9 months:
    - First 7 months in order to uninstall the devices.
    - Last 2 months to perform the removal of electrical and mechanical parts.

- Traffic Management System (TMS):
  - The strategy for the implementation of the TMS sub-system within the standalone application requires to elaborate the software development, the modification of current tools, the laboratory testing, hardware upgrade to host VCTS-TS system, the interface with TMS through the Integration Layer and the ACS Gateway.
  - All these required technical tasks are shown in the migration plan of Section 8.3.3 of this document.
  - These tasks have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or

deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 3 years:
    - First 21 months in order to elaborate the specification, design, development and implementation of the SW parts.
    - From the second quarter of the year two to the first quarter of the year three in order to perform the integration and testing.
    - During the third year, the deployment and commissioning tasks will be performed in order to finish the migration process.

- Automatic Train Operation (ATO):
  - The strategy for the implementation of the ATO sub-system within the standalone application requires to elaborate the software development, the laboratory testing, the software upgrade and configuration with new version and the on-board testing.
  - All these required technical tasks are shown in the migration plan of Section 8.4.3 of this document.
  - These tasks have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 3 years:
    - First 21 months in order to elaborate the specification, design, development and implementation of the SW parts.
    - From the second quarter of the year two to the first quarter of the year three in order to perform the integration and testing.
    - During the third year, the deployment and commissioning tasks will be performed in order to finish the migration process.

- Trains (Positioning and Integrity)
  - The strategy for the implementation of the Positioning and Integrity sub-systems within the standalone application requires to elaborate the hardware development to comply with both integrity and positioning services, the software development to comply with continuous communication with VCTS-OB, laboratory testing, hardware installation, the software upgrade and configuration with new version and the on board testing.
  - All these required technical tasks are shown in the migration plan of Section 8.5.3 of this document.
  - These tasks have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 3 years:
    - First 21 months in order to elaborate the specification, design, development and implementation of the HW and SW parts.
    - From the second quarter of the year two to the first quarter of the year three in order to perform the integration and testing.

- During the third year, the deployment and commissioning tasks will be performed in order to finish the migration process.

- Communications:
    - The strategy for the implementation of Communications system within the standalone application requires to elaborate the hardware development and integration to ensure communications with conventional networks, the software development to comply with VCTS connections, the laboratory testing, the HW installation, the SW upgrade and configuration with new version and the functional testing.
    - All these required technical tasks are shown in the migration plan of Section 8.6.3 of this document.
    - These tasks have been specified by the use of a Gantt diagram, based on our experience in the railway sector, especially in terms of migration and/or deployment of safety solutions, both on board and infrastructure side. It requires a migration plan of 3 years:
        - First 24 months in order to elaborate the specification, design, development and implementation of the HW and SW parts.
        - From the second quarter of the year two to the first quarter of the year three in order to perform the integration and testing.
        - During the third year, the deployment and commissioning tasks will be performed in order to finish the migration process.

Thus, after all the analyses performed in this chapter, we can determine how all these migration actions might be elaborated in a parallel way, optimizing the time for deployment and implementation of the complete VCTS system for standalone case. In order to complete the migration to VCTS standalone, the VCTS sub-system has to be successfully integrated with all the other related systems mentioned in this chapter due to the required interaction with them in order to perform all the VCTS functionality.

The migration plan of the previous Train Protection systems does not have any impact with all the migration steps defined for the VCTS sub-system due to this plan only requires of the dismantling of the previous system and this can be carried out in parallel with all the VCTS sub-system defined processes.

The evaluation of the other sub-systems migration plans has been developed taking into account the possibility of reducing the complete time for implementation, adjusting all the possible parallel tasks in order to complete the deployment and commissioning in a coordinate way, taking into account the technical differences in the implementation of each sub-system. Then, in the case of the TMS, the deployment and validation steps are depicted in parallel with the VCTS sub-system ones. This process has been designed based on the differences between both systems, where the defined periods consider both the individual requirements and the combinational requirements. This allows the parallelization of specific deployment and validation tasks of each system and the subsequent validation tasks for the combination of the sub-systems features that brings the whole VCTS standalone complete functionality. Therefore, the validation and commissioning tasks depicted in both subsections have been defined in order to include the complete process of the VCTS standalone application case migration.

Similar assumptions have been taken with the rest of the sub-systems analysed in this chapter: ATO, Train Integrity, Positioning and Communications. In the case of Train Integrity, Positioning and Communications the analysis was elaborated based on the same premises than the TMS case. These final steps of Validation and Commissioning in the migration plan are planned in the same time slots than the VCTS sub-system in order to validate first the independent systems and, in a second phase, validate the combined functionality within the complete VCTS standalone approach. Then, the extracted conclusions are the same than in the analysis performed for TMS sub-system.

Regarding to ATO sub-system, there are slight differences with respect to the previous systems in terms of the duration of the complete migration process. This is mainly related to the difference of time required to the requirements definition phase development, due to the minor changes defined for the ATO sub-system within the VCTS standalone application case, in comparison with the other systems. However, this also has been included in the whole migration plan process, coordinating also the validation and commissioning phases of the ATO with the first part of the VCTS sub-system validation and commissioning phases. This allows both the validation of the system itself and the complete functionality of the combination with the VCTS sub-system required for the complete defined VCTS standalone functionality.

8.7.1 Conclusion

In conclusion, the entire migration plan has been developed optimizing the time and minimizing the risks with the aim of performing all the activities in a highly parallel way. It shows that a period of three years for the finalization of a complete migration process in low traffic lines is feasible.

9 Strategy and Vision for ETCS-Based VCTS

This chapter addresses a migration plan for the ETCS application case according to the architecture described above in Figure 7-1. The assumptions are referring to an ETCS system implementing On-Board Train Integrity, Train Length determination and adopting a radio communication system compliant to FRMCS.

The sub-systems evaluated in this analysis are VCTS-OB and VCTS-TS, ATP and RBC, TMS, ATO, OTI and the radio communication system.

For these sub-systems this document provides an analysis of an expected migration plan focused on technical steps, non-technical steps and finally a summary of the high-level migration plan.

The migration plan proposed in Figure 9-1 is intended as an integrated plan to implement and test a first complete demonstrator for the Virtual Coupling (VC) system on-site in a period of three years.

	Activity	Duration	Predecessors
1	**Specification**	**360 days**	
2	Functional Requirements and Interface Specifications	260 days	
3	Operational Procedures	100 days	2
4	**Implementation**	**620 days**	**1SS**
5	Hardware design and development (VCTS-OB, VCTS-TS)	360 days	
6	**Software development (VCTS-OB, VCTS-TS)**	**360 days**	
7	Functional implementation	260 days	
8	Interfaces implementation	100 days	2;7
9	Software design development (RBC, TMS, ATP, ATO)	180 days	3
10	HW/SW integration and sub-system level	40 days	6;5;9
11	Functional testing and sub-system level	40 days	10
12	**Laboratory integration and testing**	**80 days**	**4**
13	System Integration activities	40 days	
14	System Functional Testing	40 days	13
15	**Site testing activities**	**60 days**	**12**
16	On-Board HW installation (VCTS-OB)	20 days	
17	On-Board SW installation (VCTS, ATP, ATO)	1 day	
18	Trackside HW installation (VCTS-TS)	20 days	
19	Trackside SW installation (RBC, TMS)	1 day	17
20	System integration	20 days	19;16;17;18
21	System functional testing	20 days	20
22	Safety and Security assessment	20 days	1;4;12;15

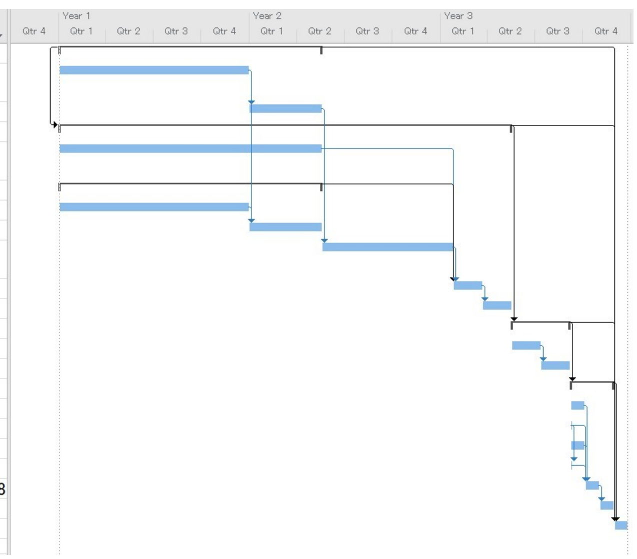


Figure 9-1 General implementation and testing plan

The analysis also includes a real application case in Germany, a business model evaluation according to LinX4Rail guidelines [13] and finally a proposal for integrating Virtual Coupling functionality in RCA and OCORA reference architectures.

9.1 VCTS-OB Sub-system

9.1.1 Technical Steps

The high-level migration plan proposed in the following is based on the VCTS concept and specification work defined within the framework of the X2Rail-3 project.

No further specification work is foreseen for this sub-system as it has been extensively developed in previous X2Rail-3 project documents.

Since the VCTS system will be the core of train control for improving performance and reliability, one of the most important tasks is the implementation phase that would include:

- Hardware development compliant to VCTS-OB specifications
- Software development to implement Virtual Coupling functionalities
- Sub-system laboratory functional testing

A relevant effort refers to integration activities with other sub-systems including the handover functions with the ATP sub-system during set-up and termination procedures and train protection management during coupled driving. In addition, VCTS-OB communicates with VCTS-TS to acquire data about platoon composition and with other VCTS-OBs to exchange additional information acquired from OTI, ATP (e.g., train integrity, position, speed, breaking status) thus respecting safe distance and assigned headway. Finally, VCTS-OB communicates with ATO in platoon composition procedures and in the coupled driving phase.

As for all the sub-systems subsequently analysed, laboratory test campaigns are planned to verify the quality of the product before on-field testing.

For the installation aspect of VCTS-OB, it is necessary to perform a target train survey and to provide mechanical and electrical designs to host a VCTS-OB unit and related wiring towards ATP, ATO, JRU, Radio and TCMS.

The last step would consist in on-board installation and testing implying at least:

- Hardware and Software installation for VCTS-OB
- Software upgrade and configuration for ATP and ATO
- On-board integration and functional testing execution

Note that VCTS-TS sub-system implementation and testing is addressed in Section 9.2.

An onboard-trackside integration test campaign must be conducted after the functional tests of each sub-systems to verify the functionality of the entire system.

9.1.2 Non-Technical Steps

Based on the results of specification, implementation and site testing activities, the following steps should be addressed:

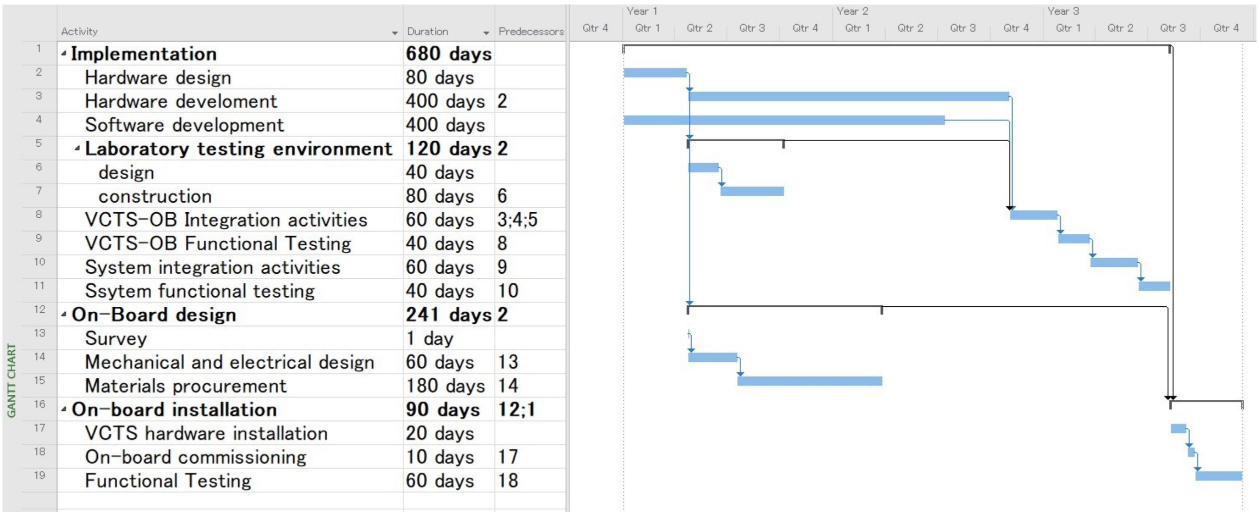
- Standardization proposal formulation for new specifications and related operational procedures
- Certification process
- Training activities

VCTS-OB requires extensive certification work as it has to take responsibility over ATP in coupled driving.

Finally, a migration plan in terms of installation in existing railway networks can be formulated.

9.1.3 Migration Plan

A migration plan for VCTS-OB, based on the steps detailed in the previous sections, is shown in Figure 9-2. Further activities related to the certification process and standardization proposal formulation need to be taken into account.



	Activity	Duration	Predecessors
1	**Implementation**	**680 days**	
2	Hardware design	80 days	
3	Hardware develoment	400 days	2
4	Software development	400 days	
5	**Laboratory testing environment**	**120 days**	**2**
6	design	40 days	
7	construction	80 days	6
8	VCTS-OB Integration activities	60 days	3;4;5
9	VCTS-OB Functional Testing	40 days	8
10	System integration activities	60 days	9
11	Ssytem functional testing	40 days	10
12	**On-Board design**	**241 days**	**2**
13	Survey	1 day	
14	Mechanical and electrical design	60 days	13
15	Materials procurement	180 days	14
16	**On-board installation**	**90 days**	**12;1**
17	VCTS hardware installation	20 days	
18	On-board commissioning	10 days	17
19	Functional Testing	60 days	18

Figure 9-2 VCTS-OB implementation and testing plan

9.2 VCTS-TS Sub-system

9.2.1 Technical Steps

As mentioned in the previous paragraph, the high-level migration plan is based on requirements defined within the X2Rail-3 project framework, therefore no further specification activities are planned.

The implementation phase would include:

- Hardware development compliant to VCTS-TS specifications
- Software development for platoon management functionalities
- Sub-system laboratory functional testing

For the hardware design, it is advisable to use an already developed platform, thus reducing design and certification duration and effort. The platform needs to host at least an Ethernet interface to communicate with the TMS and a Radio FRMCS interface to be able to communicate with VCTS-OBs. If these interfaces are not present, they need to be developed.

Since the TMS does not provide any safety integrity level (SIL), the VCTS-TS sub-system must acquire the information received from it and send it to the various VCTS-OBs in order to guarantee SIL4. Testing specification for laboratory and site phases are also required.

The last step would consist in site installation and testing, implying at least:

- Hardware installation for the VCTS-TS sub-system, interface with TMS by means of Integration Layer, ACS Gateway for FRMCS communication towards VCTS-OB entities.
- TMS software upgrade and configuration for platoon timetable management
- Integration and functional testing execution

An onboard-trackside integration test campaign must be conducted after the functional tests of each sub-system to verify the functionality of the entire system.

9.2.2 Non-Technical Steps

Based on results of specification, implementation and site testing activities, the following steps should be addressed:

- standardization proposal formulation for new specifications and related operational procedures
- certification process
- training activities

This sub-system implements new safety-critical functionalities, therefore a validation and certification process is required. Introducing new operational rules for platoon management requires a training phase for TMS operators.

Finally, a migration plan in terms of installation in existing railway network can be formulated.

9.2.3 Migration Plan

A migration plan for VCTS-TS, based on the steps detailed in the previous sections, is shown in Figure 9-3. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

	Activity	Duration	Predecessors
1	**Implementation**	**270 days**	
2	Hardware design	20 days	
3	Hardware develoment	80 days	2
4	Software development	100 days	
5	**Laboratory testing environment**	**80 days**	**2**
6	design	20 days	
7	construction	60 days	6
8	VCTS-TS Integration activities	50 days	3;4;5
9	VCTS-TS Functional Testing	30 days	8
10	System integration activities	50 days	9
11	Sisytem functional testing	40 days	10
12	**Specific application design**	**241 days**	**2**
13	Survey	1 day	
14	Mechanical and electrical design	60 days	13
15	Materials procurement	180 days	14
16	**Installation**	**80 days**	**12;1**
17	VCTS hardware installation	20 days	
18	On-board commissioning	10 days	17
19	Functional Testing	50 days	18

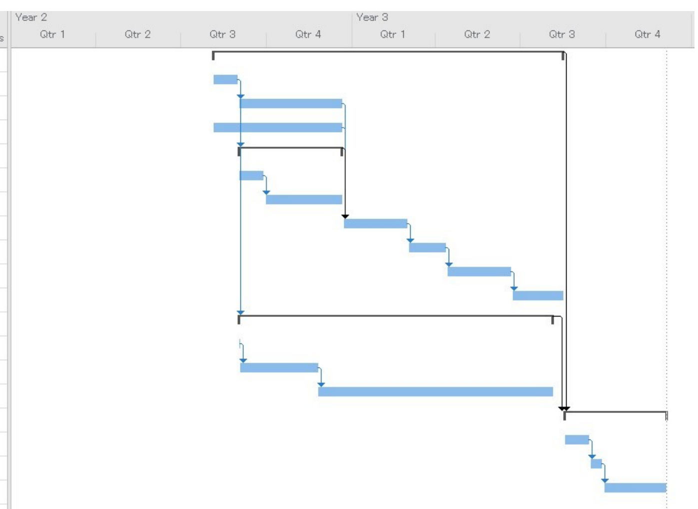


Figure 9-3 VCTS-TS implementation and testing plan

9.3 Train Protection On-board and Trackside (ATP and RBC)

9.3.1 Technical Steps

The plan proposed in the following is based on Virtual Coupling requirements specified in X2Rail-3 Task 7.3 and the impact analysis performed in Task 7.4. The first step of an overall migration plan implies a detailed RBC and ATP specification activity to host virtual coupling functionalities. At least the specification work would need to address updating:

- Functional Requirements Specifications
- Functional Architecture Specification
- Functional Interface Specification
- Operator Interface Specification
- System Requirements Specification
- Operation Procedures

Functional requirements need to be updated for both RBC and ATP to define the behaviour of the system and how these have to communicate with other sub-systems.

New interfaces are required between ATP and VCTS-OB; this interface is necessary to handle the handover between ATP during the ETCS Level 2 / Level 3 normal operation and the Virtual Coupling operation when the VCTS-OB takes responsibility of train protection for the trains.

The interfaces regarding RBC need to be updated. The TMS will provide new information to VCTS-TS about platoon formation and platoon timetables and will receive the position and updated length of the platoon from RBC. The interface between RBC and ETCS-OB require additional information at least in Position Report (PR) and Movement Authority (MA) messages, specifically for master and slave trains. Finally, the interface RBC-RBC need to manage handovers of platoons.

The HMI of RBC requires an extension to permit the operator to have all the information about platoons and trains running on the line (e.g., with different icons or different colours).

Since no further Driver Machine Interface (DMI) for VTCS is planned, the ATP DMI will provide all information related to VCTS functionality such as set-up and termination procedures.

The main new functions for RBC refer to assigning a MA to a platoon with unique ID, to handle dynamic changes of platoon length and composition. The main new functions for ATP consist in providing dynamic data to VCTS-OB (e.g., current speed and position), managing the hand-over procedures with VCTS-OB and the communications with RBC.

The RBC implementation phase would include:

- Software development to manage movement authority and position report for platoons
- Tools upgrade to manage platoon data
- RBC configuration process for platoons
- Laboratory functional testing

All the RBC functionalities described above and defined in the specification phase must be developed and configured in the specific plan and tested in the laboratory.

The last step consists of site testing implying at least:

- Software upgrade and configuration with new version for platoon traffic management
- Functional testing execution

ATP also requires a specification phase for platoon-related functions (e.g., new interface with VCTS-OB, handover procedures, new information in interface with RBC), at least a software upgrade to manage the new interaction with VCTS-OB over an Ethernet link, new visualizations on DMI, new messages to RBC. Testing specification for laboratory and site phases are also required. As for other involved sub-systems, a final integrated test campaign is planned to verify the complete system behaviour on field.

9.3.2 Non-Technical Steps

Based on results of specification, implementation and site testing activities, the following steps should be addressed:

- standardization proposal formulation for new specifications and related operational procedures
- certification process
- training activities

Since the RBC and ATP systems are safety-critical systems with SIL4 target (the highest), it's verification and validation activities need to be executed and a safety case has to be provided.

Finally, a training campaign is required for both control room operators and drivers to learn the new functions and new operating procedures.

9.3.3 Migration Plan

A migration plan for RBC, based on the steps detailed in the previous sections, is shown in Figure 9-4. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

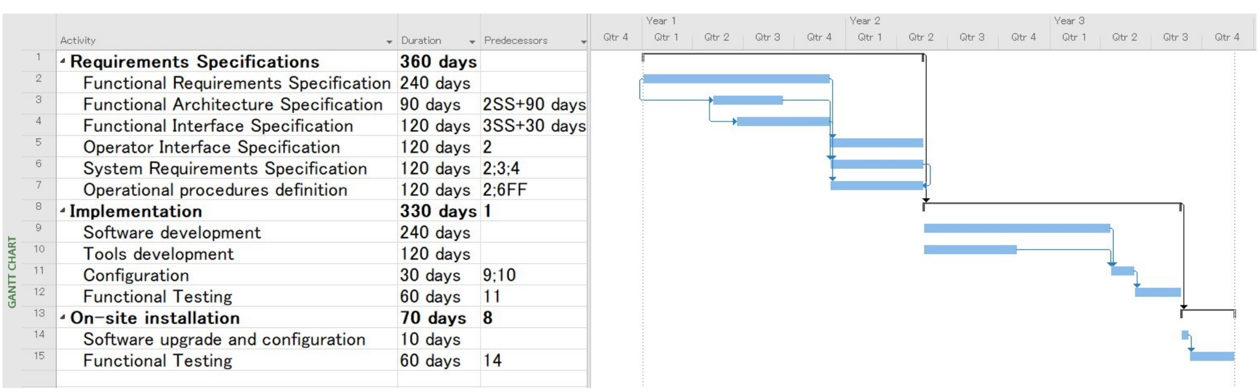

	Activity	Duration	Predecessors
1	**Requirements Specifications**	**360 days**	
2	Functional Requirements Specification	240 days	
3	Functional Architecture Specification	90 days	2SS+90 days
4	Functional Interface Specification	120 days	3SS+30 days
5	Operator Interface Specification	120 days	2
6	System Requirements Specification	120 days	2;3;4
7	Operational procedures definition	120 days	2;6FF
8	**Implementation**	**330 days**	**1**
9	Software development	240 days	
10	Tools development	120 days	
11	Configuration	30 days	9;10
12	Functional Testing	60 days	11
13	**On-site installation**	**70 days**	**8**
14	Software upgrade and configuration	10 days	
15	Functional Testing	60 days	14

Figure 9-4 RBC implementation and testing plan

A migration plan for ATP, based on the steps detailed in the previous sections, is shown in Figure 9-5. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

GANTT CHART

	Activity	Duration	Predecessors
1	**Requirements Specifications**	**360 days**	
2	Functional Requirements Specification	240 days	
3	Functional Architecture Specification	90 days	2SS+90 days
4	Functional Interface Specification	120 days	3SS+30 days
5	Operator Interface Specification	120 days	2
6	System Requirements Specification	120 days	2;3;4
7	Operational procedures definition	120 days	2;6FF
8	**Implementation**	**300 days**	**1**
9	Software development	240 days	
10	Functional Testing	60 days	9
11	**On-board installation**	**90 days**	**8**
12	Hardware upgrade	20 days	
13	Software upgrade and configuration	10 days	12
14	Functional Testing	60 days	13

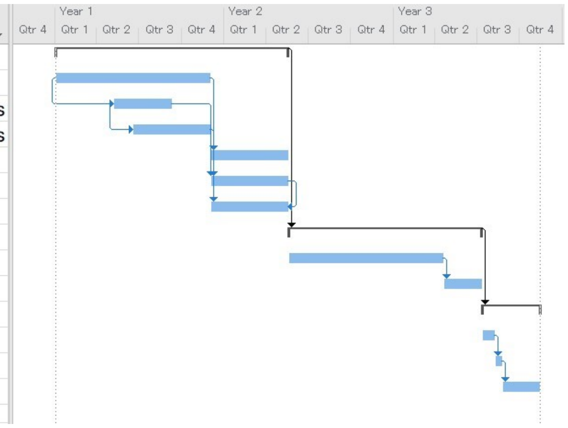


Figure 9-5 ATP implementation and testing plan

9.4 Traffic Management System

9.4.1 Technical Steps

The high-level migration plan proposed in the following is based on new generation TMS as specified within TMS TD2.9 (e.g., Canonical Data Model and Integration Layer). Based on Virtual Coupling specifications and impact analysis, the first step of a migration plan implies a detailed TMS specification phase to host virtual coupling functionality. At least the TMS specification work would need to be addressed for updating:

- Functional Requirements Specifications
- Functional Architecture Specification
- Functional Interface Specification
- Operator Interface Specification
- System Requirements Specification
- Operation Procedures Definition

The requirements activities need to consider platoon composition data and platoon timetables as well as performance and reliability aspects. In this context, new data (e.g., platoon identifier and platoon composition) need to be added in the Canonical Data Model (CDM) and a new physical TMS-VCTS interface is required implying for example update of the integration layer communication protocol. Finally, the existing RBC-TMS interface needs an update to include the platoons' status in terms of dynamic length and position.

Similar to RBC, also the TMS operator interface needs an update to show platoons and trains in a different way and to manage the platoons' operational procedures.

The implementation phase would include:

- Software development in relation to traffic management for platoons including data related to platoon composition and platoon timetable.

- Tools development to generate platoon timetables
- TMS configuration process for platoons
- Laboratory functional testing

In the implementation phase, the VCTS functionalities are integrated into TMS; the main functionalities necessary for this purpose are to manage and define all the platoon entities with new logic that aggregates trains to form the platoon and assign a unique ID to it, a conflict manager to monitor and to solve possible clashes. In addition, the database with CDM needs to be updated in order to include VCTS platoons. Finally, it is necessary to develop a tool to generate platoon timetables analogously to those of trains.

Testing specification for laboratory and site phases are also required.

Since the TMS is bound to the design of the specific project, a configuration phase is also required to implement the previously defined functionality.

The last step consists of site testing implying at least:

- Hardware upgrade for TMS-VCTS interface
- Software upgrade and configuration with new version for platoon traffic management
- Functional testing execution

9.4.2 Non-Technical Steps

Based on results of specification, implementation and site testing activities, the following steps should be addressed:

- standardization proposal formulation for new specifications and related operational procedures
- certification process
- training activities

TMS does not need a safety related change since this system is not SIL4, the safety-critical functions are hosted in the VCTS-TS sub-system. In relation to newly defined operational rules, training activities are necessary for new platoon functions and visualizations of the HMI and new platoon timetables.

Finally, a migration plan in terms of installation in existing railway network can be formulated.

9.4.3 Migration Plan

A migration plan for TMS, based on the steps detailed in the previous sections, is shown in Figure 9-6. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

GANTT CHART

	activity	Duration	Predecessors
1	Requirements Specifications	360 days	
2	Functional Requirements Specification	240 days	
3	Functional Architecture Specification	90 days	2SS+90 days
4	Functional Interface Specification	120 days	3SS+30 days
5	Operator Interface Specification	120 days	2
6	System Requirements Specification	120 days	2;3;4
7	Operational procedures definition	120 days	2;6FF
8	Implementation	330 days	1
9	Software development	240 days	
10	Tools development	120 days	
11	Configuration	30 days	9;10
12	Functional Testing	60 days	11
13	On-site installation	90 days	8
14	Hardware upgrade	20 days	
15	Software upgrade and configuration	10 days	14
16	Functional Testing	60 days	15

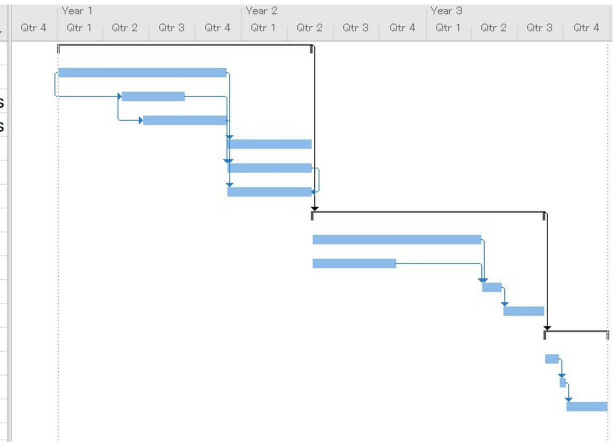


Figure 9-6 TMS implementation and testing plan

9.5 Automatic Train Operation

9.5.1 Technical Steps

The high-level migration plan proposed in the following is based on ATO with GoA2. Based on Virtual Coupling specifications and impact analysis, the first step of a migration plan implies a detailed ATO specification phase to analyse the VCTS functionality. At least the ATO specification work would need to be address for updating:

- Functional Requirements Specifications
- Functional Architecture Specification
- Functional Interface Specification
- Operator Interface Specification
- System Requirements Specification
- Operation Procedures Definition

In order to obtain a good degree of efficiency, ATO is required to manage the dynamic coupling/decoupling procedures and to keep appropriate distancing between the trains of the platoon with autonomous driving. In this context, the ATO must involve a change in its architecture to be able to communicate with VCTS-OB. The handover between the different modes must also be developed both at the level of operational procedures and at the level of interface with the driver. ATP supervises the safety-critical handover procedure between ATP and VCTS-OB.

The implementation phase would include:

- Software development to cooperate in platoon set-up/termination procedures, communication with VCTS-OB and dynamic control of speed and distance in coupled driving
- Laboratory functional testing

No hardware development is planned since the ATO system considered is GoA2 (semi-automatic operation).

The last step consists of site testing implying at least:

- Software upgrade and configuration
- Functional testing execution

Testing specification for laboratory and site phases are also required.

9.5.2 Non-Technical Steps

Based on results of specification, implementation and site testing activities, the following steps are required:

- standardization proposal formulation for new specifications and related operational procedures
- certification process
- training activities

Similar to ATP, drivers need to learn operating procedures about handover and degraded situations. Furthermore, a training campaign is required due to the update of DMI.

Finally, a migration plan in terms of installation in existing railway network can be formulated.

9.5.3 Migration Plan

A migration plan for ATO, based on the steps detailed in the previous sections, is shown in Figure 9-7. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

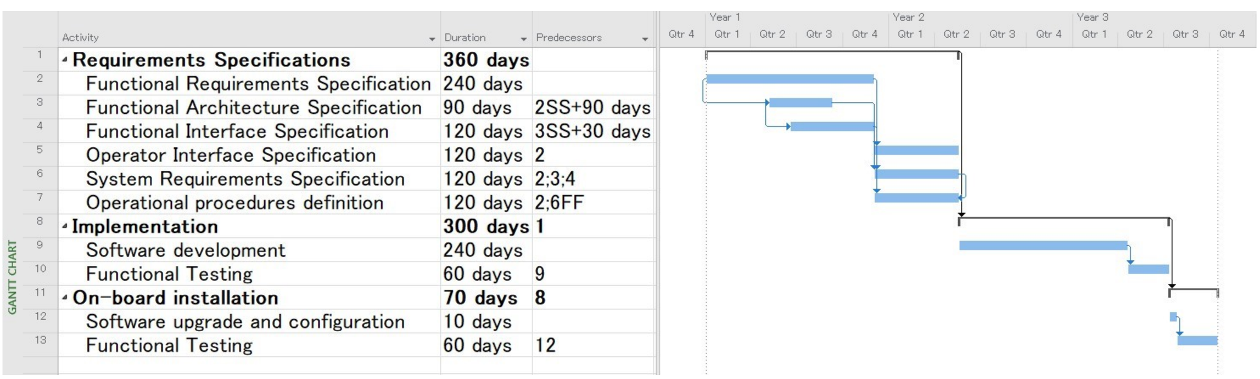


Figure 9-7 ATO implementation and testing plan

9.6 On-board Train Integrity

9.6.1 Technical Steps

According to TD2.5 safety analysis and requirement specifications, the safety target for on-board train integrity is SIL2 and the safety target for train length determination is SIL4. The OTI specification work also included two options for an OTI-ETCS interface: *base option*, which only provides integrity status to ETCS, and *enhanced option*, which additionally provides OTI equipment status and latency of train integrity status. The period recommended for passenger applications with Moving Blocks functionality is 1 sec, which can be applicable for VCTS as well.

The VCTS functional architecture for ETCS applications [D7.2] remarked that SIL4 is the safety target required for on-board train integrity functionality in virtual coupling applications. To ensure good performances, the train integrity status needs to be acquired by ETCS directly from OTI and not through the ATP.

The high-level migration plan proposed in the following is based on the enhanced interface option for OTI-ETCS interface and SIL4 as OTI safety target both for on-board train integrity and train length determination functionalities.

In general, the OTI equipment for VCTS applications needs to ensure a SIL4 safety target, provide direct enhanced interface to VCTS-OB and a shorter communication period (less than 1 sec).

OTI SIL4 is not yet a baseline so it could be necessary to upgrade a OTI SIL2 sub-system for on-board train integrity functionality that grant the expected VCTS safety target. In case the OTI devices provide both function with SIL4 safety target, no impact in expected.

Minor changes are required to implement communication between OTI and VCTS-OB. In the considered VCTS architecture, it means an additional logical channel over the existing Ethernet physical interface.

In case the preceding train derails, its braking space would be shorter than the emergency brake space. This situation could lead to trains collision. A mitigation could consist in adopting derailment detection system at on-board level. In case a derailment detection function is embedded in OTI sub-system, then hardware and software development, integration and testing activities should be considered.

9.6.2 Non-Technical Steps

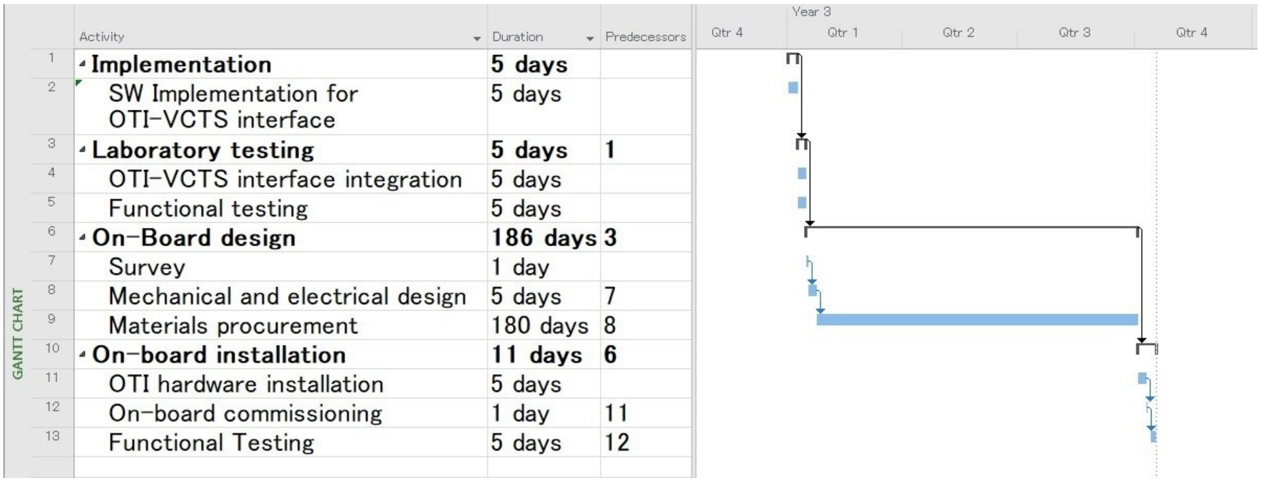
Based on results of implementation, laboratory and site testing activities, the following steps should be addressed:

- formulation of a standardization proposal for SIL4 safety target for on-board train integrity and for an additional OTI-VCTS interface
- certification process

9.6.3 Migration Plan

A migration plan for OTI, based on the steps detailed in the previous sections, is shown in Figure 9-7. Further activities related to the certification process and standardization proposal formulation need to be taken into account.

The assumption is that on-board train integrity and train length determination functionality are hosted within same OTI SIL4 platform, therefore no hardware upgrade is required.



	Activity	Duration	Predecessors
1	**Implementation**	**5 days**	
2	SW Implementation for OTI-VCTS interface	5 days	
3	**Laboratory testing**	**5 days**	**1**
4	OTI-VCTS interface integration	5 days	
5	Functional testing	5 days	
6	**On-Board design**	**186 days**	**3**
7	Survey	1 day	
8	Mechanical and electrical design	5 days	7
9	Materials procurement	180 days	8
10	**On-board installation**	**11 days**	**6**
11	OTI hardware installation	5 days	
12	On-board commissioning	1 day	11
13	Functional Testing	5 days	12

Figure 9-8 OTI implementation and testing plan

9.7 Communications (T2T and T2G)

9.7.1 Technical Steps

The impact analysis is based on the assumption that the trains are already equipped with ETCS and FRMCS equipment. In this context, a migration plan includes at first a comparison between latest FRMCS specifications and VCTS communication needs. The ACS Gateway (i.e., the FRMCS on-board device) need to be configured according to VCTS communication needs for T2T and T2G communications. Similar to RBC-ETCS communication, also the VCTS T2T and T2G communications need an appropriate protocol to ensure the required safety and security communication level (e.g., a new version of the EURORADIO Safety Layer). Communication tests need to be performed in the laboratory before integration with the overall Virtual Coupling system for subsequent site testing. The timeframe for the quoted activities could be less than 1 year, anyway shorter than the timeframe related to other sub-systems (e.g. RBC or TMS).

9.7.2 Non-Technical Steps

The standardization process should be addressed after evaluating system performances in the context of site integration test. A certification is required to assess the safety and security grade of the communication system.

9.7.3 Migration Plan

Main activities consist in software integration of latest version of Safety Layer Euro-radio, complaint to security regulations, within the VCTS communication context (i.e. VCTS-OB and VCTS-TS sub-systems).

9.8 Risk and Opportunities

The main criticalities in the presented plan toile in achieving coherence among the overall specification activities, which could require longer time. In addition, laboratory and on-field system integration have a relevant complexity that could require longer than estimated. Considering the safety and security implications transversal to the entire system, the final assessment also requires significant effort. For these reasons, the proposed plan could have a duration between 3 and 5 years. The overall duration also depends on resources assigned to planned activities.

The presented plan includes hardware upgrades at VCTS-OB and VCTS-TS level. Another alternative consists in hosting these functionalities respectively within ATP and RBC, thus limiting the plan to software implementation activities. This option would simplify the complexity and the duration for overall implementation and testing and would simplify the overall migration in real applications that would be limited to software upgrades.

9.9 Vision for a VCTS Implementation based on the RCA and OCORA reference architectures

9.9.1 Introduction

Assuming a vision of a railway architecture based on current efforts to provide open and modular standards (the RCA system architecture and OCORA on-board architecture), this section describes a high-level impact analysis and migration plan for implementing ETCS-based VCTS.

9.9.2 RCA and OCORA overview

RCA is an initiative of the ERTMS Users Group (EUG) and the EULYNX consortium aimed at defining a reference Control Command and Signalling (CCS) architecture to increase performances compared to existing implementations (in terms of cost, reliability, safety, capacity and fast migration). These improvements shall be achieved by defining an open framework that allows the development of functionality in replaceable modules.

The figure reported below is extracted from the public RCA documentation[6] and depicts main components and related high-level functionalities.

[6] https://ertms.be

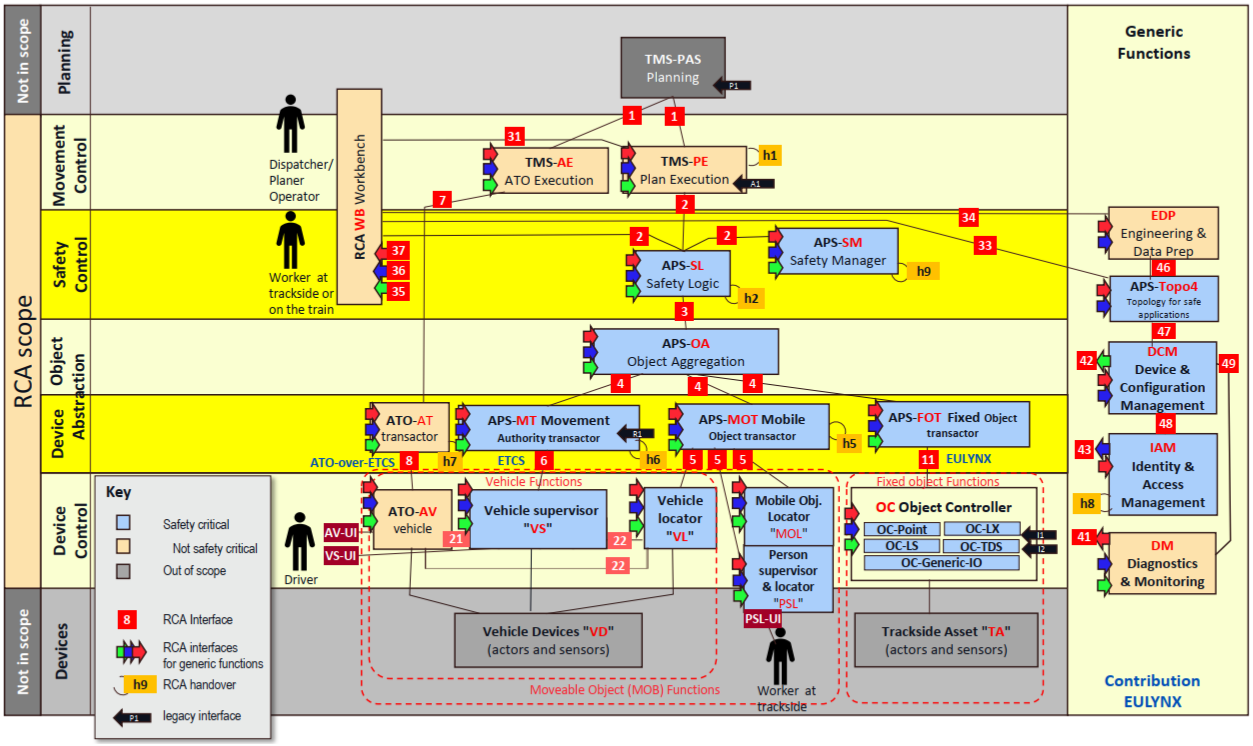


Figure 9-9 RCA reference architecture

Open CCS On-board Reference Architecture (OCORA) initiative promoted by NS, SNCF, DB, SBB and ÖBB. As stated in OCORA public documentation[7], this initiative aims at reducing life-cycle costs and facilitating the introduction of innovation and digital technologies beyond the current proprietary interfaces, by establishing a modular, upgradeable, reliable and secure CCS on-board architecture.

The figures reported below are extracted from OCORA public documentation and depicts the components and related interfaces for the defined on-board architecture. The OCORA initiative also formulates a proposal with a modular approach for the computing platform.

[7] https://github.com/OCORA-Public/Publication

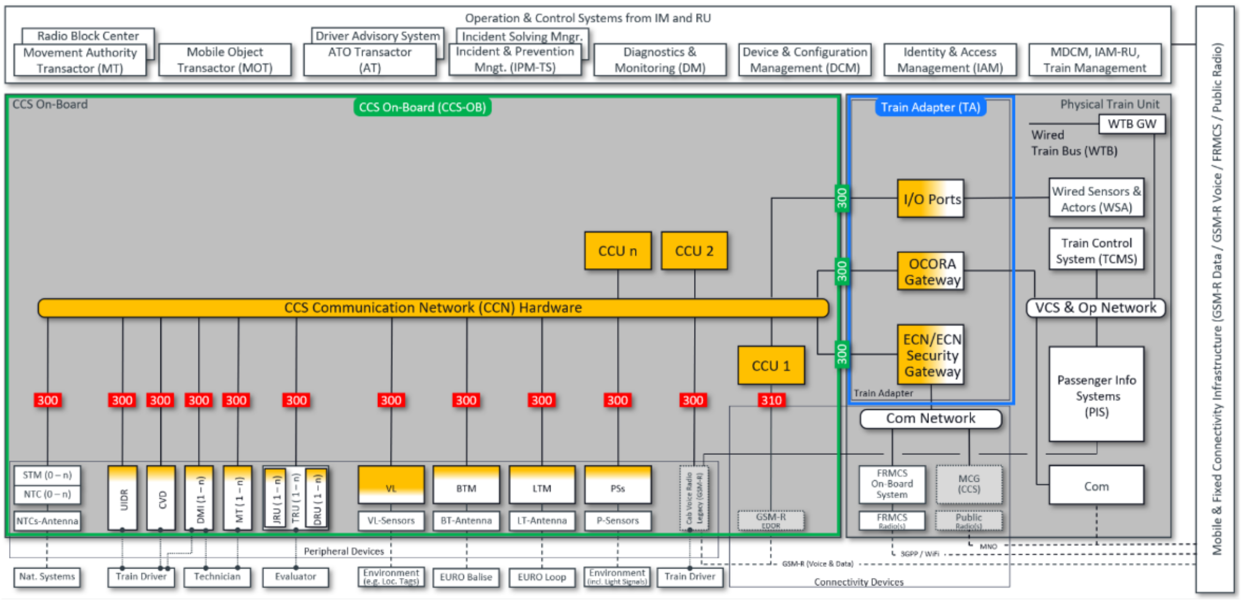


Figure 9-10 OCORA reference architecture

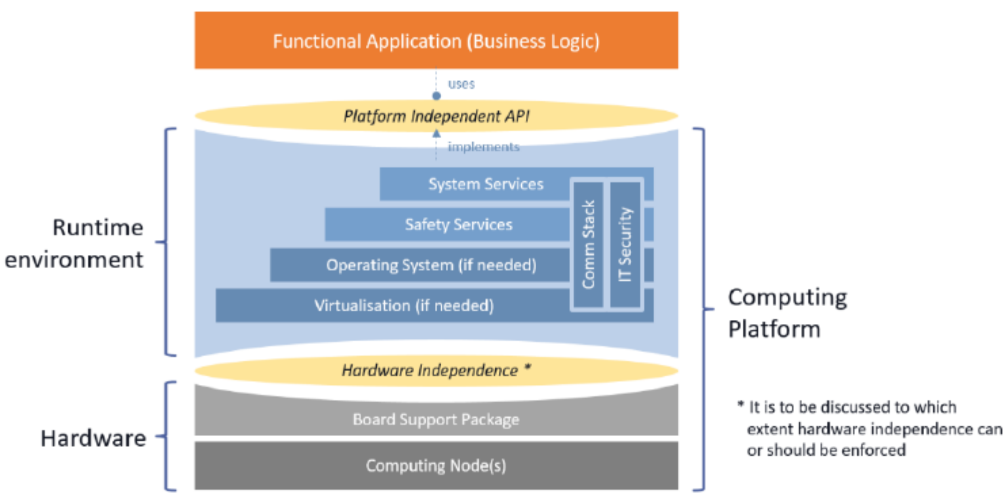


Figure 9-11 OCORA computing platform

In summary, RCA represents the trackside and OCORA the on-board effort for an open reference architecture, respectively.

9.9.3 Impact Analysis

In the RCA system architecture, the following high-level implications should be considered to host VCTS trackside functionalities:

- hosting platoon planning functionality in “TMS Plan Execution” component
- hosting VCTS-TS functionalities for platoon set-up and termination in “APS MT Movement Authorities transactions”

- hosting movement authority and position report management for platoons in “APS MT Movement Authorities transactions”

In OCORA on-board architecture, the following high-level implications should be considered to host VCTS on-board functionalities:

- Hosting VCTS-OB application in on-board safe platform
- Integrating in ATO application the functionalities to manage interactions with VCTS-OB application
- Integrating in ATP application the functionalities to manage interactions with VCTS-OB application

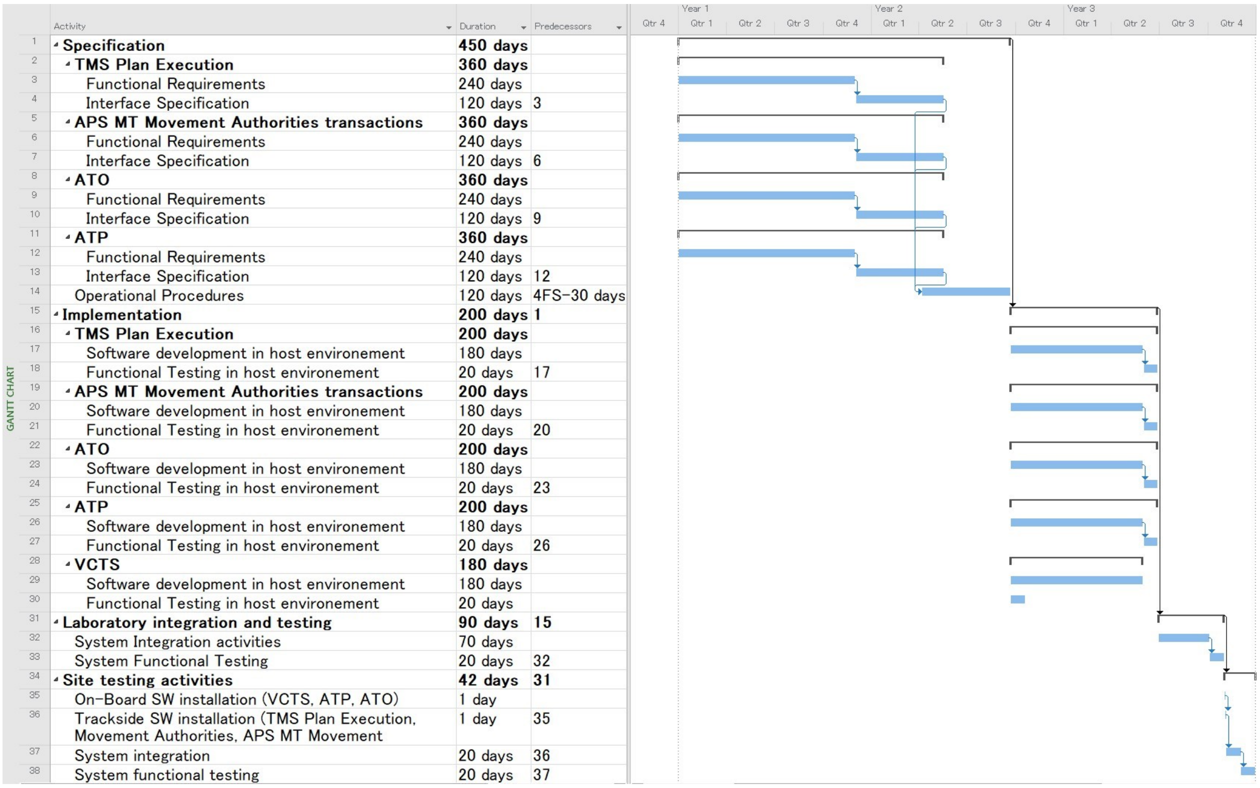
In conclusion, the integration of Virtual Coupling functionalities in RCA and OCORA initiatives would result in implementing new functionalities within defined system and on-board reference architecture.

9.9.4 Migration Plan

The assumption is the availability of an implementation for RCA and OCORA reference architectures.

The implementation of VCTS functionalities in RCA and OCORA reference architecture implies a specification phase to host new functionalities in defined components and interface specification phase to include new messages in defined interfaces. Then the laboratory activities for implementation, system integration and functional testing. Finally on-site deployment, integration and testing.

Figure 4 depicts an implementation plan with a hypothetical start date. Proposed planning addresses specification, implementation and testing activities within 3 years.



	Activity	Duration	Predecessors
1	**Specification**	**450 days**	
2	**TMS Plan Execution**	**360 days**	
3	Functional Requirements	240 days	
4	Interface Specification	120 days	3
5	**APS MT Movement Authorities transactions**	**360 days**	
6	Functional Requirements	240 days	
7	Interface Specification	120 days	6
8	**ATO**	**360 days**	
9	Functional Requirements	240 days	
10	Interface Specification	120 days	9
11	**ATP**	**360 days**	
12	Functional Requirements	240 days	
13	Interface Specification	120 days	12
14	Operational Procedures	120 days	4FS-30 days
15	**Implementation**	**200 days**	**1**
16	**TMS Plan Execution**	**200 days**	
17	Software development in host environement	180 days	
18	Functional Testing in host environement	20 days	17
19	**APS MT Movement Authorities transactions**	**200 days**	
20	Software development in host environement	180 days	
21	Functional Testing in host environement	20 days	20
22	**ATO**	**200 days**	
23	Software development in host environement	180 days	
24	Functional Testing in host environement	20 days	23
25	**ATP**	**200 days**	
26	Software development in host environement	180 days	
27	Functional Testing in host environement	20 days	26
28	**VCTS**	**180 days**	
29	Software development in host environement	180 days	
30	Functional Testing in host environement	20 days	
31	**Laboratory integration and testing**	**90 days**	**15**
32	System Integration activities	70 days	
33	System Functional Testing	20 days	32
34	**Site testing activities**	**42 days**	**31**
35	On-Board SW installation (VCTS, ATP, ATO)	1 day	
36	Trackside SW installation (TMS Plan Execution, Movement Authorities, APS MT Movement	1 day	35
37	System integration	20 days	36
38	System functional testing	20 days	37

Figure 9-12 VCTS implementation plan in RCA and OCORA context

9.9.5 Conclusion

The analysis above reported demonstrates that implementing Virtual Coupling functionality in the RCA and OCORA reference architectures would imply software implementation, laboratory and site testing activities without hardware impacts. This means, having open and modular reference architecture, the efforts required for implementing ETCS-based VCTS would be greatly reduced.

9.10 Application Example: Munich – Bremen – Hannover – Hamburg

In the following, the possibility of using VCTS on existing lines of the German rail network (DB) is analysed and discussed in a case study.

9.10.1 Input

This section provides input data based on real data provided by Deutsche Bahn.

The lines considered are:

- Munich Hbf – Hannover Hbf (640 km) in Figure 9-13
- Hannover Hbf – Bremen Hbf (124 km) in Figure 9-14
- Hannover Hbf – Hamburg Hbf (180 km) in Figure 9-15

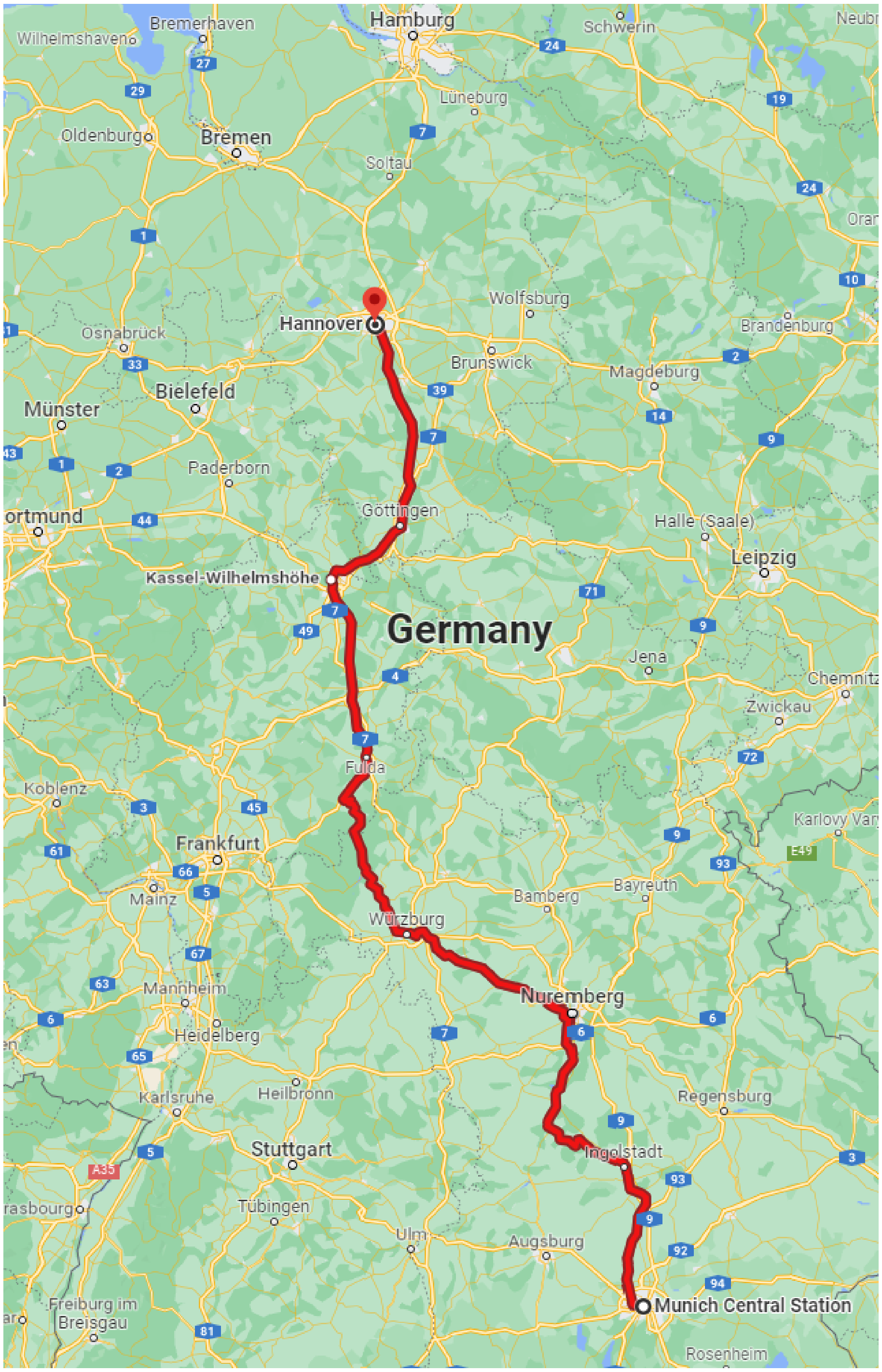


Figure 9-13 Line Munich Hbf – Hannover Hbf, from Google Maps

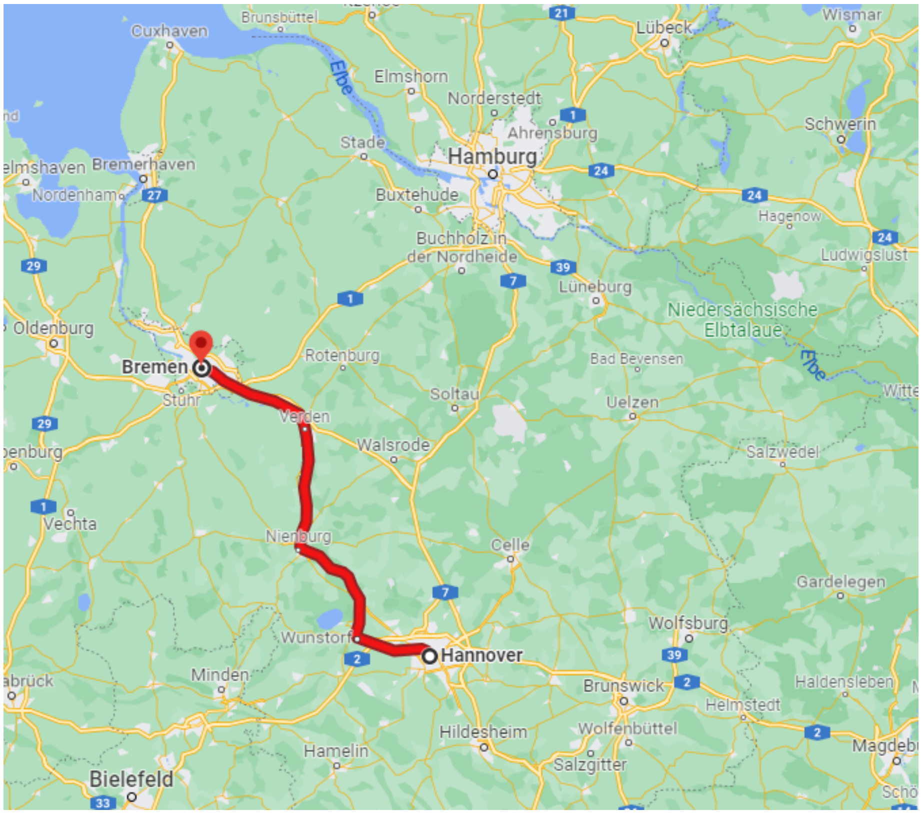


Figure 9-14 Line Hannover Hbf – Bremen Hbf, from Google Maps

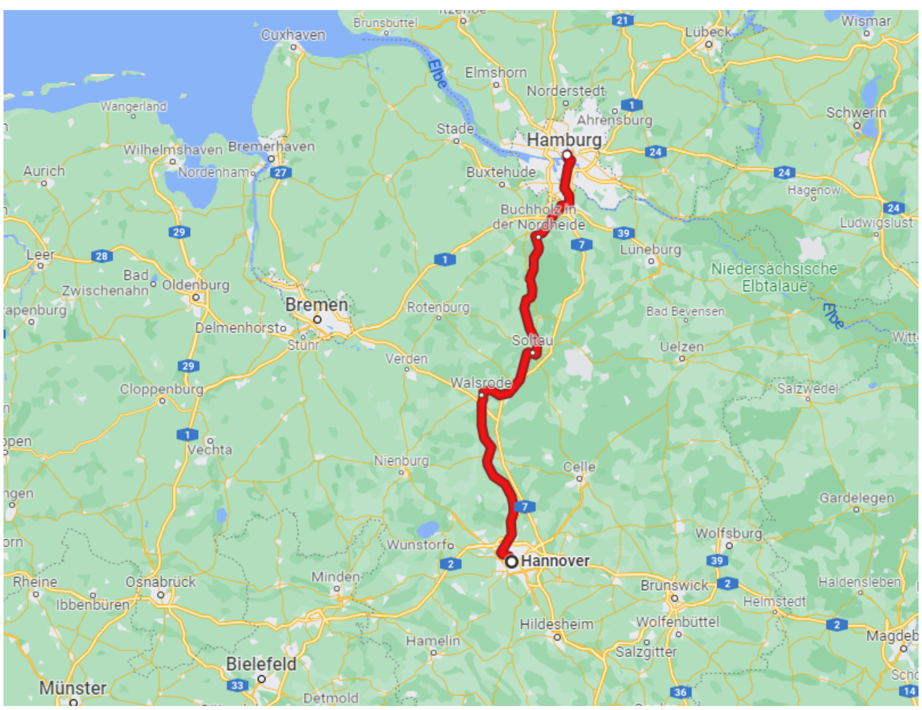


Figure 9-15 Line Hannover Hbf **–** Hamburg Hbf, from Google Maps

The number of stations at which to stop depends on the type of train.

For the considered line, the use of three TMSs is foreseen, one for the central part, one for the north and one for the south; the number of RBCs is assumed to be equal to the number of TMSs. Finally, the throughput of 200 trains per day is considered.

9.10.2 Timetable Analysis

A brief excerpt from the timetable for Hannover Hbf (Hauptbahnhof), the central station, is shown in Figure 9-16

Current departure time in Hannover Hbf at 06:00 o'clock

Actual information for your journey can only be given 4320 minutes in advance.

Time	Train	Direction / stops on the way
↑ earlier		
06:03	S 2	**Haste** Hannover Hbf 06:03 - Hannover Bismarckstr. 06:06 ⊙ Ronnenberg 06:18 - Weetzen 06:22 - Lemmie 06:25 - Winninghausen 06:40 - Haste 06:53
06:04	S 7	**Celle** Hannover Hbf 06:04 - Hannover-Kleefeld 06:07 ⊙ Lehrte 06:20 - Aligse 06:29 - Burgdorf 06:33 - Otze 06:37 - Celle 06:49
06:05	S 5	**Hannover Flughafen** Hannover Hbf 06:05 - Hannover-Nordstadt 06:08 ⊙ Hannover-Ledeburg 06:11 - Hannover-Vinnhorst 06:13 - Langenhagen Mitte 06:16 - Langenhagen Pferdemarkt 06:18 - Hannover Flughafen 06:23
06:07	IC 60400	**Hamburg-Altona** Hannover Hbf 06:07 - Lüneburg 07:15 - Hamburg-Harburg 07:39 - Hamburg Hbf 07:53 - Hamburg Dammtor 08:00 - Hamburg-Altona 08:09
06:09	WFB RE70 (95820)	**Bielefeld Hbf** Hannover Hbf 06:09 - Wunstorf 06:21 - Haste 06:27 - Stadthagen 06:36 ⊙ Bückeburg 06:47 - Porta Westfalica 07:06 - Löhne(Westf) 07:18 - Herford 07:25 - Brake(b Bielefeld) 07:31 - Bielefeld Hbf 07:39
06:10	S 4	**Bennemühlen** Hannover Hbf 06:10 - Hannover-Nordstadt 06:13 ⊙ Langenhagen Pferdemarkt 06:23 - Langenhagen-Kaltenweide 06:26 - Bissendorf 06:30 - Mellendorf 06:33 - Bennemühlen 06:37
06:14	WFB RE70 (95751)	**Braunschweig Hbf** Hannover Hbf 06:14 - Lehrte 06:27 - Hämelerwald 06:34 - Vöhrum 06:38 - Peine 06:42 - Vechelde 06:52 - Braunschweig Hbf 07:02
06:15	S 51	**Seelze** Hannover Hbf 06:15 - Letter 06:20 - Seelze 06:23
06:18	RE 8 (4404)	**Bremerhaven-Lehe** Hannover Hbf 06:18 - Wunstorf 06:30 - Neustadt am Rübenberge 06:39 ⊙ Dörverden 07:09 - Verden(Aller) 07:16 - Bremen-Mahndorf 07:31 - Osterholz-Scharmbeck 08:10 - Bremerhaven-Lehe 08:35
06:19	S 4	**Hildesheim Hbf** Hannover Hbf 06:19 - Hannover Bismarckstr. 06:22 ⊙ Rethen(Leine) 06:29 - Sarstedt 06:34 - Barnten 06:37 - Emmerke 06:43 - Hildesheim Hbf 06:49
06:21	ICE 646	**Düsseldorf Hbf** Hannover Hbf 06:21 - Minden(Westf) 06:49 - Herford 07:09 - Bielefeld Hbf 07:19 - Hamm(Westf)Hbf 07:47 - Dortmund Hbf 08:10 - Bochum Hbf 08:23 - Essen Hbf 08:35 - Duisburg Hbf 08:48 - Düsseldorf Hbf 09:03
06:21	ICE 656	**Köln Hbf** Hannover Hbf 06:21 - Minden(Westf) 06:49 - Herford 07:09 - Bielefeld Hbf 07:19 - Hamm(Westf)Hbf 07:47 - Hagen Hbf 08:21 - Wuppertal Hbf 08:38 - Köln Hbf 09:09
06:25	S 5	**Bad Pyrmont** Hannover Hbf 06:25 - Hannover Bismarckstr. 06:28 ⊙ Holtensen/Linderte 06:43 - Völksen/Eldagsen 06:51 - Hameln 07:10 - Emmerthal 07:16 - Bad Pyrmont 07:25

Figure 9-16 Hannover Hbf Timetable, from reiseauskunft.bahn.de

The timetable shown in Figure 9-16 lists the main types of trains in service on German lines:

- Intercity Express (ICE), a high-speed train service (up to 300km/h) characterised by a few stops in major cities
- EuroCity and InterCity (EC and IC), after the ICE are the two fastest train classes operated in Germany with a similar frequency to the ICE and a slightly higher number of stops
- Nahverkehrszüge (NV), are local and regional trains like the Regional Express (RE) characterised by high frequency, relatively low speed and a higher number of stops than the trains presented above
- S-Bahn, is a suburban service train with a very high frequency and many stops within the metro area

Freight trains are not listed in the timetable. The assumption is that these trains run on an uncongested line (with particular attention to time slots and stations), so they should not affect this analysis.

The S-Bahn network runs on a separate line, parallel to the lines used by other trains, so it does not overload the main lines, but a stand-alone solution VCTS could be used for this type of service to increase timetable robustness.

As mentioned in Section 6.5, the optimal use of VCTS is on high-speed lines with few stations such as ICE, IC, and EC. With the current timetable, the trains are evenly spaced to avoid congestion of the central stations. Considering the implementation of VCTS, there are many line sections shared by two or more routes, especially around the main cities. For these sections, trains from different routes could depart together coupled in a platoon and therefore less line occupation would be achieved. The ICE network is shown in Figure 9-17 as an example of the interconnection between the sections that would allow reducing congestions on the line and increasing its capacity by slightly changing the timetable. Similarly to the ICE network, a map containing the IC network is available. The analysis of these maps shows that timetable optimizations would be possible by creating platoons of 4 or more consists. In general, the maximum number of trains that can be coupled depends on the characteristics of the lines and the needs of the operator.

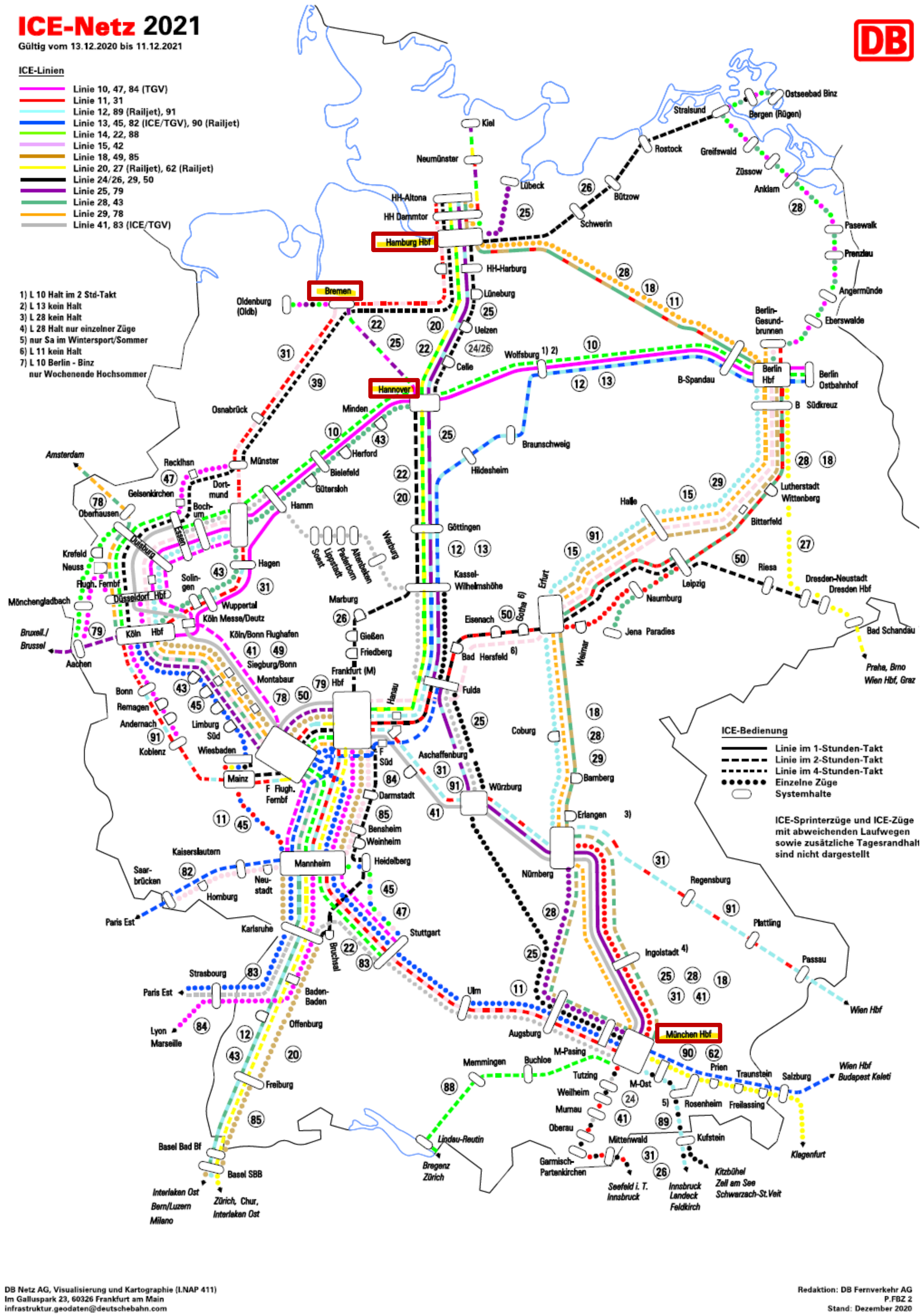


Figure 9-17 ICE network for 2021, highlighting the four stations analysed

9.10.3 Platform Analysis

This section evaluates briefly the possibility of keeping the platoon inside the stations to simplify operations management.

This analysis focuses on the use of IC and ICE trains characterised by higher usability in VCTS and greater length. In particular, the two trainsets considered are the ICE 2 and ICE 3, the two newer models, with an approximate length of 150 m and 200 m, respectively. Therefore, in order to allow the stop of a platoon of 2 consists it is assumed that 350 and 400 m of platform are necessary, respectively.

The platform data of the four stations involved in the study (Munich, Bremen, Hamburg, and Hannover) available from the DB website has been taken into account. The data shown in Table 9-1 reflects the current situation, i.e., most of the tracks prepared for IC and ICE can accommodate a platoon of two consist already today.

Platform	Station	height [cm]	Length [m]
11	**Munich Hbf Main hall**	38	509
12		76	436
13		76	436
14		76	432
15		76	432
16		76	346
17		76	346
18		76	432
19		76	432
20		76	366
21		76	366
22		76	520
23		76	520
24		76	370
25		76	370
26		76	474
	Platmform accept 2 consist platoon		10

Platform	Station	height [cm]	Length [m]
1	**Bremen Hbf**	76	318
2		76	376
3		76	376
5		76	449
6		76	449
7		76	416
8		76	416
9		76	420
10		76	420
	Platmform accept 2 consist platoon		6

Platform	Station	height [cm]	Length [m]
1	**Hamburg Hbf**	96	220,5
2		96	220,5
3		96	239,5
4		96	239,5
5		76	438
6		76	438
7		76	627
8		76	627
11		76	475
12		76	475
13		76	438
14		76	438
	Platmform accept 2 consist platoon		8

Platform	Station	height [cm]	Length [m]
1	**Hannover Hbf**	76	244
2		76	244
3		76	422
4		76	422
7		76	409,3
8		76	436
9		76	429,6
10		76	456
11		76	453
12		76	453
13		76	454
14		76	454
310		76	91
	Platmform accept 2 consist platoon		10

Table 9-1 Platform size data

9.10.4 Conclusion

The previous considerations lead to the conclusion that the main German high-speed lines would benefit from the use of VCTS by optimising occupancy both on the line and in stations where trains can be accommodated in pairs.

9.11 LinX4Rail Common Business Objectives of Railway Systems

This section describes the VCTS business case following the business objectives identified by the LinX4Rail project (Grant Agreement 881826) for business cases in railway applications as reported in [13]. The analysis is structured as a comparison between the ETCS-based VCTS application case and the existing ETCS system according to the assumptions reported in Section 7.2, i.e., requiring the availability for the following functionalities and sub-systems:

- ATO and OTI functionalities
- FRMCS on-board radio and communication protocols compliant to latest cyber regulations
- new generation TMS implementing Integration Layer

Additionally, the inputs from MOVINGRAIL (see Chapter 6) are taken into account and referred to where applicable.

9.11.1 Business Objectives

This section addresses the business objective proposed by LinX4Rail for IMs, RUs and suppliers.

Business Objectives	IMs	RUs	Suppliers
Affordable life cycle costs	x		
Increased capacity	x		
Improved performance, reliability, availability, maintainability, safety and security (PRAMSS)	x		
High level of services for customers	x		
Improved asset management	x		
Fast migration and rollout	x		

Figure 9-18 Business Objectives for IMs, from LinX4Rail D5.1

9.11.1.1 Affordable life cycle

VCTS system implies changes in existing ETCS on-board (ATP, ATO) and trackside sub-systems (RBC, TMS) and installation of additional VCTS-OB and VCTS-TS sub-systems.

At deployment level, the following impact is expected:

- RBC, TMS, ATP and ATO sub-systems requires software upgrade
- VCTS-OB requires installation on the train, connection with ATP, ATO and JRU, connection with on-board FRMCS radio for T2T communication with other VCTS-OB sub-systems and T2G communication with VCTS-TS sub-system
- VCTS-TS requires installation, connection to TMS through Integration Layer, connection to VCTS-OB through FRMCS communication equipment

At maintenance level:

- RBC, TMS, ATP and ATO sub-systems requires similar maintenance with respect to existing ETCS
- VCTS-OB and VCTS-TS sub-systems requires new maintenance activities

In general, the most relevant economic implications, both at deployment and maintenance level, are referred to VCTS-OB and VCTS-TS sub-systems.

9.11.1.2 Increased capacity

VCTS system ensures higher capacity by reducing the distance between trains and the time for train composition procedures see [14] and Section 6.2.1.

9.11.1.3 Improved performance, reliability, availability, maintainability, safety and security (PRAMSS)

In terms of performances, the VCTS system increases timetable robustness in nearly saturated lines with benefit for punctuality and provides in general a higher capacity, see [14] and Section 6.2.1.

At reliability level and availability level, potential faults to VCTS-OB or VCTS-TS sub-systems would not interrupt the service, which could continue as ETCS.

No changes at safety level, in fact VCTS-OB and VCTS-TS sub-systems ensure SIL4 safety target as ensured by existing ETCS system.

No changes at security level, in fact VCTS system relies on FRMCS radio communication and related security mechanism.

9.11.1.4 High level of services for customers

VCTS system provides higher capacity, better punctuality for the customers and, potentially, more frequent travel (see Sections 6.2.3 and 6.2.4).

9.11.1.5 Improved asset management

The VCTS system simplifies joining-splitting procedures; in fact, no manual operations are required thanks to automatic platoon management.

9.11.1.6 Fast migration and rollout

Migration implies software upgrade at RBC, TMS, ATP and ATO level and new VCTS-OB and VCTS-TS sub-systems. The migration process requires at first the software upgrade at trackside level (i.e. RBC, TMS), then deployment of VCTS-TS sub-system and incremental upgrade at on-board level (i.e. ATP, ATO, VCTS-OB). This is detailed in the previous sections.

Business Objectives	IMs	RUs	Suppliers
Punctuality		x	
Profitability (shareholder value)		x	
Productivity		x	
Adaptive design (features)		x	
Transportation capacity		x	
Asset performance		x	
Asset capacity		x	
Network performance		x	
Network capacity		x	
Validation of performance		x	

Figure 9-19 Business Objectives for RUs, from LinX4Rail D5.1

9.11.1.7 Punctuality

As above reported, VCTS system provides higher punctuality thanks to increased timetable robustness, see Section 6.2.3.

9.11.1.8 Profitability (shareholder value)

The VCTS system delivers an increased capacity and automation, thus, an increased profitability (see Section 6.2.2.2).

9.11.1.9 Productivity

VCTS system ensures increase productivity thanks to automation of joining/splitting procedures and automatic platoon management. Therefore, no manual operations are required for train composition and no manual operators are required to manage platoons joining-splitting. See also Section 6.2.2.2.

9.11.1.10 Adaptive design (features)

The approach for system requirements specification is independent for specific technologies. The implementation of the ETCS-based application case was evaluated within the Impact Analysis (D7.4) and migration plan (see previous section of this chapter) and included also guidelines for integrating Virtual Coupling functionality in OCORA/RCA reference architecture (see Section 9.9).

9.11.1.11 Transportation capacity

VCTS system reduces ensures higher transportation capacity with same number of trains (see Section 6.2.1).

9.11.1.12 Asset performance

Asset performance is improved by automation of train composition procedures.

9.11.1.13 Asset capacity

VCTS reduces ensures higher transportation capacity with same number of trains.

9.11.1.14 Network performance

VCTS reduces ensures higher transportation capacity with same number of trains and higher timetable robustness (see Sections 6.2.1 and 6.2.3).

9.11.1.15 Network capacity

VCTS ensures higher transportation capacity with same number of trains (see Section 6.2.1)

9.11.1.16 Validation of performance

Simulations showed capacity increase, faster and automated train composition procedures, increased timetable robustness in nearly saturated lines, see [14] as well as Sections 6.2.1 and 6.2.3.

Business Objectives	IMs	RUs	Suppliers
Increase customer satisfaction, meet customer needs			x
Compliance with customer requirements			x
Economically attractive for customer			x
The revenue must justify the expenditure			x
Managed variability of products			x
Minimized risk			x
Global market potential			x
Long term customer relationship			x
Fair competition			x

Figure 9-20 Business Objectives for Suppliers, from LinX4Rail D5.1

9.11.1.17 Increase customer satisfaction, meet customer needs

As above, VCTS system ensures higher capacity and increased timetable robustness (i.e., punctuality, see Sections 6.2.3 and 6.2.4).

9.11.1.18 Compliance with customer requirements

VCTS requirements have been specified within the X2Rail-3 project [2], [4]. The development would be addressed in compliancy to defined requirements.

9.11.1.19 Economically attractive for customer

As above, VCTS system ensures higher capacity and increased timetable robustness (i.e. punctuality). For the negative impact of a potential increase in ticket pricing see Section 6.2.4.

9.11.1.20 The revenue must justify the expenditure

Most significant costs are referred to new VCTS-OB and VCTS-TS sub-systems to be installed at on-board and trackside level. The result is an increased capacity with the same infrastructure and same number of trains (see Section 6.2).

9.11.1.21 Managed variability of products

Interface specification ensures interoperability, thus avowing variability of products.

9.11.1.22 Minimized risk

The considered application case is aimed at reducing the complexity and the migration plan has been defined to support the introduction of new technology. A discussion of business risks can be found in Section 6.4.

9.11.1.23 Global market potential

The proposed application case is based on ETCS Level 2 / Level 3 with new generation FRMCS communication system. This compatibility provides a clear global market potential.

9.11.1.24 Long term customer relationship

The operational procedures definition, as part of the migration plan, ensures interoperability and allows applying VCTS functionality to the existing ETCS system.

9.11.1.25 Fair competition

The interface specification ensures interoperability and it is the vision to implement VCTS based on reference architectures (see Section 9.9), thus, ensuring fair competition.

9.11.2 Cost efficiency

This section evaluates the cost efficiency objectives, see also Section 6.2.

Business Objectives	IMs	RUs	Suppliers
Cost efficiency	x	x	x
- Harmonisation of operation	x	x	x
- Simplification of regulations, procedures, standardisation & acceptance process	x	x	x
- Standardisation of architecture	x	x	x
- Efficient system integration, testing and validation	x	x	x
- Affordable system updates	x	x	x

Figure 9-21 Cost efficiency objectives, from LinX4Rail D5.1

9.11.2.1 Harmonisation of operation

The proposed migration plan includes definition of operational procedures that ensure harmonised operation.

9.11.2.2 Simplification of regulations, procedures, standardisation & acceptance process

The proposed migration plan includes interface specification, operational procedures definition and standardization activities that would benefit from simplified processes.

9.11.2.3 Standardisation of architecture

Reference architectures have been considered as an input for impact analysis and migration plan definition of the ETCS-based application case. The proposal for the implementation of VCTS based on OCORA/RCA reference architectures has been also provided, see Section 9.9.

9.11.2.4 Efficient system integration, testing and validation

The proposed migration plan addresses system integration and testing activities in laboratory and on-site that would benefit from efficient procedures.

9.11.2.5 Affordable system updates

No changes respect to existing ETCS. Positive effects can be expected from using reference architectures (see Section 9.9).

9.11.3 Quick Adaptation and deployment

This section evaluates the quick adaptation and deployment objectives.

Business Objectives	**IMs**	**RUs**	**Suppliers**
Quick adaptation and deployment	x	x	x
- Increase in flexibility	x	x	x
- Reduced time to market	x	x	x
- Ease of procurement	x	x	x
- Effective migration strategies	x	x	x

Figure 9-22 Quick adaptation and deployment objectives, from LinX4Rail D5.1

9.11.3.1 Increase in flexibility

Performed simulation activities showed an increased timetable robustness. Additionally, VCTS allows coupling of consists from different manufacturers and of different types, providing a great increase in coupling flexibility. See [14] and Section 6.2.3.

9.11.3.2 Reduced time to market

The proposed ETCS-based application case limits the hardware development activities and related installation to VCTS-OB and VCTS-TS sub-systems. Further simplification consists in integrating Virtual Coupling functionality in RCA/OCORA reference architectures, see Section 9.9.

9.11.3.3 Ease of procurement

Procurement is limited to VCTS-OB and VCTS-TS sub-systems. Further simplification consists in integrating Virtual Coupling functionality in RCA/OCORA reference architectures, see Section 9.9.

9.11.3.4 Effective migration strategies

The proposed ETCS-based application case limits the installation activities to VCTS-OB and VCTS-TS sub-systems and implies software upgrade at trackside for RBC and TMS and at on-board level for ATP and ATO.

9.11.4 Better performance

This section evaluates the objectives to achieve better performance.

Business Objectives	IMs	RUs	Suppliers
Better performance	x	x	x
- Increase in capacity	x	x	x
- Greater reliability and availability	x	x	x
- Environmental sustainability	x	x	x

Figure 9-23 Better performance objectives, from LinX4Rail D5.1

9.11.4.1 Increase in capacity

Virtual Coupling reduces the distance between trains and the time for train composition procedures thus increasing the capacity increase and the timetable robustness in nearly saturated lines (see Sections 6.2.1 and 6.2.3).

9.11.4.2 Greater reliability and availability

Adoption of Adaptable Communication System, based on multi-bearers communication, increase the system availability. Embedding Virtual Coupling functionality within RCA/OCORA reference architecture would ensure even higher availability (see Sections 6.2.1 and 6.2.3).

9.11.4.3 Environmental sustainability

VCTS ensures a capacity increase with the same number of trains and with same infrastructure thanks to a reduction of relative distance between trains and a reduction in time required for train composition procedures. Additionally, increased automation and increased algorithmic optimization opportunities will lead to reduced energy consumption and thus, reduced CO_2 emissions (see Section 6.2.5).

9.11.5 Achieve proper level of safety and security

This section evaluates the objectives to achieve proper level of safety and performance.

Business Objectives	IMs	RUs	Suppliers
Achieve proper level of safety and security	x	x	x
- Compliance with safety regulations and standards	x	x	x
- Compliance with security regulations and standards	x	x	x
- Business continuity strategy	x	x	x

Figure 9-24 Achieve proper level of safety and security, from LinX4Rail D5.1

9.11.5.1 Compliance with safety regulations and standards

The proposed migration plan includes the activities for compliancy to safety standards.

9.11.5.2 Compliance with security regulations and standards

The proposed migration plan includes the activities for compliancy to security standards.

9.11.5.3 Business continuity strategy

The flexibility of VCTS allows that platoon composition and timetables can be changes dynamically according to the needs of the commercial service.

9.12 Conclusion

The presented analysis proposes an ETCS-based VCTS application case targeting a 3-5 years migration plan. An upgrade of the existing ETCS system would imply on-board and trackside upgrades to integrate VCTS-OB and VCTS-TS functions. The general strategy presented implies hardware installation activities at on-board and TMS levels. Further improvement consists in hosting the VCTS-OB function within the ATP safe platform and the VCTS-TS function within the RBC safe platform, thus limiting the migration plan to software upgrade activities. The presented vision foresees that VCTS would be implemented based on the RCA and OCORA reference architectures. This would allow a simplified VCTS implementation, consisting of only software changes.

Virtual coupling ensures faster train composition procedures and shorter distance between trains. This approach increases line capacity and the robustness of the timetable in nearly saturated lines. Benefits provided to the infrastructure managers, operators and customer are evaluated according to LinX4Rail guidelines.

10 Conclusions

This document (D7.5) is the result of X2Rail-3 Task 7.5 “Analysis of the Business Model”. Together with the impact analysis provided in D7.4, it concludes the VCTS workstream of the Shift2Rail project X2Rail-3. The VCTS concept developed as well as the analyses provided in Work Packages 6 and 7 of X2Rail-3 form the basis for this work and the input provided by the MOVINGRAIL project were compared to it. Generally, the understanding of VCTS and the results obtained within MOVINGRAIL and X2Rail-3 agree with each other. The most notable difference identified was the base signalling system assumed for the implementation of VCTS. While MOVINGRAIL sees VCTS as the next level after ETCS Level 3 not only conceptually, but also technically, a more technology independent point of view is presented in this work. This is motivated by the risk of interfering with the ERTMS implementation roadmap and very long time it might take to migrate to ETCS Level 3, as well as the fact that any ETCS level could technically support VCTS operation as long as train integrity detection can be provided. A more independent implementation of VCTS further provides the opportunity for intermediate implementations such as the standalone VCTS application case presented in this document.

Standalone VCTS is a limited implementation of VCTS that can be used to foster the required technology until a widely applicable implementation can be achieved. It can be summarized as a low-cost onboard train protection system and has the objectives of providing an economically interesting upgrade path for Class B systems on low-traffic lines and at the same time raising the maturity the underlying technology required for VCTS. The migration plan presented in this document takes train protection, traffic management, automatic train operation, on-board train integrity, communication and VCTS (on-board) sub-systems into account and bolsters the feasibility of implementing and on-site testing a first complete demonstrator within a period of three to five years.

The second implementation case presented is ETCS-based VCTS, an application of VCTS that focuses on high-traffic lines and bases on ETCS Level 2 or Level 3. As the actual goal of the VCTS concept, ETCS-based VCTS has the main objectives of reducing headway and improving flexibility of operation in order to increase line capacity and provide the technical basis for innovative business models. Similar to the standalone VCTS case, the presented migration plan presented takes train protection, traffic management, automatic train operation, on-board train integrity, communication and VCTS (on-board and trackside) sub-systems into account and even in this case, the feasibility of implementing and on-site testing a first complete demonstrator within a period of three to five years is supported.

Beyond the migration strategies, the presented vision of implementing ETCS-based VCTS within the RCA and OCORA reference architectures would imply software changes only and, thus, simplify the migration considerably. Finally, the comparison of the impact of VCTS against the business objectives identified in the LinX4Rail project shows that VCTS is in line with the RUs’, IMs’ and suppliers’ business objectives. This fact is supported by the presented migration strategies and the input from MOVINGRAIL.

It can be noted that the introduction of VCTS does not change the fundamental principles of any of the existing signalling sub-systems. While the introduction of a standardized VCTS will have implications on operational and engineering rules in the analysed sub-systems and new standards, subsets or modifications of the TSI will be necessary, a full rework is not required. New maintenance measures may be required, while other maintenance activities can be reduced due to the removal of maintenance-intensive components as mechanical coupler itself. Clear positive impacts on operational expenditures can be expected by reduced personnel per train due to increased automation. However, the acceptance of the concept by both, railway personnel- and passengers needs to be supported by training and education projects as mentioned in the migration plans and stressed by the business risks identified in MOVINGRAIL. VCTS is an innovative concept whose safety can be achieved within the near future as detailed in this document. This needs to be communicated clearly in order to avoid scepticism by operators and the general public. Then, VCTS can not only improve current railway operation with increased capacity and reliability, but even provide the basis for novel business models that benefit from the increased flexibility.

11 References

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