X2Rail-3

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Virtual Train Coupling System Concept and Application Conditions

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VCTS Context Diagram	**7.2**	**CAF**	**DLR, INDRA, TRV, STS, SNCF**
VCTS Main Functions	**7.4**	**STS, CAF**	**DLR, INDRA, TRV, CAF, SNCF**
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VCTS Applications	**8**	**STS, DLR**	**INDRA, TRV, CAF, SNCF**
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Future Work	**10**	**DLR**	**CAF, STS, INDRA, SNCF, TRV**

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1 Table of Contents

1.1 Summary of Sections

1.2 Index of Figures

2 Abbreviations and acronyms

Abbreviation / Acronyms	Description
ABDS	Absolute Braking Distance Supervision
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CAM	Cooperative Awareness Message
CapEx	Capital Expenditure
CBTC	Communication-Based Train Control
CENELEC	European Committee for Electrotechnical Standardization
COM	Communication
CTRL	Controller
CSM-RA	Common Safety Method Risk Assessment
EBuLa	Elektronischer Buchfahrplan mit Verzeichnis der Langsamfahrstellen (German locomotives on-board timetables display devics)
EN	European Standard
EoA	End of Authority
ERA	European Union Agency for Railways
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
EU	European Union
FMECA	Failure Mode, Effects, and Criticality Analysis
FRS	Functional Requirements Specification
GA	Grant Agreement
GoA	Grade of Automation
GSM	Global System for Mobile Communication
HW	Hardware
IM	Infrastructure Manager
IXL	Interlocking
KPI	Key Performance Indicator
LCC	Life-Cycle-Costing
LIDAR	Light Detection and Ranging
LX	Level Crossing

LZB	Linienzugbeeinflussung
MaaS	Mobility as a Service
MCTS	Mechanically coupled Train Set
O&M AC	Operational & Maintenance Application
OpEx	Operational Expenditure
PHA	Preliminary Hazard Analysis
PZB	Punktförmige Zugbeeinflussung
RBC	Radio Block Centre
RU	Railway Undertaking
S2R	Shift2Rail
SCMT	Sistema di Controllo della Marcia del Treno
SENS	Sensors
SIL	Safety Integrity Level
SPD	System Platform Demonstrator
SRS	System Requirements Specification
SW	Software
T2T	Train-to-Train (communication)
T2G2T	Train-to-ground-to-Train (communication)
TCMS	Train Control and Management System
TCP/IP	Transmission Control Protocol/ Internet Protocol
TD	Technical Demonstrator
THR	Tolerated Hazard Rates
TMS	Traffic Management System
USB	Universal Media Bus
UDP	User Datagram Protocol
VCTS	Virtually coupled Train Sets
WLTB	Wireless Train Backbone
WP	Work Package

3 Glossary of Terms

Term	Meaning
Absolute Braking Distance Monitoring	A train headway control strategy in which each train determines its permitted speed according to: • Braking curves which only take into account its own specific parameters and configuration Movement limitations which are provided by the wayside infrastructure (i.e.: any signalling system typology).
Consist	Single vehicle or a group of vehicles which are not separated during normal operation. (source: D2.3 X2Rail-1, ID WP4_039) Additional definition: A consist has a dedicated traction and braking capability.
Cooperative Awareness Messages (CAMs)	A set of messages exchanged by mean of a protocol with the adequate level of safety and integrity, to allow master and slave trains to implement the necessary controls and supervision functions according to the Virtual Coupling concept.
Coordinated Braking Distance Monitoring	A train headway control strategy in which each train determines its permitted speed according to braking curves which take into account not only its own specific parameters and configuration, but also data related to other trains in the platoon as current speed, relative distance, ongoing controls, etc.
Dynamic state	Parameters related to movement (velocity, acceleration, position), typically changing during operations.
Master	Train equipped with the necessary Virtual Coupling devices, in charge of leading the virtually coupled platoon. The Master train is typically the one running ahead of all other trains in the Virtually coupled platoon.
Platoon	Two or more trains, mechanically coupled, as well as sharing the same Train Control and Management System (TCMS) network.
Slave	Train equipped with the necessary Virtual Coupling devices, in charge of implementing the controls and supervision of train movements according to the information exchanged with the Virtually coupled master as well as other slaves in the same Virtually coupled Train Set (VCTS).
State	All the parameters that define the vehicle in a given time

Static state	Parameters that do not change dynamically during operations.
Train	A set of cars or traction units.
Train Positioning	Information generated by a function which is external to the Virtual Coupling, and providing mainly travelled distance (or absolute position) and speed measurement with the adequate level of safety integrity to support Virtual Coupling functions. The methodology and technology adopted to generate the train sposition (wheel sensors, radars, accelerometers, GPS, optical, etc…) are out of the scope of this conceptual analysis.
Virtually Coupled Platoon (VCTS)	1 train made of 2 or more consists, which are not mechanically coupled. At this stage, it is not defined if they share or not the same TCMS network.

4 Reference Documents

Ref.	Source	Rev.	Title
[1]	Shift2Rail Project FINE-1	2018	Energy Baseline
[2]	Shift2Rail Project IMPACT-1	2017	Reference Scenarios

5 Background

5.1 Innovation Programme #IP2 and X2Rail-3

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 to expand the level of standardization in an increasingly challenging economic climate.

The pillar (IP2) challenge is to increase functionalities of the existing signalling and automation systems and related design and validation processes 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 a longer term Shift2Rail IP2 strategy towards a flexible, real-time, intelligent traffic control management and decision support system.

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 aim to investigate an innovative concept of Virtual Train Coupling, capable of operating physical traction units much closer to one another and providing the basic functionalities to dynamically modify their own composition on the move.

5.2 VCTS within X2Rail-3

5.2.1 Work Packages associated to TD2.8 VCTS

VCTS within X2Rail-3 is divided into two main work packages, Work Package 6 (WP6) and 7 (WP7). WP6 mostly targets the definition of the VCTS concept, the overall functional requirements and a preliminary operational safety analysis, in order to first establish a baseline definition on how the VCTS must work, which operational use cases must be covered and consequently, which safety hazards must be mitigated by its practical implementation in terms of requirements on the technologies.

WP7 then develops the concept defined by WP6 into a technological evaluation of potential implementations, and associated impact on the existing infrastructures, in order to structure a business model analysis that must support the evaluation on the actual benefits given by the introduction of the VCTS concept.

5.2.2 Deliverables of WP6

ID	Title	Content
6.1	Concept Analysis and Application Conditions	The actions associated to this deliverable aim to identify: • the context diagram • the field of the analysis • the systems description; the boundary of the system (what is included in the analysis and what is external that can have relationship with VCTS) • the main VCTS functions and their relationship with the VCTS environment • the application conditions (Identify the Operating & Maintenance Conditions)
6.2	Performance and Safety Analysis	This task will provide the basic documents foreseen by the standards (e.g.: System Hazard & Safety Risk Analysis, Hazard Log, Risk Assessment etc.) related to the introduction of the Virtual Coupling concept.

Table 5-1: List of Deliverables for WP6

5.2.3 Deliverables of WP7

ID	Title	Content
7.1	Feasibility Analysis	On the basis of the results of the tasks 6.2 and 6.3, this task will investigate the technical feasibility, the applicability of some aspects and parts of the system. The objective is to identify critical aspects (technical and operational) for the accomplishment of the project (e.g. what radio system / network could be used, its availability, including those of frequencies, as well as the migration aspects from the old to the new system etc.).
7.2	System Requirements Specification	On the basis of the result of tasks 6.2, 6.3, 7.2, in particular on the result of the proof of Concept, Feasibility and Performance & Safety analysis, this task will provide the definition of the basic system documents (System Functional Architecture Specification, Functional and not Functional Requirement Specification) in order to outline the functional behaviour and the potential functional architectural structure.
7.3	System Impact Analysis	The objective is to identify and quantify the necessary preliminary technical and operational modifications/ adaptations and the related possible expected range of impact (estimated in percentage of change) the introduction of VCTS would bring (e.g.: on Interlocking, Radio Block Centre (RBC), Traffic Management System (TMS), Automatic Train Protection (ATP), Automatic Train Operation (ATO), Communications, infrastructure, track layout, trains etc.).
7.4	Analysis of the Business Model	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 Railway Undertakings (RU), Infrastructure Managers (IM) and the Suppliers for fostering and introducing the VCTS

Table 5-2: List of Deliverables for WP7

5.2.4 From Concept to Detailed Requirements

The approach to the overall concept definition of virtual coupling is reflected by the structure of deliverables included in the two work packages 6 and 7 of the X2Rail-3 project. The whole design is initiated by identifying a set of basic scenarios describing the main operational context and challenges that the VCTS is aimed to solve. This step is also supported by synergies with external projects as MovingRail (GA 826347), especially in order to assess the compliance of the scenarios with market expectations. MovingRail WP4 includes in its scope the investigation with main relevant stakeholders (infrastructure managers, railway operators, etc.) of potential scenarios of interest where the VCTS may realise an actual benefit for the end user.

Based on the selected basic scenarios, the functional description of the VCTS is then developed through its core functionalities (see Section 7.4 which are described in terms of main principles and targets. These VCTS technical functions address the overall description of the system in terms of its actual role and scope within the existing infrastructure, as well as a the identification of the boundaries of the VCTS in terms of tasks assigned or requirements exported to external subsystems.

Once VCTS boundaries and accountabilities are identified, the conceptual design moves into the detailed Functional Requirement Specifications (FRS), that is submitted as input to the Deliverable 6.2 of this same Work Package (Safety Risk Analysis – SRA). On the basis of this analysis, it is also possible to associate the list of Operational & Maintenance Application Conditions (O&M AC) to VCTS. Moreover, the same FRS may also take the output of the SRA as an input, especially to develop the necessary mitigations to risks that may arise from the safety analysis.

The FRS and O&M AC are then the core input to support the later deliverables of WP7 which also take into account input data from projects which are both external and internal to X2Rail-3, i.e.: X2Rail1 (GA 730640)-WP3, CONNECTA-2 (GA 826098) WP1 & WP2 and X2Rail-3-WP3 – adaptable communication systems). The following figure (Figure 5-1) depicts this approach.

As a remark for this figure, deliverable 6.2 is represented as an input to 6.1 despite being planned at later stage. This is mostly due to the review process involved in the safety assessment: while the system concept is used as input to carry out the safety analysis, the safety analysis itself is supposed to generate feedbacks to the system concept, e.g.: review of specific functions addressing a particular safety requirement.

5.2.5 Safety Analysis

Together with the description of the VCTS main functions, the Performance and Safety assessment is crucial to the finalisation of the whole workstream of WP6 and 7. The VCTS must provide a solution that is '*at least as safe as the solutions/systems already existing'*. According to EU regulations, safety of railway systems is assessed by the applicable safety standards provided by CENELEC (European Committee for Electrotechnical Standardization), which address the overall safety of the railway infrastructure at different levels and whose extensive list and mutual relationships are depicted in following Figure 5-2 and Figure 5-3.

European Standard (EN) 50126 provides the generic guidelines and approach to be followed in order to implement safety principles within the railway infrastructure and associated supervision system, providing the methodologies and guidance to implement them into system design. Associated to EN 50126, safety principles are then developed into detailed system and subsystem design according to EN 50128 and 50129 norms, mostly addressing Hardware (HW) and Software (SW) design safety guidance.

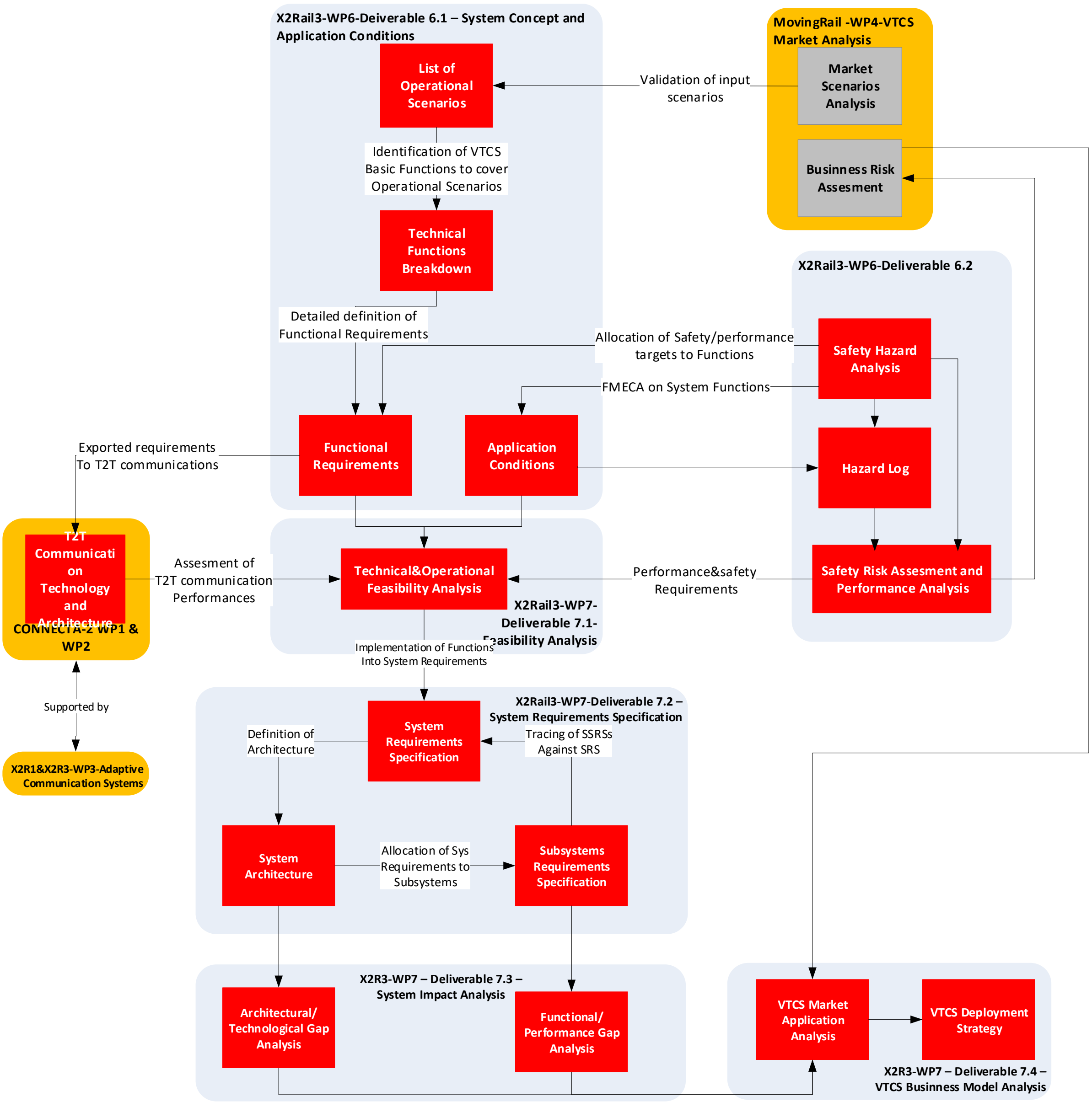

Figure 5-1: Workflow of Deliverables for WP6 & 7

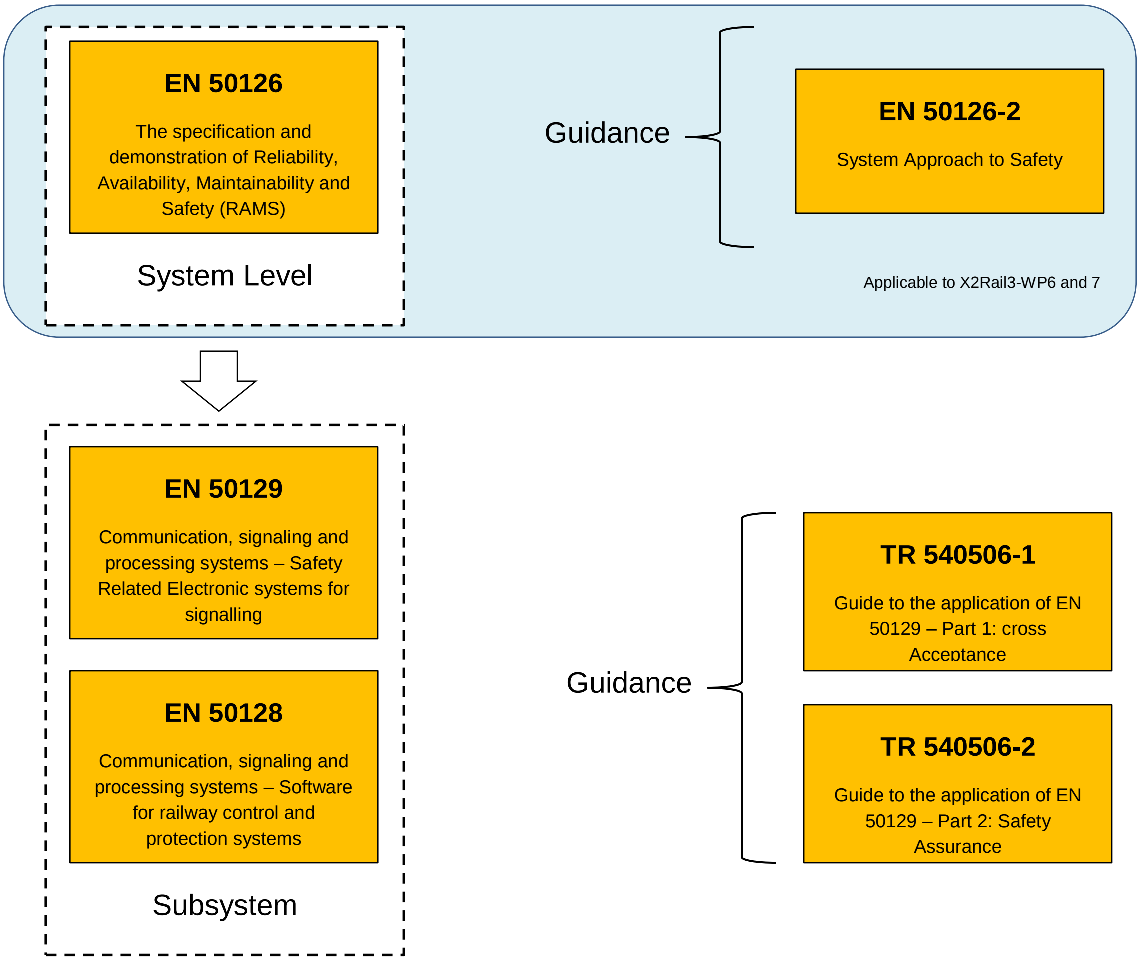

Figure 5-2: Overview of Railway Safety Standards

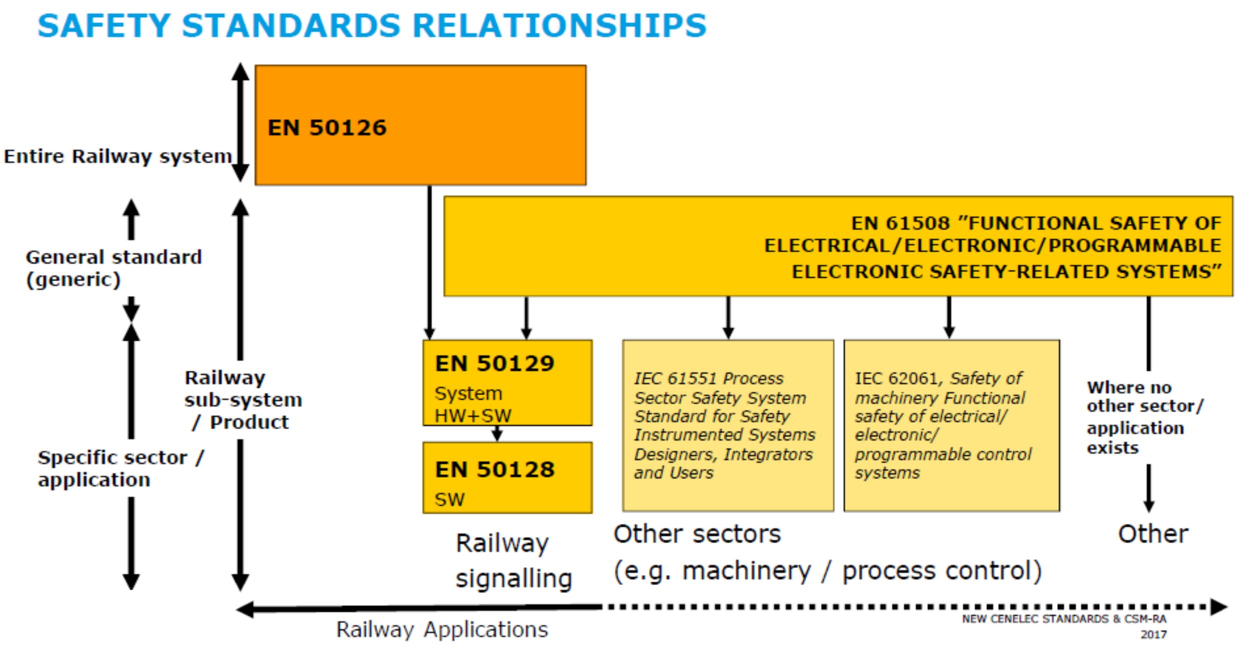

Figure 5-3: Relationships between Railway Safety Standards

The EN 50126 defines thus the basic lifecycle of safety assessment from the conceptual definition up to the final deployment of the system. Considering the scope of X2Rail-3 WP6 & 7, the analysis will not implement the complete assessment foreseen by the so called 'V-Cycle' described by EN50126 norm, but it will be limited to the steps from 1 to 5 (from the conceptual design up to the apportionment of system requirements, see following Figure 5-4.

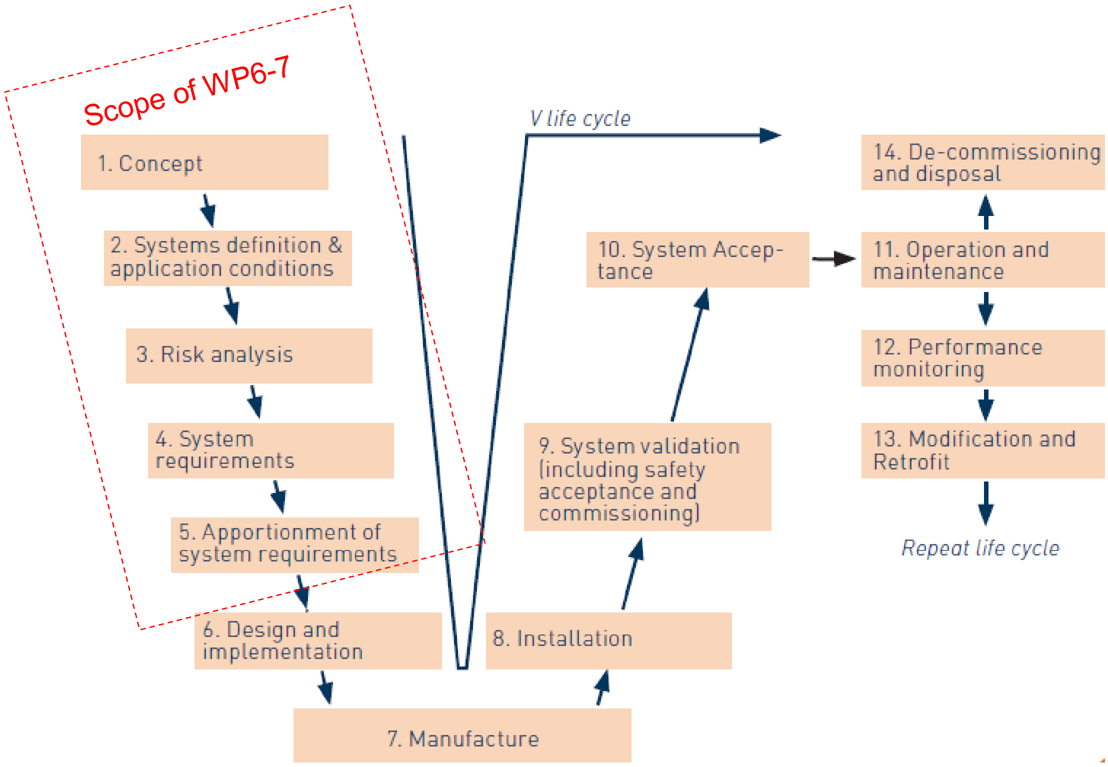

Figure 5-4: V-Cycle (extract from EN 50126 norm)

Following this main guideline, a preliminary hazard analysis will be carried out on the system functions in order to determine the safety targets to be achieved for each function. Additionally the mitigations that the system will need to fulfil to cope with the identified hazards will be assessed. The Preliminary Hazard Analysis (PHA) is based on a Failure Mode, Effects and Criticality Analysis (FMECA) which is focused in the analysis of the causes of possible failures of the system functions, taking also into account the human factor aspects. Each system requirement is then analysed to determine any additional mitigation that is necessary to reach the required Safety Integrity Level (SIL), in accordance to CENELEC standards.

The outcome of this phase is the hazard log, which is then used (and updated) through the later stages of requirements development. Especially, the system architecture must be developed according to the hazard log in order to mitigate any hazard that could arise as a consequence of a failure at the interfaces.
The resulting architecture and subsystem requirements specification must also ensure that the expected Tolerated Hazard Rates (THRs) are met by the overall VCTS. According then to the applicable European regulations (i.e.: Annex III to Directive 2004/49/EC) Common Safety Method Risk Assessment (CSM-RA) must be applied to any change of the railway system (either of technical, operational or organisational nature), so that the hazards whose

associated risk is judged as 'not broadly acceptable' must be evaluated using one or more of the following risk acceptance principles:

- **The application of codes of practice**: a written set of rules that, when correctly applied, can be used to control one or more specific hazards
- **A comparison with similar systems (reference systems)**: systems proven in use to have an acceptable safety level and against which the acceptability of the risks from a system under assessment can be evaluated by comparison
- **An explicit risk estimation**: an assessment of the risks associated with hazard(s), where risk is defined as a combination of the rate of the occurrence of the hazard or hazardous event causing harm (the frequency) and the degree of severity of the harm (the consequence)

The application of these risk acceptance principles will lead to the identification of possible safety measures that avoid the risk or render it acceptable. The safety measures applied to control the risk must become safety requirements to be fulfilled.

5.3 Technical View of this document

The content of this document develops the deliverable 6.1 of WP6, especially as outcome of Task 6.2 of the whole X2Rail3 Work Package 6, regarding the concept analysis of VCTS. With regards to this concept, the action associated to this deliverable aims **to identify**:

- The context diagram
- The field of the analysis
- The systems description, the boundary of the system (what is included in the analysis and what is external that can have relationship with VCTS);
- The main VCTS functions and their relationship with the VCTS environment
- The application conditions (Identify the Operating & Maintenance Conditions)

This document aims therefore to provide the most generic overview of this VCTS concept, regardless of the application in which it may operate.

For this reason, the following sections develop specific use cases of Virtual Coupling which do not refer to a specific typology of railway (freight, regional, high speed or metro), nor to any particular solution regarding the signalling infrastructure, trains protection system, or communication technologies. This actually means that this early definition of VCTS only summarizes the expectations what VCTS is and how the system should operate. It does not indicate the technical implementation and the strategy that is necessary to put in place.

However, this conceptual definition already allows a preliminary insight on the VCTS, especially with regards to the potential, technical challenges that must be addressed during the actual implementation of the concept itself. For this reason, together with the VCTS Operational Scenarios description, this document also introduces an additional section in which the core functions of the VCTS are preliminarily identified.

This document also defines the context of VCTS application (i.e. infrastructure characteristics, train type, operational procedures, …) in different market segments and serves as an input for the further development of VCTS in the task 6.3.

6 Aim of VCTS

6.1 State of the Art: The braking wall

Nowadays, typical implementations of train protection systems are based on the absolute braking distance of the trains, as depicted in the Figure 6-1 (fixed blocks principle) and Figure 6-2 (moving blocks principle). These are the two most common philosophies currently applied across Europe and worldwide.

- With **fixed blocks** (applicable for instance to ERTMS L1/L2 system, as well as most of the national signalling systems), the track is divided into several sections, and train movements are authorised up to the entry point of the next occupied sections (i.e.: the next signal at red). This solution does not maximise the railway capacity, as it is mainly limited by the fact that once one train enters a track section, the whole section becomes unavailable for other trains. This means all other trains using absolute braking distance monitoring, will set their target for stopping (hereafter End of Authority – EoA) at the beginning of the occupied section, irrespectively from the position of the train that is currently occupying that section.

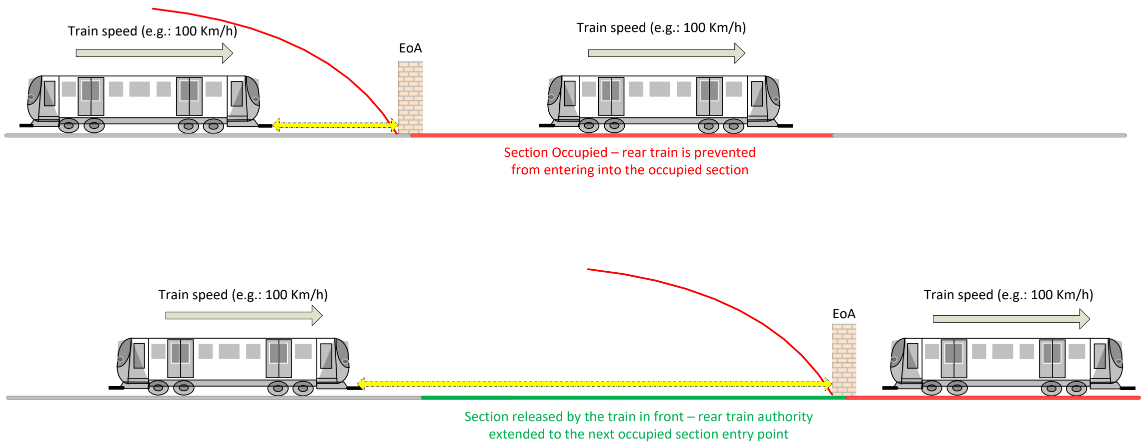

Figure 6-1: Train headway based on Fixed Blocks Approach

- Moving blocks approach (applicable for example to ERTMS Level 3) tries to overcome the limitation of fixed blocks, as trains are supposed to safely determine their minimum safe rear end (by mean of train integrity function), so that the EoA of the following trains does not need to be set to the entry point of a specific section, but it can be directly associated to the rear end of the front train. However, also in this case the braking curve monitoring inefficient, as it considers that the second trains must be able to fully stop before the current position of the front train, regardless of the current speed and braking curve of the front train.

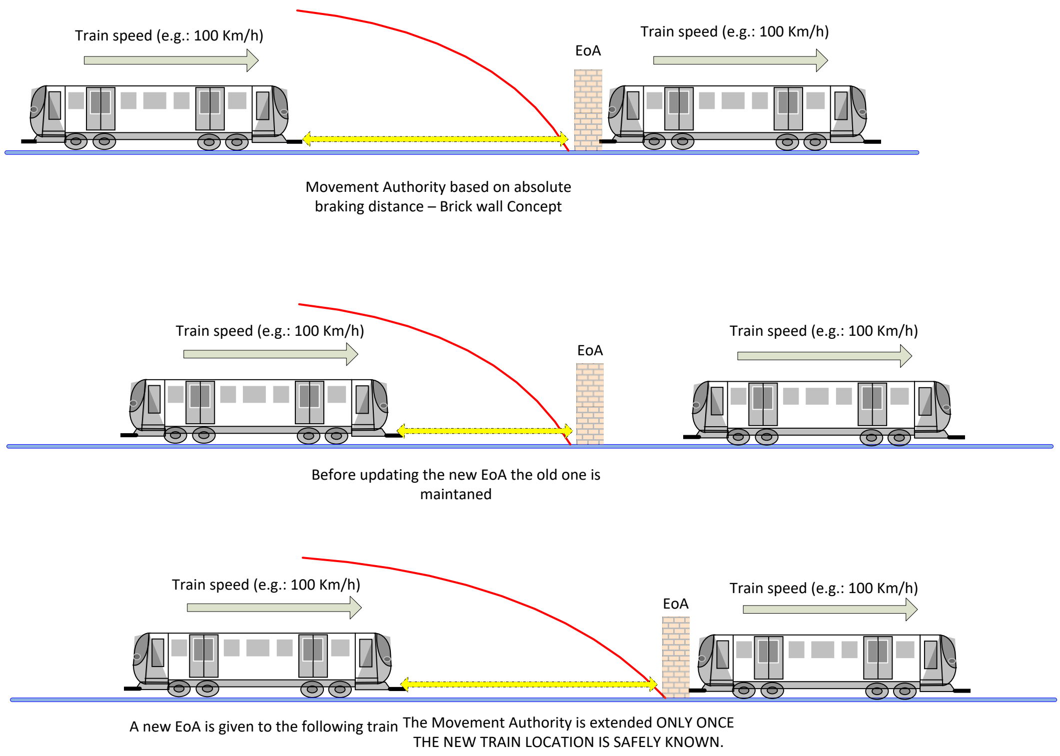

Figure 6-2: Train Separation Based on Moving Blocks Approach

Both fixed and moving blocks approaches involve limitations to the potential headway of the line, due to the absolute braking distance supervision (ABDS): each train takes into consideration only its own braking characteristics to determine its permitted speed. For this reason following trains are kept at a distance that is unnecessarily high, compared to the actual possibilities, by the protection functions. Current systems have been optimized in order to maximize the capacity within this paradigm and today, the railway technology is reaching a limit where the cost and complexity of adding one vehicle on an already congested link grows exponentially. In order to gain more capacity, this paradigm must be challenged.

Furthermore, another aspect that is relevant for the development of VCTS is the communication between trains. Today's communication architectures are highly centralized. For information to be transferred from a vehicle to another, it must go through numerous systems that centralize it, process it and redistribute it. This mode of communication induces delays in information's processing and transfer between trains, which is another obstacle to be challenged by the VCTS concept.

6.1 VCTS: Disrupting operation by breaking the braking wall

Considering the state of the art, the VCTS might require disruptive innovations to overcome “the braking wall” limitations of today’s railway system.

Today’s railway system is characterized by centralized intelligence and lack of information in the moving units. VCTS is based on a cooperative system view, where intelligence and relevant information are distributed among the all moving units within the system. If we look at nature, we have lots of “swarm” intelligence from which we can derive best practice for our application – ants, bees, birds, fish and maybe humans. Some of the basic principles of these swarms or colonies are:

- They use intelligence in the individual moving units (single animal) to coordinate movements
- The moving units are aware of their environment
- The moving units act according to a pre-defined set of rules that represents the maneuvers and actions to be performed in certain scenarios
- Each individual moving unit is equipped with on-board sensors (sensory organs) to detect what's happening around the unit
- Each individual moving unit is equipped with communication devices to interact with other moving units within a certain range
- Some swarms use markers on their environment (e.g. scent marks) to communicate even if no direct face-to-face communication is possible
- The individual moving unit is strongly dedicated to a cooperative behavior and to guide other moving units

Swarm intelligence can provide some insight of how the requirements of the VCTS solution: For example, it requires that all necessary **information is available on board of the trains**. Switching from a centralized architecture to a decentralized one would also dramatically shrink the communication delays of the current railway system.

Furthermore, like in swarms, the moving units in railway system could have a defined set of rules (maneuvers, actions) that define how they must act in certain situations. In case of failure or special situations the awareness of the maneuver taken by the other VCTS partner(s) would help to initiate appropriate maneuvers for the individual moving unit. Examples:

- Emergency brake: the required deceleration of the leading train is per definition slightly smaller than the deceleration of following the train – intrinsically avoiding a collision
- Approaching manoeuvre during coupling at $v >> 0$: both trains negotiate their speed trajectories before approach is started – relative speed between trains is limited, $v_{relative}$ is a function of distance between trains
- Emergency brake: due to communication link loss between trains, the back train cannot know if the leading train is braking with full effort to avoid collision

6.2 A data and information driven approach to VCTS

6.2.1 Intelligent, information-driven VCTS

The information needed for a VCTS train journey can be clustered into different types. Basically we distinguish between **static and dynamic information**.

Static information

In this context static means, that the information is supposed be well-defined and constant over time. Under normal circumstances it is not changing during the train journey.

Examples for static information:

- Track information:
  - Speed limits
  - Gradients
  - Station positions
  - Tunnels – position and characteristics
  - Radii / curvature
  - Crossings
  - …

- Mission information:
  - Time table
  - …

- Static train characteristics:
  - Tractive effort and braking capabilities (fully operational and degraded). Tractive effort may anyway be subjected to dynamic variables due to adhesion factor, track slope, etc.
  - Train tare mass
  - Train resistance (that anyway may also be subjected to dynamic factors (i. e.: wind)
  - …

- ...

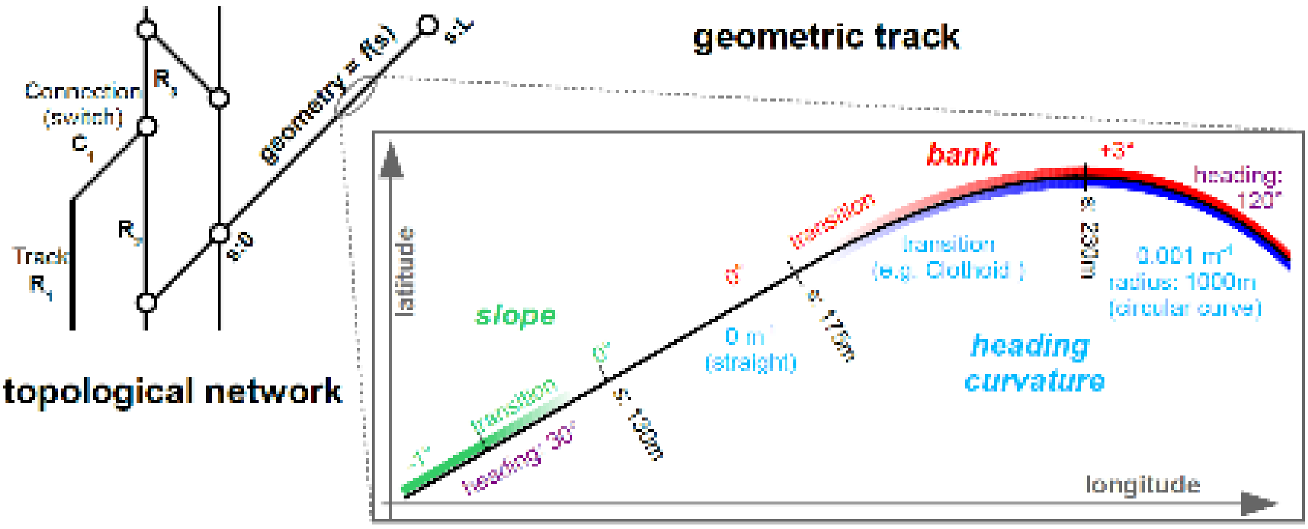

Figure 6-3: Static Information related to Track Determining Train Separation

Static information needs to be made available to the train(s) at a certain time prior to the journey. **Static information is never time critical**, it might be transferred by the train driver via USB-Sticks, via EBuLa, Wi-Fi, GSM or any other channel.

The main challenge for static information is to provide it in a safe and consistent way and open to all the information users. Thus the responsibility for providing the information and keeping it up-to-date is to be clearly distributed between:

- Track information: Network infrastructure manager

- Mission information: Train operator
- Train characteristics: Train manufacturer
- …

Dynamic Information

Dynamic information summarizes a wide field of information with only one common aspect: the **dynamic information changes during the journey**. So dynamic information might be clustered according to the rate of change into sub-classes such as:

- Quasi-static information:
  - Time table updates – in case of delays
  - …

- Infrequently changing information:
  - Degradation of traction systems – changes in tractive effort
  - …

- Regularly changing information:
  - Speed trajectories predicted for a defined time horizon
  - Train occupancy ←→ train mass
  - Acceleration and deceleration capabilities
  - …

- Highly dynamic information:
  - Train states: current position, speed and acceleration
  - Platoon states: Distance between trains, relative speed, relative acceleration
  - Emergency brake signal
  - Control signals, control lever of the leading train in case of human driver
  - …

In addition to the rate of change the "level of criticality" in terms of safe operation could be a metric to classify information (and the underlying signals), for example:

- Highly critical:
  - Distance between trains
  - …

- Low criticality:
  - Speed trajectories
  - …

- Not critical:
  - Time table update
  - …

Criticality of information might be changing during a maneuver. For example, during an approach the distance between trains doesn't have to be very accurate, while trains are far away from each other (> absolute brake distance). The closer they get, the better the quality and the communication of the information has to be.

6.2.2 Sensors and communications

Following the approach described above, functional requirements can be derived for the eyes (sensors) and ears (communication systems) of the VCTS components referring to the needs of information quality and distribution rates:

- Sensors for
  - Absolute position
  - Relative position (=distance) between trains
  - Speed (relative, absolute)
  - Acceleration (relative, absolute)
  - …

- Communication
  - How often has information to be exchanged between trains?
  - What information has to be exchanged?
  - How often has the information to be exchanged?
  - What's the amount of data to be communicated (without overhead)?
  - …

Technologies available at the time being can be characterised according to their capability to offer their functionality, depending on the distance range to be reached (as depicted in following Figure 6-4). The closer the distance, the larger is the number of means available to implement both relative position/speed/acceleration measurements as well as data transfer.

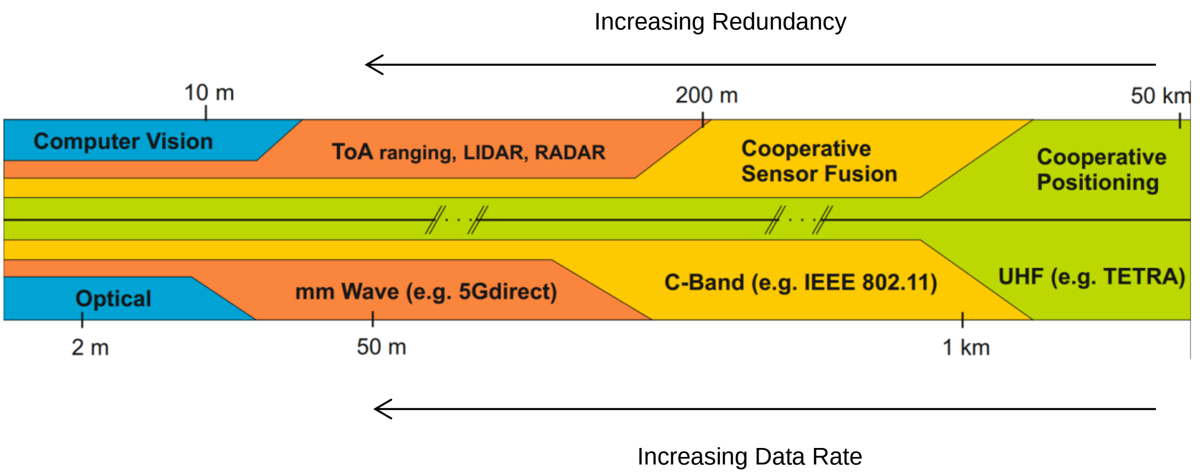

Figure 6-4: Technological Means to Implement Coordinated Movements

6.2.3 Maneuvers and actions

If we compare today's railway system to these basic swarm principles, it is obvious, that in railway system the intelligence is centralized and the moving units are basically following indications coming from this central control. So distributing information amongst individual intelligent units is not a new approach at all, but within the railway system it bears the potential for disruptive innovations.

6.3 VCTS: Expectations and applications

The main expectation driving VCTS principles of application is the replacement of the mechanical coupling mechanism between two or more trainsets, in order to build longer consists. This concept, pushed to the limit could for example be applied to freight trains. Today, a loaded wagon on a train has to wait for the other ones to be fully loaded inducing delays. This limit can be lifted by making shipments independent from each other. Freight trains would be autonomous storage units circulating on the railway network and communicating with each other in order to harmoniously circulate and optimize their behaviours. A unit having to part ways from the train would inform the other units and separate itself at the proper turnout.

This situation thus highlights the relevance of VCTS and thus its main target, that is to replace the mechanical coupling procedure (time consuming) with a more flexible and agile process allowed by a ‘virtual’ coupling that does not need an actual mechanical device that connects the trainsets, but indeed provides a more evolved system that allows trainsets to circulate together as mechanically coupled, but with no physical connection at all.

Another application could be on urban systems, today's limitation mostly lies in the dwell time and the fact that when going from A to B, subways stop at intermediate stations. Passengers getting in, out and staying on the carriage increases the dwell time. Creating specific carriages running from a specific station to another would optimize operations. The carriages would let passengers get in at one specific station, then go on line, couple themselves to other carriages running on the network then uncouple when reaching the destination station.

The next table shows some examples of the kind of applications that can rely on this technical tool. Each one is merely specified in terms of consistency perimeters, expectations and terms in which they could be implemented. Some comments are made too.

System	Framework	Application	Examples	Leverage: < headway	Leverage: < entropy	Leverage: > mechanical	Leverage: < LCC	Expectations	Term: short	Term: mid	Term: long	Comment
HSL	HSL current platoons	The HSL grid is drawn with new headway allowance specifications. Capacity is increased, such as timetable design plasticity. Instability is mitigated thanks to the VCTS which will avoid the butterfly effect.	- any HSL	++	++			●●●●○		x		If easily compatible with ERTMS It shall allow a smooth migration from existing systems (e.g ERTMS L2 or L3,..). At minimum, the trackside systems (inclusive of supervision) currently equipped with secondary detection have to be updated to manage to allow two different units on the same zone. The gain on headway can be high since some portions are saturated and the high speed imposes high distance between trains for braking
	HSL hubs	The VCTS allow to treat convergence / divergence with foresseing and optimisation (conveyor belt) Could be used as a regulation tool in order to get trains through hubs	- Y griego vasco (ES) - LGV d'interconnexion (FR) - Shuttle (UK|FR)		++	+		●●●○○			x	The switches have to be VCTS driven The onboard may have a role in the reservation of trackside resources (migration of CBI / Zone controler functionalities from trackside to onboard). Issue of calculation capacity of onboard systems to be addressed in this case. It shall allow a smooth migration from existing systems Interest can be quite high considering the slash in processing and communicating times. Should probably be used along with automatic driving functions.
Classic rail	Classic node	The VTCS allow to treat a strategic interstation like a conveyor belt between two stations where trains stop to increase the flow and robustness. The virtual coupling is established during the passengers service	- Brussels (BG) - RER B/D tunnel (FR)	++	++			●●●●●		x		Once again it could be used as a regulaition tool, probably very useful on dense areas, not at all on other areas.The switches have to be VCTS driven or VCTS & interlocking must find a way to interact. The onboard may have a role in the reservation of trackside resources This implementation needs track layout optimization not to limit the flow because of a weak capacity in stations. It shall allow a smooth migration from existing systems.
	Classic node	The VTCS allow switches zones (cf. UIC 406 leaflet) to be dealt with like one track platoons in order to increase the funnel capacity and elasticity	- any national-span station	++	++	+		●●○○○			x	The switches have to be VCTS driven or VCTS & interlocking must find a way to interact. The onboard may have a role in the reservation of trackside resources It shall allow a smooth migration from existing systems
	National-span line	The VCTS is used on a long distance for homogenic trains batteries May lead to power optimizations : if we can couple trains and power them together rather than separately, maybe we can save some costs and optimize power supply	- any national-span line	++	++	+		●●○○○			x	The choice to engage VCTS or not is complicated to make. Experience suggests it won't be used for the grid not being as standardized as HSL ones.
	National-span line	The VCTS is used to rule freight convoys batteries Could change the way freight is done. Independant mobiles with storing capacity would couple and uncouple in order to be groupped on main section	- national-span line included in RET-T corridors	++	+	+		●●○○○			x	The market is more about regularly paced pathes por freight s (such as rail-route container services) Need to have an increase in freight market to be very interesting
	Mass transit line	The VCTS is implemented as the operation leader of the line through distributed intelligence and decision making The onboard VCTS units are able to manage functions that are managed by the trackside in current solutions : movement authority definition (RBC), points locking (IXL) or even regulation (TMS)	- any MT line to come or to be modernised	++	+	+		●●●●○		x		Interfaces ate to be watched out carefully Can possibly reduce the cost of a TMS : no real estate, no need for a "super computer", no operators...
	Railway line (isolated)	As a forgotten line operation is reconsidered, virtual coupling helps to optimise operation manoeuvers and costs Considering the railway line was closed, probably low traffic. VCTS could be used to replace heavy signalling (assuming speed limits are known one way or another) to ensure trains safety.	- UIC 7 to 9 lines			++	++	●●●●○		x		The system seems rather sphisticated for such cases, and a priori not meant for these opportunistic applications Expectation could be high if the VCTS solution proposed functions onboard. The interest of the system is that it would bear the safety functions. We can imagine passive interlockings, receiving orders from the tran I'm afraid this system is something else though. it centralizes too many functions however we could upgrade operation on lines from shuttle
Light Rail	metro line	The VCTS is implemented as the TMS of the line	- any metro line to come or to be modernised	++	+	+		●●●●○		x		Economies are expected within the ground-based systems. The stations must not limit the benefit of the platoon potential headway
	metro line	Exchanges with the industrial site : technical movements can be mutualised through virtual coupling	- any metro line / yards to come or to be modernised			++		●●○○○		x		Really relevant but on few cases only
	tram	The VCTS is implemented as the TMS of the line	- any metro line to come or to be modernised	++	+	+	++	●●●○○		x		VTCS vs visual driving must be assessed economies are expected within the ground-based systems. The stations must not limit the benefit of the platoon potential headway interesting at forks ? The gain can be high if the VCTS solution limits the trackside infrastructure. Easier in cas of tramway since the track layout is simple In case of driverless system, the obstacle detection has to remain active on the following units but able to allow close driving with the unit ahead
Road	trucks	truck chains are integrated	- to be defined (out of scope)					●●○○○		x		
	autonomous vehicles	VCTS could be added to existing algorythms	- to be defined (out of scope)					●●●●○	x			

Table 6-1: Application Perimeter of Virtual Coupling

6.4 VCTS: Objectives

The work packages (WP6 and WP7) are defined to perform a comprehensive study focusing on the new concept of "Virtual coupling", which foresees that trains – here the consists inside a VCTS - will be able to run much closer to one another (within their absolute or relative braking distance) and to dynamically modify their own composition on the move (virtual coupling/uncoupling of platoons). However, while the core aspect of Virtual Coupling is the identification of solutions to allow trains to run closer, the objectives of VCTS target a broader set of advantages over the traditional way to operate a railway network, e.g.:

- To replace the mechanical coupling, in order to enhance efficiency and flexibility of consist building procedure
- To increase line capacity by reducing the headway
- To reduce maintenance cost in relation with best use / max capacity of the line
- To increase competitiveness making more efficient goods and passengers transportation over the railway network with respect to the road transportation
- To improve the use of the existing station platforms. One platoon can be shared using several platform tracks
- To reduce global investment costs by adding on board and trackside signaling/electronic systems, instead of tracks or heavy changes of the infrastructure
- To increase operational flexibility ensuring interoperability
- To save cabling, materials, weight and design constraints of on-board rolling stock

For this reason, the coupling concept of this innovative solution moves from the principles of mechanical coupling to a new paradigm based on a 'virtual' approach, based on new technologies allowing trains/consists to control their headway beyond the limitations that are imposed from the underlying train separation/protection systems. The target of this new system is thus to allow consists to be coupled not through mechanical joints, but by mean of a virtual link that regulates and minimises headway of the consists within the train with the same (or similar) dynamic behaviour as if they were mechanically coupled.

With reference to Figure 6-5 the concept of operation for VCTS is developed around the principle of overcoming the limitation imposed on headway of trains caused by the application of absolute braking distance

To overcome this limitation, a train headway control system that leverages on cooperative braking must rely on a mutual exchange of relevant information between two or more following trains, in order to allow them to run at closer distance than the absolute braking distance of the rear consist(s). This methodology is actually referred as 'cooperative', as trains running as 'virtually coupled' must be capable to communicate to each other the set of data regarding their specific dynamic behaviour. That way the consist is able to compute 'cooperative' braking curves, which integrate the parameters related to the braking characteristics and status of the consists within the virtually coupled train, as well as other parameters as communication network delay, etc. in their algorithm …. As a result, consists inside the virtually coupled train must be allowed to run at closer distance than the current absolute braking distance paradigm, in order to form a 'virtually coupled platoon'.

The core of the Virtually Coupled Platoon is thus the capability of the consists inside a platoon to interact by mean of a dedicated communication link to exchange data and allow the consist of the virtual coupled train to implement the headway control strategy described above.

This should be achieved while ensuring at least the same level of safety currently provided by standard platoons connected by mean of mechanical/electrical coupling. The action has for objective to define the behaviour, the system, the architecture, the functions, the real feasibility & applicability, the potential performance increase to be achieved as well as the safety level.

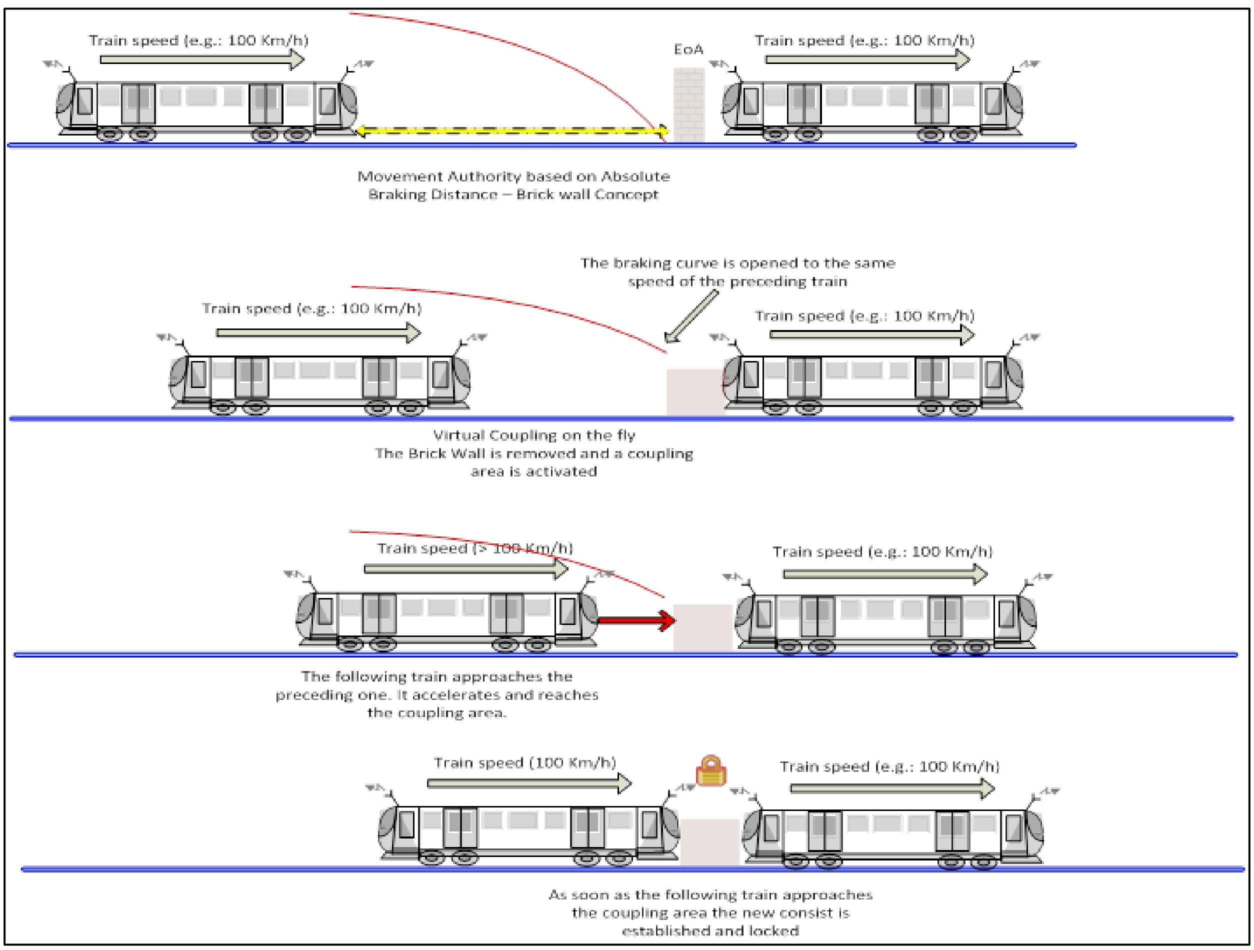

Figure 6-5: VCTS Conceptual Approach

A New Model of Headway Control

The core of VCTS is to safely maintain a controlled headway between consists which are virtually coupled, which is typically shorter than the conventional absolute braking distance. Each consist manages the computation of its headway based on:

- its own specific braking characteristics
- the characteristics of other *'virtually coupled'* consists
- the current dynamic information as speed, position, etc. of all consists

Each train of the Virtually Coupled Platoon cooperates to exchange the relevant data to implement a coordinated supervision of movements, based on the characteristics of all trains belonging to the platoon.

This leads to the maximisation of the network capacity, by allowing trains to run at a distance (and so, headway) that is the minimum achievable with a specific technology. Under this perspective, the analysis and definitions provided in this document intentionally abstract from the specific solution available and mostly aims to export constraints to the technology in terms of:

- *Performance*: the technology available is the key driver in terms of performance achievable by the VCTS in terms of network capacity, reliability, etc. Depending on the selected technology, the VCTS will be allowed to achieve a certain level of performances.
- *Safety*: whatever is the technical solution applied to implement VCTS, it must comply with the safety targets of the VCTS functions which rely on it in any case

This means that, once the goal of the VCTS are clarified, it is necessary to identify the main interactions of the system with the overall railway infrastructure, as also initially drafted in the context diagram of which at Section 7.2.

7 System Description

7.1 Methodology Applied

The implementation of Virtual Coupling concept requires first to identify the actors of the railway infrastructure which will intervene to allow the VCTS to become effective. Especially, the description of the system requires to apply a formal methodology to describe how VCTS is structured not only in terms of physical architecture, but even earlier in terms of functional architecture that shall then support the allocation of functions onto physical components of the existing infrastructure (or new component required to achieve VCTS objectives).

For this reason the following section approaches the system description by first detailing the VCTS context diagram, in which the different functional layers of the system are identified. Once layers and associated functions/accountability in the implementation of VCTS concept are defined, the field of study is then analysed in order to understand which are the main interfaces of VCTS with the external entities of the railway infrastructure, and which kind of relationship is addressed by each interface (e.g.: providing a service, exporting a requirement, etc.).

Once the functional structure and the interfaces are clarified, the VCTS concept is then developed according to the main functional components that allow the practical implementation of the system definition to be put in place. The functional components (either internal or external to the VCTS) are system elements which are in charge of providing some of the functions of the VCTS and that shall cover the entire set of use cases defined in following Section 9.

7.2 VCTS Context Diagram

A context diagram shows the system under consideration and gives an overview of it. It is a kind of high level data flow diagram. Usually the context diagram only contains one process which represents the whole system or could be split into several major processes to give more details.

Context diagrams show the interactions between the system under consideration and other actors (external factors) with which will interface by design.

As they may be helpful in understanding the environment or ecosystem of which the system will be part, context diagrams are used in early phases of projects in order to define their scope.

Figure 7-1 depicts the context diagram of the virtual coupling system. As a remark, the diagram does not necessarily impose a specific architectural solution on VCTS. For example:

- The TMS may also communicate directly to the ATO
- Train to ground and train to train communication infrastructure may not be necessarily two distinguished entities/links
- The signaling system may be an ATP or any other typology of system offering similar functionalities and services

- Track information (gradient, curves, etc.) may come either from the ATP itself, or from any other supporting equipment different from the ATP
- Entities in the diagram are not all mandatory but the VCTS shall be able to cope with the absence of some of the entities in the diagram with alternative solutions/functions

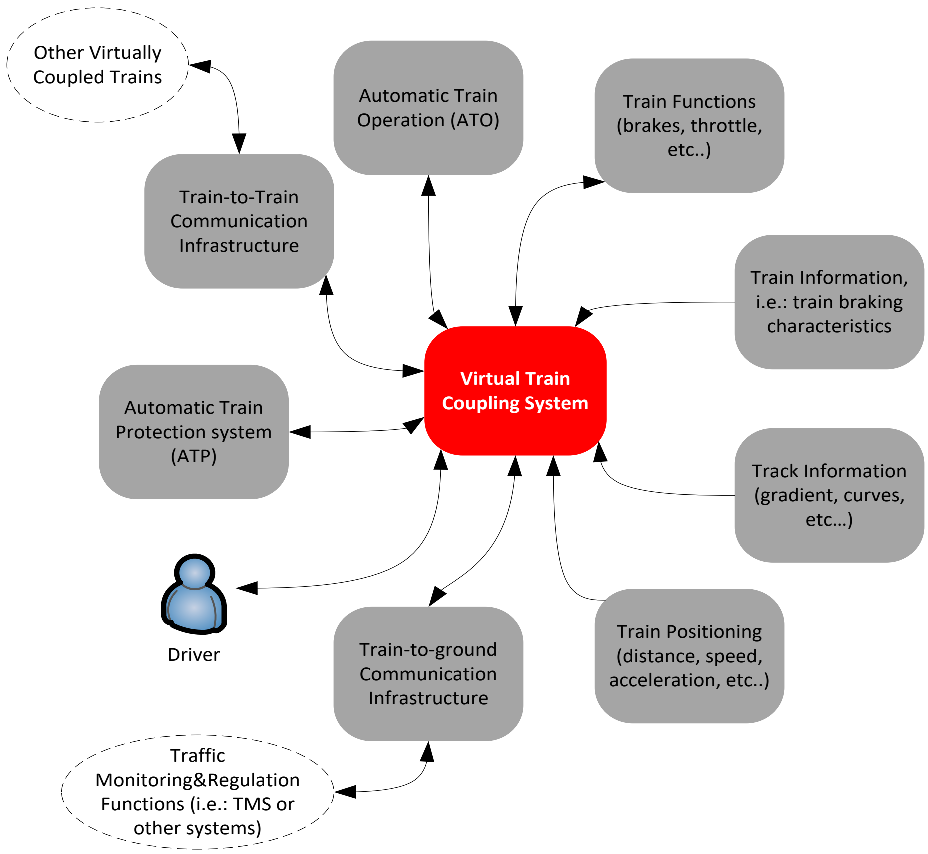

Figure 7-1: VCTS Context Diagram: Interfaces with other Railway Infrastructure Functions

As another remark with reference to previous Figure 7-1, the referred ‘TMS’ shall not be misunderstood as the ‘VCTS-TMS’ that is later referred along the document, but indeed it represents the existing infrastructure aimed to regulate traffic, manage timetables, resolve conflicts, etc.

In this case the system has been decomposed in four major processes which interact between themselves and with external actors. The system under consideration within this deliverable is framed in orange, while in any case the whole VCTS shall be represented by the entire following picture Figure 7-2.

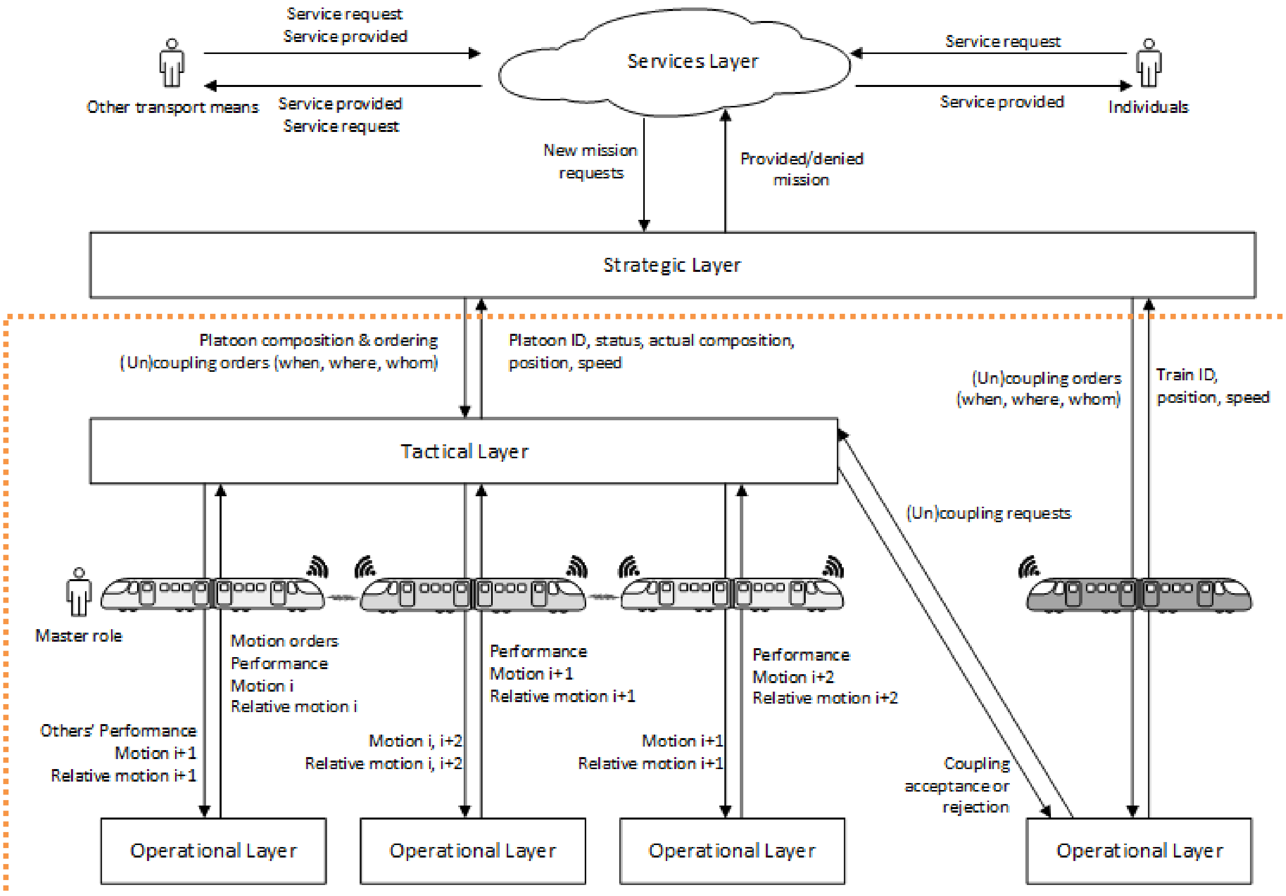

Figure 7-2: VCTS and functional layers

Each of the four processes corresponds to a functional layer. Those functional layers are:

1. The **service layer** is integrated in the mobility-as-a-service (MaaS) platform and asks for new rail services (missions).
2. The **strategic layer** is in charge of defining the platoons, their composition and ordering, based on compatibility, destinations and schedules. It also defines when and where the trains are joining and leaving the platoon. The objective of this layer is to maximise the capacity of the infrastructure, identify potential conflicts, deal with delays and disruptions and supervise the traffic flow and its safety.
3. The **tactical layer** coordinates the actual platoon movements and manoeuvres like the joining and leaving operations. It manages unexpected events and sudden degraded modes of any of the platoon units. This layer is connected to the signalling system and is responsible for defining the speed and acceleration targets and the headway between trains. Although the master of the tactical layer could be taken by any of the units -forming the platoon, the leading consist will typically master the platoon.
4. The **operational layer** is in charge of the local control (accelerating and braking) of each unit assuring that commands established by the tactical layer are safely executed, including the ones related to joining or leaving the platoon. The main control task is to

regulate the headway while keeping the stability of the platoon, which is challenging due to the nature of the railway system, its big inertias and the metallic wheel-rail contact.

7.2.1 Service Layer

This layer belongs to the service provider and is out of the scope of the virtual coupling system itself. It is in charge of coordinating the needs for new services upon demand and interacts with the users, which could be individuals accessing the rail booking systems or other transport modes platforms.

On the other hand, this layer requests new and ongoing missions from the strategic layer to comply with the requested services.

7.2.2 Strategic Layer

Following the service requests coming from the upper layer an algorithm (based on artificial intelligence, machine learning, etc.) determines how the platoons should be created in order to reach the defined targets in terms of capacity, punctuality, operational costs, travelling time or waiting time, among other.

This layer determines where and when the trains are joining and leaving the platoons and hence a permanent communication link should be established between this subsystem and the trains.

Individual trains inform about their position and speed and eventually receive commands regarding virtual coupling procedures, like the time and location where the coupling should take place. The latter should allow the joining train to optimally adjust the journey to the coupling point. Obviously the trackside also informs about the platoon (or master train) ID needed to communicate the coordination of the operation

The functions related to the strategic layer could be integrated into the Traffic Management System (TMS). However, detailed description of strategic layer functions is outside of the scope of this document. Strategic layer scenarios will be anyway evaluated in order to drive the tactical layer description consistently with the services that may be required from the upper layer.

7.2.3 Tactical Layer

The tactical layer is in charge of coordinating the movement of the trains composing the platoon from the instance a joining request is received until the platoon is dissolved.

When a train is commanded to join a train or an existing platoon, it tries to establish the remote radio contact (T2T or T2G2T) with the targeted platoon. A dialogue starts in order to verify the coupling ability and to get the coupling acceptance. If this kind of “handshake” is finished successfully the approaching can start. This procedure is ruled by the existing signalling system (e.g. ERTMS) based on absolute braking distance, until the VCTS takes over control, and the minimum headway is allowed by the system (based on relative braking distance monitoring). From that instance the joining train can continue the approach under the virtual coupling rules.

Once the platoon is created and its units are running with the defined headway between them, the tactical layer is responsible for the stable movement of the platoon. This movement is governed by the master train (usually the leading train) and the following trains shall keep the headway stable. To achieve this, the undisturbed and permanent exchange of information between trains is crucial. The master train has to know the traction and braking performance of all units in order to keep the motion under the combined performance envelope (i.e. cooperative braking curves) and this information must be updated upon any relevant change.

The uncoupling procedure can be started in two ways: controlled and unplanned (or abnormal). A controlled uncoupling is done by a train that wants to leave the platoon for operational reasons (e.g. going to a different destination). It informs the platoon about the manoeuvre and starts moving away until it reaches the absolute braking distance required by the signalling system, where a handover to this system can be performed and the virtual coupling is finalised.

An unplanned uncoupling could be caused by a kind of failure that might be related to the virtual coupling function or not. The consequence is the sudden segmentation of the platoon into smaller platoons or single units, each operating under a new master authority (or on their own). Under the newly formed performance envelope will reach a safe headway (i.e. minimum headway allowed by the signalling system based on absolute braking distance) by braking.

The strategic layer should be capable to arrange, manage and divide virtually coupled train sets operationally efficient, in order to avoid difficult joining or leaving manoeuvres. In case of necessity the tactical layer would be also in charge of managing the operation by controlling individual distances inside the platoon.

The functions related to the tactical layer could be performed by the master train.

7.2.4 Operational Layer

The operational layer manages the local movement of each train following the commands provided by the tactical layer in a safe way. These commands basically refer to motion orders, for example, in terms of acceleration, and also refer to headway.

Hence, the main function of this layer is to regulate the headway while keeping the stability of the platoon. The control algorithms may have to consider several parameters, like the relative distance, speed and acceleration between the local train and the adjacent vehicles, and between the local train and the master train. The exact parameter list and control algorithms will be defined later on.

This layer should be executed locally in each train and should consider the actual performance of the train at all times. In addition it should monitor the status of the radio communication links, whose number can vary depending on the number of trains inside the platoon.

The detailed architecture will be defined in next steps of the virtual coupling studies, but it can be foreseen that the operational layer could rely on at least two sources of information for determining the relative motion between the local train and the neighbour trains/consists inside the platoon. First, accurate, safe and continuous positioning and speed data will be required, to be compared with similar received data from other trains inside the platoon. Secondly, advance sensors (e.g.

radars, cameras…) will provide equivalent information to be used as redundant source. The exchange of information between trains should be ideally done through CAM (Cooperative Awareness Messages) messages, associated with appropriate frequency and time constraints depending on their criticality.

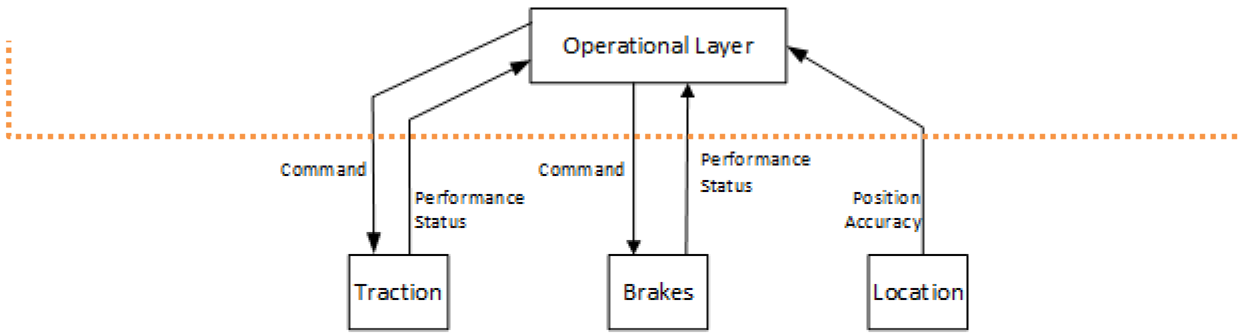

Figure 7-3: Links to train subsystems

The operational layer should be intrinsically linked to subsystems like traction and brakes (see Figure 7-3), whose actual performance will be required for computing the performance envelope and for providing accurate control. As aforementioned, the continuous train positioning is a key function for the operational layer and one of the outputs of the studies carried out in WP6 and WP7 of X2Rail-3. These outputs will be a set of requirements for Shift2Rail's TD2.4.

7.3 Field of Study

7.3.1 VCTS Concept

The VCTS is characterised by a set of functions which are explained in detail within chapter 7.4, and that can be summarised in the following main functional phases:

- *I: **Virtual Coupling Activation***: in this phase, trains not yet virtually coupled will initiate the relevant actions to become a Virtually Coupled Platoon. This includes all tasks required to open a safe connection between master and slave train(s), exchange the relevant data to allow cooperative braking monitoring and overall mission set up. At the end of this phase the Virtually Coupled Platoon is set up for running. The Activation procedure shall consider two possible scenarios:
    1) *No previous platoon yet established;*
    2) A previous platoon has been established (i.e.: at least two consists already paired in an existing VCTS) with a new consist/train being added;
- *II: **Running in Virtual Coupling Mode***: this second phase allows the platoon to move according to virtual coupling principles. Therefore it includes all tasks aimed to calculate relative braking distances, application of controls to maintain safe headway between master and slaves and the associated exchange of data across the train-to-train wireless link.

- *III:* ***Virtual Coupling Termination*****:** the last phase is the termination of the VCTS, at the end of which each consist becomes again a single, autonomous train. This phase hands back control of the mission to each single train, according to absolute braking distance principles. As for the activation, the termination will consider two different situations:
  1) *Just two trains in the dissolving VCTS;*
  2) *More than two trains, so that the result of the process is a platoon of two or more trains in a single train.*

Moreover, the task *Virtual Coupling Monitoring* is activated simultaneously with the Virtual Coupling itself. This task aims to monitor all the activities and the status of the overall Virtual Coupling procedure (i.e.: Status of the T2T link and other associated virtual coupling devices) and to apply the required actions to maintain safety of operations.

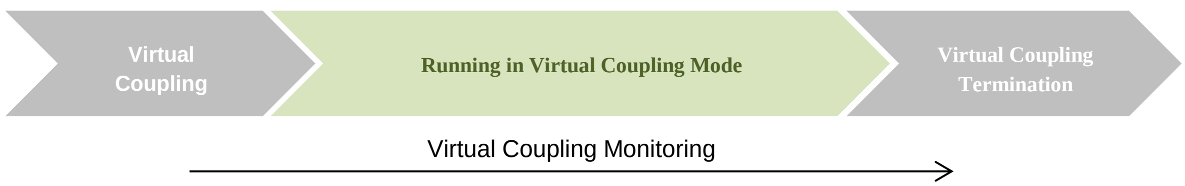

Figure 7-4: Virtual Coupling Main Functional Phases

The basic functions of the VCTS concept are derived from mechanical couplings. The mechanical coupling associates the dynamic behaviour of trains through the physical (mechanical) link; trains joined by a mechanical coupler move as a single platoon with same speed/acceleration at any time. When allowed by the on board systems, the consists within the platoon may be all associated by the same TCMS network so that controls are shared (for example with distributed braking functions), but this is not a compulsory requirement for any application.

7.3.1.1 Mechanically coupled train set

A mechanically coupled train set, or MCTS, is a train formed of two or more consists 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 information between consists and in some cases pressure of pneumatic brakes.

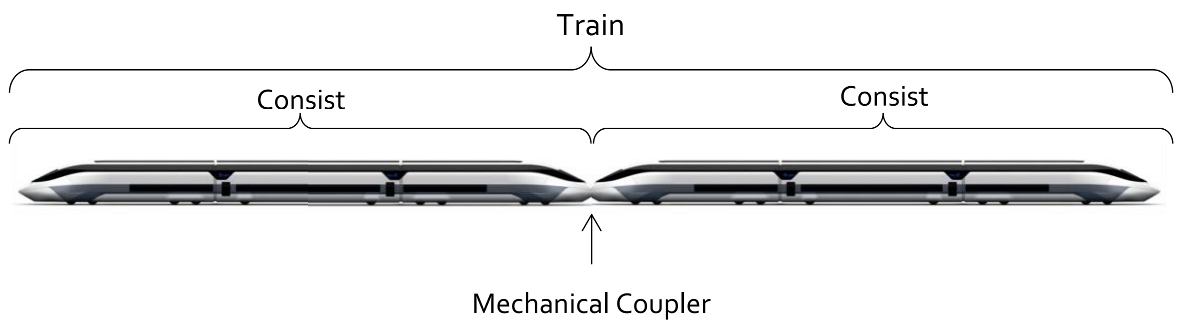

Figure 7-5: A MCTS formed of two consist

Traditionally, in mechanically coupled trains, the mechanical coupler performs two basic functions. The first basic function is to **keep the relative position between the coupled units fixed**. This positioning function works normally by transferring push and pull forces, however the positioning function may be achieved without transferring forces if the coupled units are motorized and the brake and traction forces of the units are controlled in a well-balanced cooperative way. The second basic function is the **transmission of information for braking the train** co-ordinately.

Most modern mechanical coupling systems are combined with additional functions, for example transfer of information via pipes and cables or support of collision mitigation systems. The basic and additional functions of the mechanical coupling are summarized below:

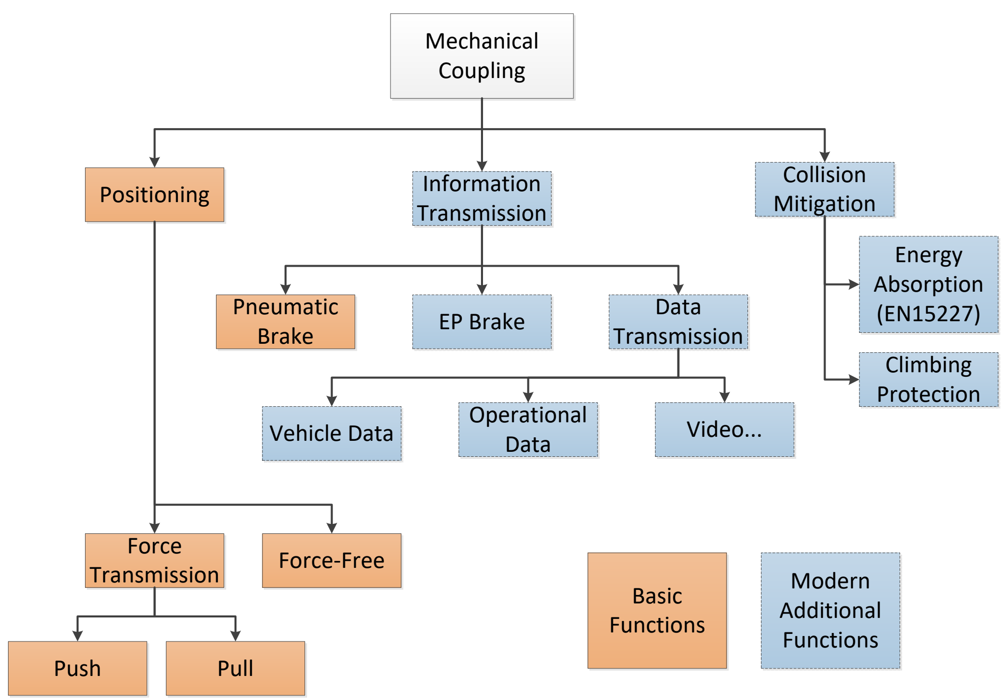

Figure 7-6: Functions of mechanical coupling system

The coupling and decoupling procedures of mechanically coupled trains are well-established in the railway system. The definition, where and when consists are joined and separated, is based on their compatibility, destinations and schedules. This definition is performed on the strategic layer and often implemented on a regular schedule.

When consists are ready to be joined (according to strategic layer definition) the tactical layer is in charge to perform the coupling procedure: the coupling devices of both trains are prepared for coupling. Then one train stays on standstill while the second one approaches at low speed (driving on sight) until the mechanical connection between trains is established. In case of non-automatic coupling, an operator has to engage and lock the mechanical connection. Air pressure pipe and other data interfaces (for example TCMS via electronic interface) are connected and the integrity of the new train is checked. This process is finalized with the event of train baptism, after which the coupled consists are recognized as one train in the signalling system.

The train is then operated by the driver of the leading consist, and ATP is only active in the leading consist.

7.3.1.2 Virtually coupled train set

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

This distinction highlights that the 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, that is necessarily implemented by mean of a specific cooperation strategy between the trains of a Virtually Coupled Platoon.

The structured approach for the development of the electronic coupling system is divided into two main steps:

1. The functions of the mechanical coupling system are transferred to an electronic system
2. Additional functions – e.g. coupling on the fly and other use cases - are integrated

Enabling technologies to implement this innovative idea are the improved performance of computer technologies and more reliable communication technologies with increased data rates (e.g. Wi-Fi or 5G). To achieve the functionality of dynamically coupling and decoupling while maintaining minimum headway, new switch-technology is also helpful.

Because of the lack of physical contact, VCTS trains can couple and decouple while driving, even in high speed, without risk of derailment. Within the VCTS concept the coupling procedure can be distinguished between the extremes of “pure static coupling” (at speed = 0, analogous to mechanical coupling process) and dynamic coupling “on the fly” at speeds > 0. At which maximum speed a coupling process is feasible and reasonable has to be analyzed within the project (Feasibility Study, D7.1).

7.3.1.3 Cooperative Train headway

In the cooperation algorithm of Virtual Coupling, master and slaves determine the minimum relative distance which is safe to maintain according to the information of each consist of the platoon. This means that each consist in the platoon must be aware of:

- *Dynamic characteristics of each consist in the train* (braking capacity/deceleration, timings, etc…). This is mostly required to:
    - Calculate the relative braking distance to be kept from the train in front (either the master or one of the slaves);
    - Harmonise braking actions, especially with respect to the braking capacity of following trains. For example, the master must be aware of the available braking deceleration of following trains, especially when lower than the available deceleration of the master itself. In this case, the master must be capable to adjust its braking effort in order to align to the deceleration achievable by other trains in the platoon, to avoid thus collision.
- *Relative positions of other trains*. Each consist must be aware, at any time, especially of its distance from the neighbouring trains in order to supervise this distance against the safety margins determined by the relative braking distance calculation. Moreover, stability of the platoon is critical, if each train refers to the train in front or itself. Headway control should be implemented with reference to the leading consist (the first consist in driving direction of the whole TCTS train). Determination of the distance to the train in front is necessary as a fall-back solution in case of failure.
- *Overall status of other trains*. Each train must be aware, at any time, of the ongoing actions as braking, throttle settings, etc. of other trains in order to react to the consequent actions locally, and maintain minimum distance safely.

From this model of cooperation, it is evident as each train must develop "*awareness"* of other trains in the platoon by exchanging a set of data through a dedicated, wireless channel with appropriate performances and requirements.

7.3.1.4 Minimum Headway Distance

While avoiding the need of a mechanical coupling of consists to build a platoon, the main advantage of virtual coupling is also to maximise the network capacity, by allowing the shift from absolute braking distance monitoring to the newer concept of *minimum headway distance* (as already summarised in Section 6). This is achieved, in practice, by mean of:

- The cooperation mechanism of Virtual Coupling, providing each consist with the awareness of the characteristics and status of other consists in the platoon, in order to implement the necessary local controls;
- The capability, for each consist, to safely compute and supervise cooperative braking distances. This functionality shall belong to each consist of the VCTS, and shall be based on the information exchanged through the cooperation mechanism.

The headway distance that is obtained is actually classified as 'minimum' because through the Virtual Coupling mechanisms, trains which are not physically coupled can move as a single platoon maintaining the actual minimum achievable distance of headway, considering the constraints of the available technologies (i.e.: performances of the communication link, or braking system).

7.3.2 Boundaries of VCTS

VCTS is not a standalone system, but indeed it interacts with a number of subsystems.

In order to achieve its main goals, the VCTS may interact with the following external elements; the interaction may be implemented with different architectural solutions that are not part of the scope of this document.

Interface	Interaction	Purpose
Train Functions	The VCTS shall be allowed to interact with the train functions both for protection purposes (i.e.: avoiding collision with the train in front) as well as to determine the current status of the train interfaces (i.e.: ongoing braking actions, throttle status, etc.).	• Protecting train movements (i.e.: avoiding collision with the train in front) • Harmonizing brake effort based on other trains' characteristics • Determining status of brakes, throttle, etc…in order to notify also other trains in the platoon
Train Information	The VCTS shall be able to access a set of information regarding the train, as braking deceleration available, mass, activation timing, maximum speed, etc…	• Calculating braking curves to determine permitted speed • Share the train characteristics with other trains in the consist
Track Information	Whenever available, the VCTS shall make use of information related to the track/route as gradient, speed profiles, etc. this can be achieved in a number of ways (i.e.: communication from wayside infrastructure, track databases, etc.).	• Calculating braking curves to determine permitted speed
Train Positioning	VCTS requires an external odometry source, providing the necessary data regarding current position, speed, acceleration and other parameters related to train kinematics at a certain time.	• Determining relative distance of separation with other trains in the VCTS • Sharing own position/ speed/ acceleration with other trains in the VCTS.
Train-to-Train Communication Infrastructure	The VCTS shall be supported by a wireless communication infrastructure to interact with other consists of the Virtually Coupled Platoon.	• Exchanging any VCTS-related data with other trains in the platoon
Train-to-Ground Communication Infrastructure	The VCTS shall be supported by a communication infrastructure in order to interact with a wayside traffic regulation	• Managing composition of the virtually coupled platoon (i.e.: determining which trains are allowed to couple)

Interface	Interaction	Purpose
	system. As a remark, this function may be replaced by manual procedures.	• Receiving other information related to the current mission (destination, stopping stations, etc.)
Automatic Train Operation (ATO)	The VCTS shall be able to interact with an external system implementing driverless functions	• Providing the necessary information to allow ATO to implement its driving strategy, taking into account VCTS input.
Automatic Train Protection (ATP)	The VCTS shall be able to interact with an external system providing Automatic Train Protection Functions.	• Providing the necessary information regarding the status of the VCTS (i.e.: active or not) • Depending on the specific ATP system, receiving VCTS-related data (gradient profile, static profiles, track conditions, etc.)
Train Operators (i.e.: drivers) driving the master/leading train	The VCTS shall support interaction with a train operator.	• Allowing the Virtual Coupling mission set up, when necessary

Table 7-1: Main VCTS Interfaces and Associated Functions

7.3.3 Exporting Requirements to Interfaces

While the extensive list of requirements will be delivered in later stages of documentation for this project, it is still possible to define a preliminary set of high level requirements that the VCTS concept shall export to the external interfaces, especially in order to better limit its boundaries and consequently the boundaries of the analysis provided in this concept.

For this reason, the list of exported requirements in Table 7-2 can be also seen as an initial set of assumptions driving the VCTS concept developed now onward.

Interface	Interaction	ID	Mandatory (M) or Optional (O)	Exported Requirement
Train Functions	The VCTS exports both functional and safety requirements to the train interface in order to fulfil the functional/performance/safety targets of the overall system. Especially, the VCTS assumes the availability at train interface of a dedicated access to vehicle-specific functions as service/emergency brakes, traction cut off, etc.	VCTS_EXT_TF1	M	The train functions shall provide an interface to VCTS to allow protection train movements with adequate level of safety (i.e.: interface to emergency/service brake or other typologies of brakes, traction cut off)
		VCTS_EXT_TF2	M	The train functions shall provide continuous information of train integrity information with adequate level of safety in order to determine rear end of vehicle

Interface	Interaction	ID	Mandatory (M) or Optional (O)	Exported Requirement
	Moreover, this VCTS concept assumes the train functions interface as compliant with the necessary safety integrity level according to the targets of the associated VCTS function.	VCTS_EXT_TF3	M	Train functions shall provide information regarding train composition and current brake percentage (or other parameters indicating achievable deceleration by the train)
Train Information	The dataset of train characteristics is assumed as correct and compliant with the class of rolling stock operating under virtual coupling concept. The VCTS is not responsible to operate checks on the information provided.	VCTS_EXT_TI1	M	The dataset of information regarding train characteristics shall provide correct values with respect to the current train configuration at any time.
		VCTS_EXT_TI2	M	The VCTS shall receive from an external system the information regarding the current achievable deceleration rate for any typology of brake available;
		VCTS_EXT_TI3	M	The VCTS shall receive from an external system the time required to apply brakes, for any typology of brakes (e.g.: time required to initiate the brake after initiating the command);
		VCTS_EXT_TI4	M	The VCTS shall receive from an external system the time from the initiation of the command to the application of full effort for all brake types available.
		VCTS_EXT_TI5	M	The VCTS shall receive from an external system the percentage of rotating masses according to the current train configuration.
		VCTS_EXT_TI6	M	The VCTS shall receive from an external system the value of maximum acceleration achievable by the train.
		VCTS_EXT_TI7	M	Train characteristics shall be provided to VCTS every time and as soon as the associated values change.
		VCTS_EXT_TI8	M	The assesment regarding validity and correctness of train information is not in charge of VCTS.
Track Data	Track information is assumed to be available from this interface, in order to compute the cooperative braking curves depending on track characteristics. The VCTS is not	VCTS_EXT_TD1	O	The VCTS shall receive from an external system the information regarding static or temporary speed restrictions applicable to the track ahead.
		VCTS_EXT_TD2	M	The VCTS shall receive from an external system the information regarding the

Interface	Interaction	ID	Mandatory (M) or Optional (O)	Exported Requirement
	responsible to operate checks on the information provided.			gradient of the track ahead (when available);
		VCTS_EXT_TD 3	M	The VCTS shall receive from an external system the information regarding the adhesion factor of the track (when available)
		VCTS_EXT_TD 4	O	The VCTS shall receive from an external system the information regarding specific track conditions (i.e.: tunnel, bridges, powerless sections) when available
		VCTS_EXT_TD 5	M	The VCTS shall not perform any additional check to ensure safety of track information received.
Train Positionin g	Train positioning function is assumed to be provided with sufficient level of accuracy and safety integrity to allow the VCTS to meet its targets of performance (in terms of Reliability, Availability, Maintainability and Safety). The train position function interface shall thus provide to the VCTS a continuous source of information regarding travelled distance, speed, acceleration, etc. that shall be characterised in terms of possible errors on the measure (i.e.: maximum underreading, overreading errors), in order to allow the VCTS to implement necessary mitigations within its native functions.	VCTS_EXT_TP 1	M	The VCTS shall continuously receive from an external train positioning function the value of current speed, travelled distance and acceleration of the train;
		VCTS_EXT_TP 2	M	The VCTS shall continuously receive from an external train positioning function the estimated accuracy on the values of speed, distance and acceleration received.
		VCTS_EXT_TP 3	M	The external train positioning function shall provide a measurement that fulfils the safety targets required for the VCTS.
		VCTS_EXT_TP 4	M	The VCTS shall not be in charge of implementing additional checks or functions to support the achievement of the necessary safety integrity level for the positioning function.
Train-to-Train Communic ation Infrastruct ure	The wireless infrastructure is supposed to comply with the performances necessary to allow the VCTS to meet its own targets (in terms of Reliability, Availability, Maintainability and Safety). It shall be possible to characterise performances of the T2T network at least under statistical criteria, in order to finalise an accurate analysis of the obtained performances of the VCTS as well as possible mitigations within the VCTS functions to overcome gaps.	VCTS_EXT_T2T 1	M	The T2T communication network shall offer a link between trains inside same platoon that complies with the requirements of Table 9-1.

Interface	Interaction	ID	Mandatory (M) or Optional (O)	Exported Requirement
Train-to-Ground Communication Infrastructure	Same requirements as the T2T communication infrastructure. In this work package, no investigation is provided regarding requirements applying to an external traffic regulation system more than the functional aspects of the interaction.	N/A	O	Not applicable to this document
Automatic Train Operation (ATO)	This concept assumes the on board ATO system to be fully in charge of the driving of the train, eventually based on the information elaborated by the VCTS (i.e.: safe distance from front train to be kept). VCTS. The presence of an ATO on board is not mandatory to allow the VCTS to operate, and the implementation of VCTS-related functions on the ATO is manufacturer-dependent. The VCTS control and stability algorithms will produce an output in terms of acceleration/speed/distance which can be forwarded to the Traction Control unit (in modern traction system) or to the ATP (if it accepts this kind of input). Otherwise it could be converted into a traction effort using appropriate train model.	VCTS_EXT_ATO1	O	The on board ATO, whenever present, shall be able to interface with the VCTS in order to receive platooning information (i.e.: safe distance from other consists, or other information to implement platoon stability control).
		VCTS_EXT_ATO2	M	The VCTS shall not be in charge of implementing any function supporting driverless operations.
		VCTS_EXT_ATO3	M	The VCTS shall allow manual control of the master/leading train by a driver
Automatic Train Protection (ATP)	The onboard ATP shall be able to manage and coexist with the onboard VCTS and to determine its mode of operation according to the status of the VCTS itself. The VCTS shall thus operate irrespectively from the existence of an ATP on board the train. In terms of protection of consist movements, controls applied by the VCTS shall be assumed as completely independent from controls applied from the ATP: the VCTS shall be able to protect train movements according to cooperative braking distance monitoring (and other VCTS supervision functions) irrespectively from the status or the presence of an ATP on board the vehicle. The result is the ATP being treated in the same way as in conventional platoons (mechanically coupled) where the master transmits external ATP	VCTS_EXT_ATP1	O	The automatic train protection system shall be able to operate irrespectively from the presence of the VCTS or not;
		VCTS_EXT_ATP2	O	When VCTS is operational, the ATP shall foresee functions allowing the consist to run irrespectively from the restrictions imposed by absolute braking distance monitoring;
		VCTS_EXT_ATP3	O	At any time during VCTS operations, the ATP shall be able to take back control of train movements in case of failure of VCTS supervision.

Interface	Interaction	ID	Mandatory (M) or Optional (O)	Exported Requirement
	information to the consist inside the platoon.			
Train Operators (i.e.: drivers)	The VCTS shall be provided with an interface to operators as drivers at least at the beginning of the VCTS mission (in order to fulfil some of the procedures to finalise the virtual coupling or to terminate it) or for diagnostics/maintenance purposes.	VCTS_EXT_TO 1	M	The VCTS shall provide an interface to operators in order to set up VCTS missions
		VCTS_EXT_TO 2	O	The VCTS shall provide an interface to carry out diagnostics and maintenance of the system.

Table 7-2: Requirements Exported to External Interfaces

7.4 VCTS Main Functions

A VCTS system has to ensure that the protection against collision of the consists inside a platoon is guaranteed. In addition the VCTS system is in charge of coordinating the movement of the trains composing the platoon from the instance a joining request is received until the platoon is dissolved. This includes also the interaction with external systems such as signalling, TMS, interlocking, etc. The main functions are depicted in Figure 7-7.

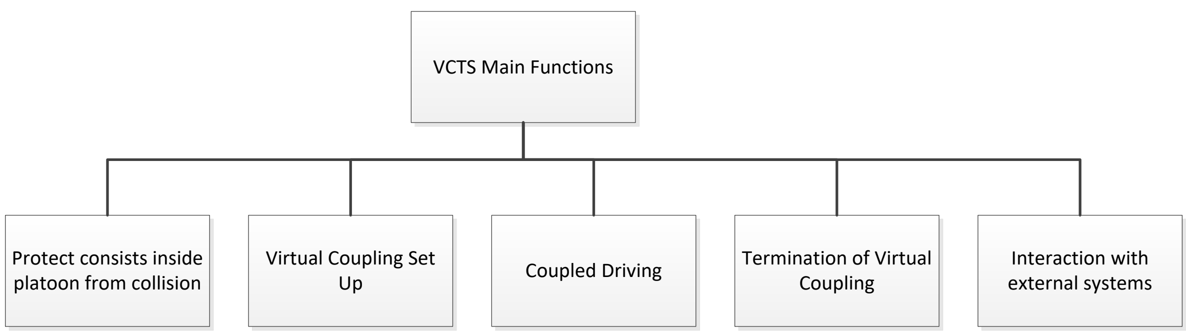

Figure 7-7: VCTS Main Functions

7.5 VCTS System Architecture

A possible structure of the system elements that are part of the VCTS system is presented in Figure 7-8. The new VCTS system elements are marked in green. They interact with the existing system elements of the consists, for example with TCMS or ATP.

The system elements and their basic functions as well as the interfaces are described in the following on a high level. These system elements, the allocation of functions to the elements and the interfaces have to be defined in more detail in the next steps of the project.

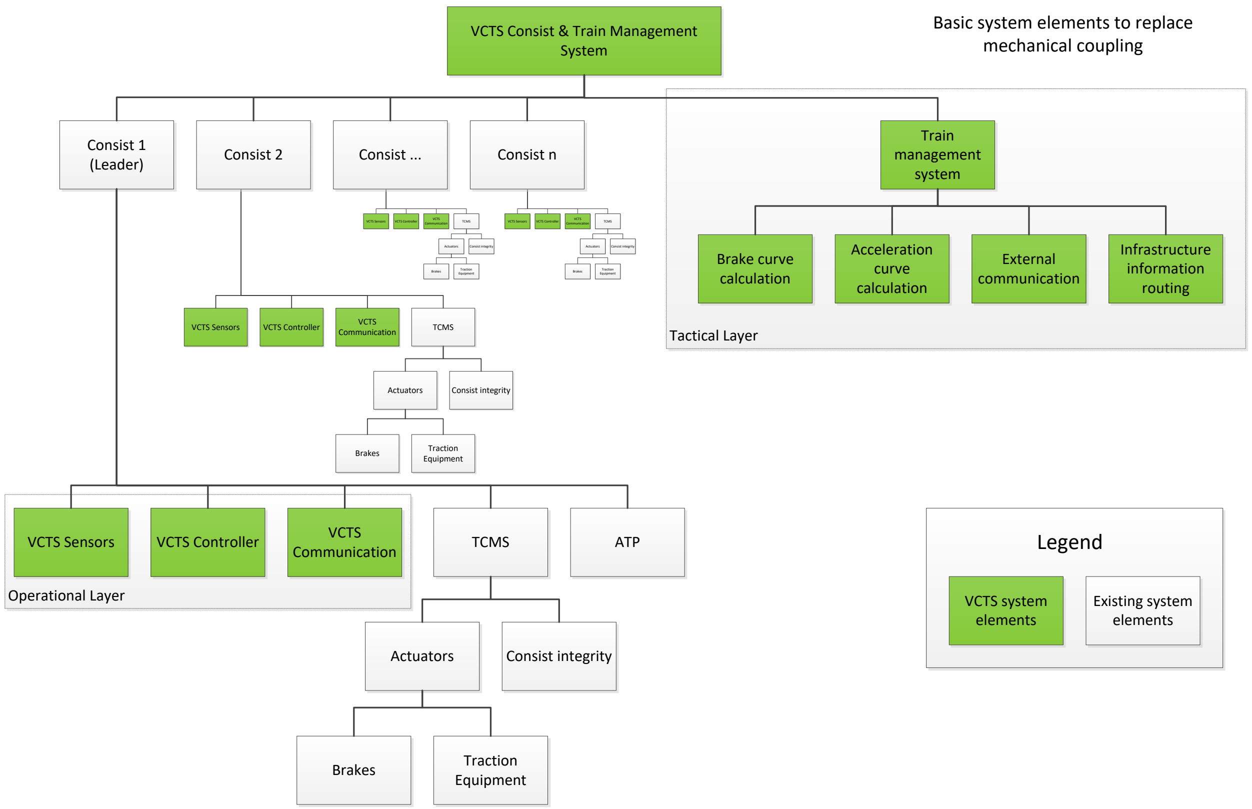

Figure 7-8: VCTS System Description

7.5.1 VCTS System elements

7.5.1.1 VCTS Train Management System (VCTS-TMS)

The VCTS Train Management System is addressing the tactical layer of the VCTS system. This system element is expected to be available on all consists being capable of joining a VCTS platoon. For error and failure detection VCTS-TMS could be installed duplex on each consist. While the VCTS TMS on one consist serves as the master to coordinate the whole VCTS train behaviour, the VCTS TMS systems on the other consists are also active to provide redundancy and integrity check for error and failure detection. The consist with the master VCTS TMS might be the leader consist or any other consist being part of the platoon. It uses the VCTS communication system of the consist, where it is active, as interface to gather and distribute data and information to the other consists of the VCTS platoon.

The main functions of VCTS TMS subsystem are

- Providing the interface to the signalling system (train ID, …) and routing of relevant information to the other consists of the platoon (interface between strategic layer and operational layer)
- Receive and transmit data such as mission data and track information

- Collect relevant information (consist integrity, local brake and acceleration capabilities, …) and derive the train characteristics (train brake curve, train acceleration curve, …)
- Provide the high level target states to every consist inside the set
- Guarantee integrity of the tactical decisions by cross-checks with redundant VCTS-TMS on the other consists of the platoon

7.5.1.2 VCTS Communication (VCTS-COM)

The VCTS communication has to be active on all consists of the platoon. The main functions are:

- Communication of current consist state (from VCTS-SENS) to the VCTS TMS and / or the other consists
- Communicate characteristics of the communication, such as maximal expected communication delay (deadline)
- Perform handshakes during coupling process and close communications after decoupling
- Communicate relevant TCMS information updates to the VCTS-TMS, for example the acceleration and braking curves of the consist
- Communicate VCTS-TMS parameters to the TCMS to update the local brake and acceleration curves of the consist according to the needs of the platoon

Remark: integrity of transmitted/received information, security aspects, etc. are assigned to the lower levels of the telecommunication protocol.

7.5.1.3 VCTS Sensors (VCTS-SENS)

Due to the high uncertainties in the dynamic state measurements of the TCMS sensors it is expected that new sensors dedicated to the VCTS systems are required (VCTS-SENS). To guarantee high quality of the measurements under all conditions, a smart combination of different physical principles is required.

The VCTS sensors are responsible to perform the following functions:

- Detect the absolute dynamic state (a, v, s) of the consist
- Detect relative dynamic states (a_{rel}, v_{rel} and distance) to neighbouring consists and to the leading consist
- Sensor fusion
- Provide a quality level or confidence interval for the detected physical values
- Check of integrity of the detected states via comparison with the states detected by the other consists. This is performed by integrating information transferred between the consists via the VCTS-COM

7.5.1.4 VCTS Controller (VCTS-CTRL)

The VCTS controller is the main system for the operational layer. It is required on each consist inside the VCTS. The main subsystem functions are:

- Receive the current dynamic state and the relative states of the own consist from VCTS-SENS
- Receive the tactical target states from VCTS-TMS via VCTS-COM

- Control consist movement by output of requested acceleration setpoints to the traction system for example via TCMS
- Interacting with the driving unit, either in human-manned operations or ATO
- Provide fall-back solutions, for example
  - perform pre-defined standard procedures based on local VCTS-SENS in case of lack of communication
  - Implementing protection strategy to avoid collision between consists

7.5.2 Existing System elements

7.5.2.1 TCMS

The TCMS is an already existing system that needs to perform three functions related to the electronic coupler. It must accelerate and brake according to the requested acceleration and update acceleration and brake curves (both from the VCTS-COM).

7.5.2.2 ATP

The ATP is an already existing function implementing protection based on absolute braking distances, and this protection function will be switched off on all consists except the leading consist during virtually coupled operations. The respective procedure is in line with the procedure applied during mechanical coupling of consists (for example, as in ERTMS Non-leading mode). It may interface (or not) with the VCTS controller to exchange relevant supervision data.

The VCTS controller must be able to enable and disable ATP protecting functions during coupling and decoupling manoeuvre.

8 VCTS Applications

8.1 The Railway Infrastructure

The main guideline for this conceptual description is to maintain the VCTS definition separated from external systems as much as possible

- Typology of railway system and service (mass transit, high speed, metro, freight). The VCTS concept shall remain applicable to any typology of railway service, provided that each feature that is specific to a particular application is either captured within the functional design, or supported by an appropriate characterisation of the VCTS. Functions of the VCTS may thus become:
    - *Applicable to a specific typology of railway (or not*): some applications may not require a particular VCTS function, but in any case the VCTS functional specification shall include that function for other applications. The VCTS concept shall thus cope with the possibility of enabling or disabling a particular function without compromising the functionality of the overall system.
    - *Configurable/characterised depending on the specific application*: peculiarity of the context in which the VCTS is used shall be captured without modifying or adapting the functional requirements, and shall be mostly addressed by mean of 'non-functional' requirements (i.e.: configuration requirements, performance requirement, etc.). An example of this may be the dimensioning of the safety margins of distance between two virtually coupled trains: the functional requirement shall describe how this distance is calculated, while a configuration requirement shall determine which variables of the calculation shall be evaluated to tune the distance according to the specific application.
- Similarly, the analysis shall not fall into the mistake of moving to a practical exercise, applied to a specific signalling solution (like ERTMS). The resulting concept shall remain applicable to any typology of signalling system, and for this reason the boundaries of VCTS shall be clearly defined and separated from any specific signalling function. The relationship between VCTS and any existing train headway control system shall be limited to a set of 'interface requirements' that may be customised depending on the specific signalling system underlying. On the other hand, core functions of the VCTS shall not be modified by the interface requirements.
- Finally, from a perspective of interfaces with external entities like an Automatic Train Operation system, this analysis shall cope with a set of interface requirements towards both human-manned as well as driverless operations, always under the paradigm of relying on interface requirements.

These principles are depicted synthetically in following, where namely the VCTS core functions are simply 'enabled' or 'disabled' depending on the actual need within the specific context of application. The disabling of some functions does not compromise the whole VCTS functionality. Moreover, the specific application determines a set of configuration and performance requirements which characterise the behaviour of the VCTS core functions, but without actually modifying their core implementation. Similarly, the signalling infrastructure does not modify the

VCTS core functions, but only limits its interaction by mean of a set of interface requirements (i.e.: a set of input and output exchanged with the VCTS system, that may vary depending on the signalling system).

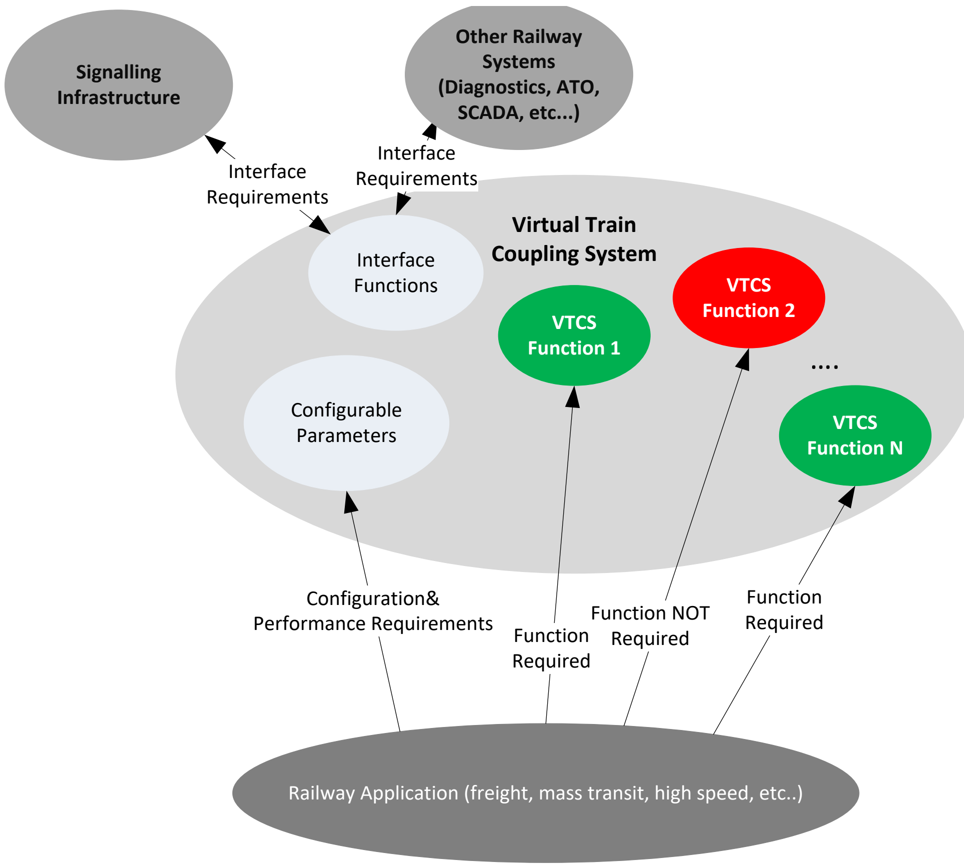

Figure 8-1: Interfaces of VCTS with the Specific Application

Some of the railway applications are reviewed in Section 8.2 with an initial evaluation of their actual impact on the characterisation of the Virtual Train Coupling System. Especially, each framework of application determines some peculiar needs and targets for the Virtual Coupling, either in terms of performances to be achieved by the technology, or in terms of extensions of its functionalities.

Similarly, VCTS shall be analysed for its consequences and impact on the existing train headway control infrastructure, i.e. the existing signalling systems, in order to ensure that the approach proposed (separating VCTS from any specific signalling system) still remains applicable. For this reason, the most common typologies of signalling system are also reviewed in following Section 8.2 in order to gather some initial guidelines to the VCTS conceptual description, supporting the proposed approach.

8.2 Typologies of Railway Networks

Intercity/High Speed Lines

Railway lines supporting operations of trains at high speed (maximum speed >200 km/h) are necessarily characterised by longer train headway distances, due to the higher speed and the correlating braking distances. This means that either by mean of functions or technological implementations, the VCTS must be able to cope with these larger distances.

Network topologies are typically simpler than in other applications, mostly due to the fact that high speed links are normally aimed to connect two metropolitan areas and therefore resulting in a track layout of limited complexity. As an example, the map of the railway network Piemonte region (Italy) is provided in following Figure 8-2 where it is possible to notice the main high Speed/Intercity lines (in red) connecting Torino straight to the metropolitan areas of Milano and Genova, while a more complex network of regional lines (in yellow) are aimed to connect urban centres of lower population density.

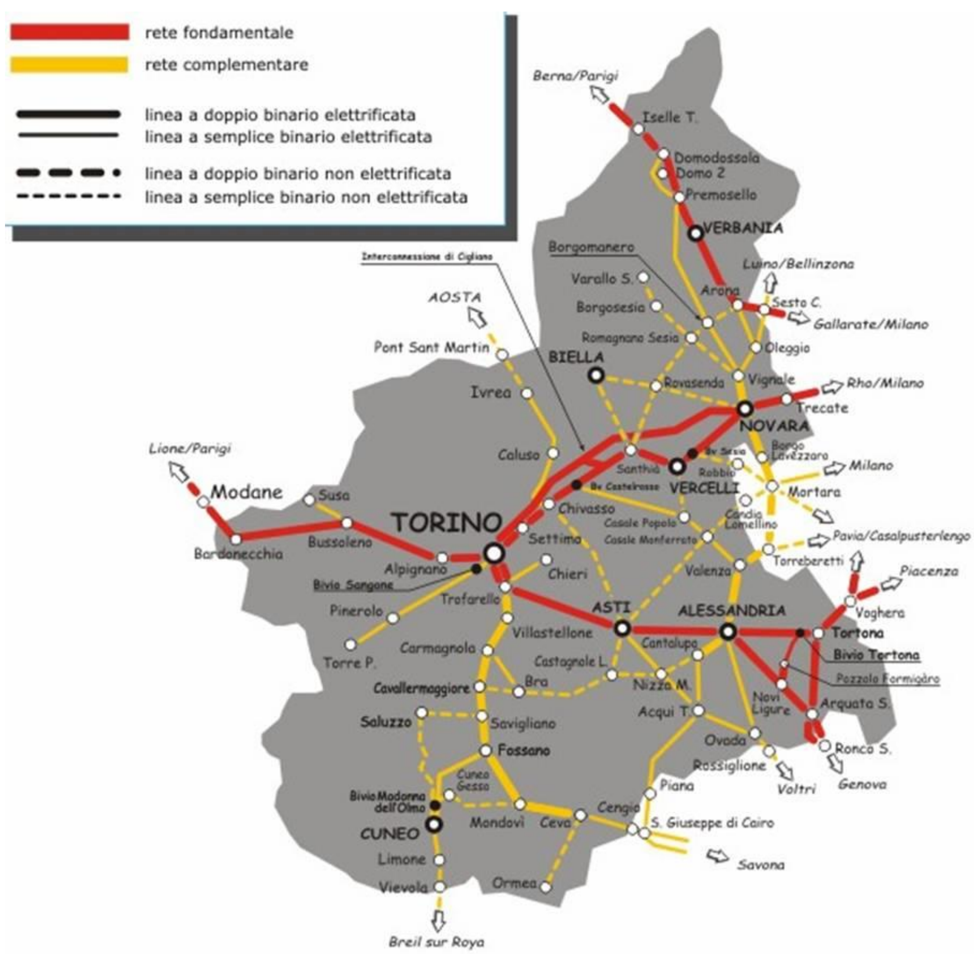

Figure 8-2: Railway Map of Piedmont Region

In this scenario, we have a number of different situations regarding train composition management, e.g.: some trains are not supposed to change their composition across the daily operations, while in some other cases operations may gain benefits from the possibility of quickly changing composition during the journey (e.g.: joining or splitting).

Regional, Urban, Suburban

Within regional, urban or suburban areas, lines are already characterised by a higher density of traffic, as well as trains composed of fewer cars. The service offered tends to cover a number of different destinations and may be subject to higher variations in terms of traffic demand, timetables adjustments, etc.

Within this typology of applications, the VCTS has presumably to cover an extended range of operational scenarios, not only aimed to build longer platoons to cope with a larger demand, but also to extend its functionality to support adaptable train composition depending for instance on destination (i.e.: a platoon may split into two at some point, as shown in following Figure 8-3 to allow the two resulting trains/platoons to reach different destinations), or to optimise routing of trains through a link between two stations (as in Figure 8-4). Appropriate interaction with wayside Traffic Monitoring System has to be supported, to allow adequate supervision of platoons moving along the network.

Remark: examples are shown with 2-consists platoon, but VCTS is supposed to operate also with more complex platoons (i.e.: N>2 consists virtually coupled in the same train).

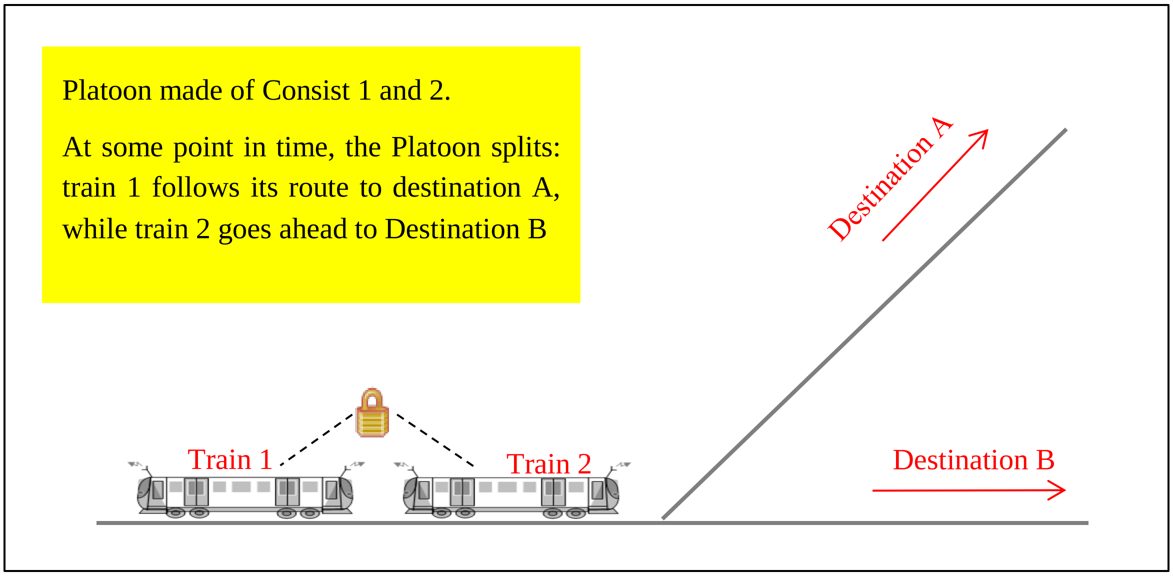

Figure 8-3: Platoon Splitting for Different Destination

These lines are traversed by small trains or platoons with good performances in terms of braking capacity. The speed of operation is lower compared to intercity/high speed lines, meaning that headway of trains may become very short in distance. While this means that higher network capacity is achievable, the exact capacity increase needs to be evaluated for each line or network.

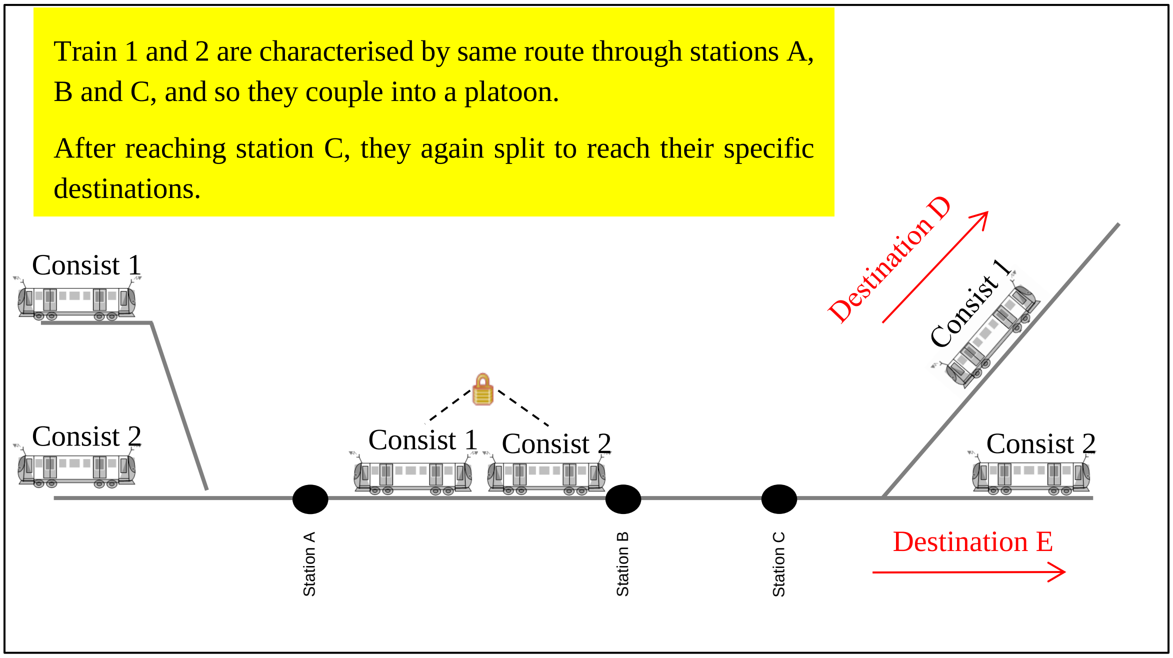

Figure 8-4: Coupling of Trains through Common Routes

Freight

Freight applications are characterised by longer trains as well as specific vehicle characteristics, for instance braking distances and reaction time. Caused by the vehicle length, a higher time of propagation of braking commands throughout all the cars is a typical feature of freight trains.

This results in extended braking distances, longer distances between lead locomotives in each train (due to length of the train itself), as well as higher inertial characteristics of the train (i.e. reduced achievable accelerations).

In terms operational requirements, freight lies somewhere in between the two previous categories: while freight lines (especially dedicated freight railways) may be characterised by a simplified layout, with regular traffic that connects two main areas (the loading and the dumping points), several scenarios may involve the need of collecting freight traffic converging on same backbone from different sources, as shown in the of Figure 8-5. In this specific scenario, trains from several mining sites are routed on the same main backbone to reach the dumping port; in the other way around, traffic coming from same backbone may be required to split at some point of the line, to reach different destinations.

The different typologies of railway network are defined in the EU Project IMPACT-1, Deliverable 4.1: Application Scenarios and are summarized in **Errore. L'origine riferimento non è stata trovata.**.

Table 8-1: VCTS Application Scenarios

Application	High Speed Line	Regional Line	Metro Line	Freight	References
Track Length	300	70	21.5	300	IMPACT-1 D4.1
Maximal Track Speed	300	140	80	100	IMPACT-1 D4.1
Maximal Track Capacity (Trains/h)	14	14	30	-	IMPACT-1 D4.1
Theoretical Capacity (Trains/h)	11	10	12	-	IMPACT-1 D4.1
Journey Time	1h47	1h09	0h41	4h17	IMPACT-1 D4.1
Stations	3	15	23		IMPACT-1 D4.1
Train Max Speed	330	140	90		IMPACT-1 D4.1
Train Length m	200	70	95		IMPACT-1 D4.1
Train Capacity pass	460	230	1000		IMPACT-1 D4.1
Avg. Energy Usage (kWh/km)	17.85	8.8	12	20	IMPACT-1 D4.1
Avg. Energy Recovered (kWh/km)	0.267	1.26	0	1.5	IMPACT-1 D4.1

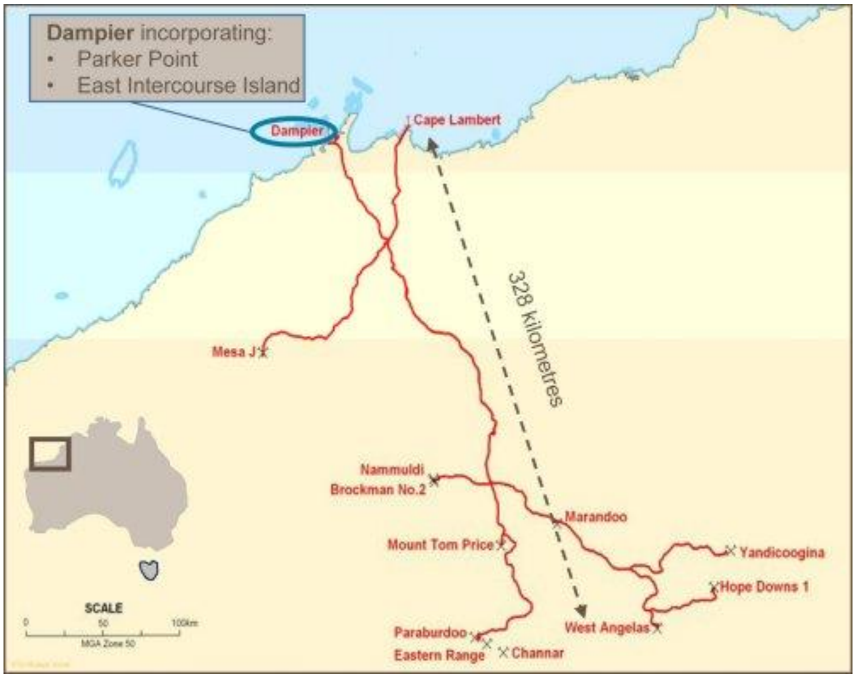

Figure 8-5: Track Map of Freight Line in Western Australia

8.3 Profile of Virtual Coupling Mission

Depending on the application, the Virtual Coupling System may be subjected to different mission profiles, corresponding to different performance and functional requirements that shall be comprehensively collected in this concept. Numerical values reported in the following table (Table 8-2) are merely indicative of the profiles for each application, and they are not intended to cover 'all possible cases' within the specific application.

Mission characterisation	High Speed/ Intercity	Regional/ Urban/ suburban	Freight
Max speed	360-160 km/h	160-120 km/h	100 km/h
Braking system	High performing (max deceleration achievable in the range of 1 m/s^2 or higher if eddy current brakes or magnetic pads are used)	High performing (max deceleration achievable in the range of 1.5 m/s^2, up to 2.8 m/s^2,in tramways)	Low performing (i.e.: deceleration of range 0.25-0.5 m/s^2)
Braking reaction time (i.e.: full effort of Pneumatic Emergency Brake)[1]	1-2 seconds	1 second	Up to 15 seconds
Maximum acceleration	0.8-1 m/s^2	1-1.2 m/s^2	0.2-0.4 m/s^2
Length of train (from head to tail)	100-400 m	50-150 m	Up to 2.5 km
Train separation (with conventional signalling, at maximum speed, according to stopping distance)[2]	4-5 km	500 m-2 km (10 meters in case of tramways)	2-3 km
Typical Headway (with current signalling infrastructure)	~50-10 minutes	~1-2 minutes (10 seconds in case of tramways)	~10-30 minutes
Braking Model (as per ERA definition)	Gamma model frequently applicable	Gamma model frequently applicable	Lambda model frequently in use

Table 8-2: Characteristics of Different Applications

9 Virtual Coupling Operational Scenarios

9.1 Introduction

The following sections provide a preliminary analysis of the scenarios on which the consequent detailed definition of the VCTS shall be based, defining thus an early baseline of system concept and operational requirements to initiate the feasibility analysis, and reflecting the functional phases detailed at previous paragraphs. This document thus does not goes into details of technical solutions, architectures or algorithms aimed to implement the VCTS concept, but focuses more on:

- A set of basic scenarios, defining actually what kind of operational issues the VCTS is aimed to solve; the scenarios are intentionally kept to the most generic level possible, without referring to specific contexts in order to keep the analysis as applicable to the wider range of applications.
- A preliminary overview of the core technical functions of the VCTS. This section does not only list the core functions to support the implementation of the virtual coupling concept, but also tries to address the main technical constraints and problematic of their actual realisation, in order to early route the analysis towards the core implementation challenges and to determine the safety requirements to focus on.

Moreover, the VCTS concept shall also apply regardless of the underlying train separation mechanism, and it shall be applicable irrespectively from the signalling infrastructure within it is applied.

9.2 Virtual Coupling Set Up

9.2.1 Initiation of Virtual Coupling

Initial conditions:

- Two trains equipped with VCTS are independently driven and kept at least at absolute braking distance
- One of the two trains initiates the virtual coupling procedure
- No specific requirements regarding train movements: the procedure can initiate with trains standstill or moving. As long as Virtual Coupling is not in operation, trains are kept separated by standard absolute braking curves paradigm.

Expected functional behaviour:

- One of the trains initiates the virtual coupling procedure by opening a communication session with the other train candidate to form a platoon; within this step, and with reference to section 7.2.2, the strategic layer shall be in charge of governing the initiation of the procedure and to implement the necessary controls over the consists which are coupling (i.e.: if the two consists are actually supposed to connect to each other or not). The concept

of VCTS provided in this document does not develop any specific definition of the strategic layer, but assumes that this later one:
  - Is aware of all the network and timetable
  - Is enabled to decide the coupling between two trains and their role inside the platoon
- Once master grants the coupling, the two exchange the relevant mission data to proceed as a virtually coupled platoon. The main principle is to replace the mechanical coupler with a ‘virtual’ coupler.
- The strategic layer assigns roles of master and slave
- During virtual coupling movements, the status of the communication link is continuously checked by both slaves and master
- The slave train is thus allowed to move closer to the master, beyond the limit imposed by the absolute braking distance. Supervision moves from absolute to coordinated braking distance monitoring.

The scenario assumes that at least the slave train includes some autonomous system that supports the driving according to the VCTS principles. At this stage of concept, manual driving is considered as leading to very unstable behaviour of the Virtual Coupled Platoon (i.e.: very frequent accelerations/decelerations to adjust distance).

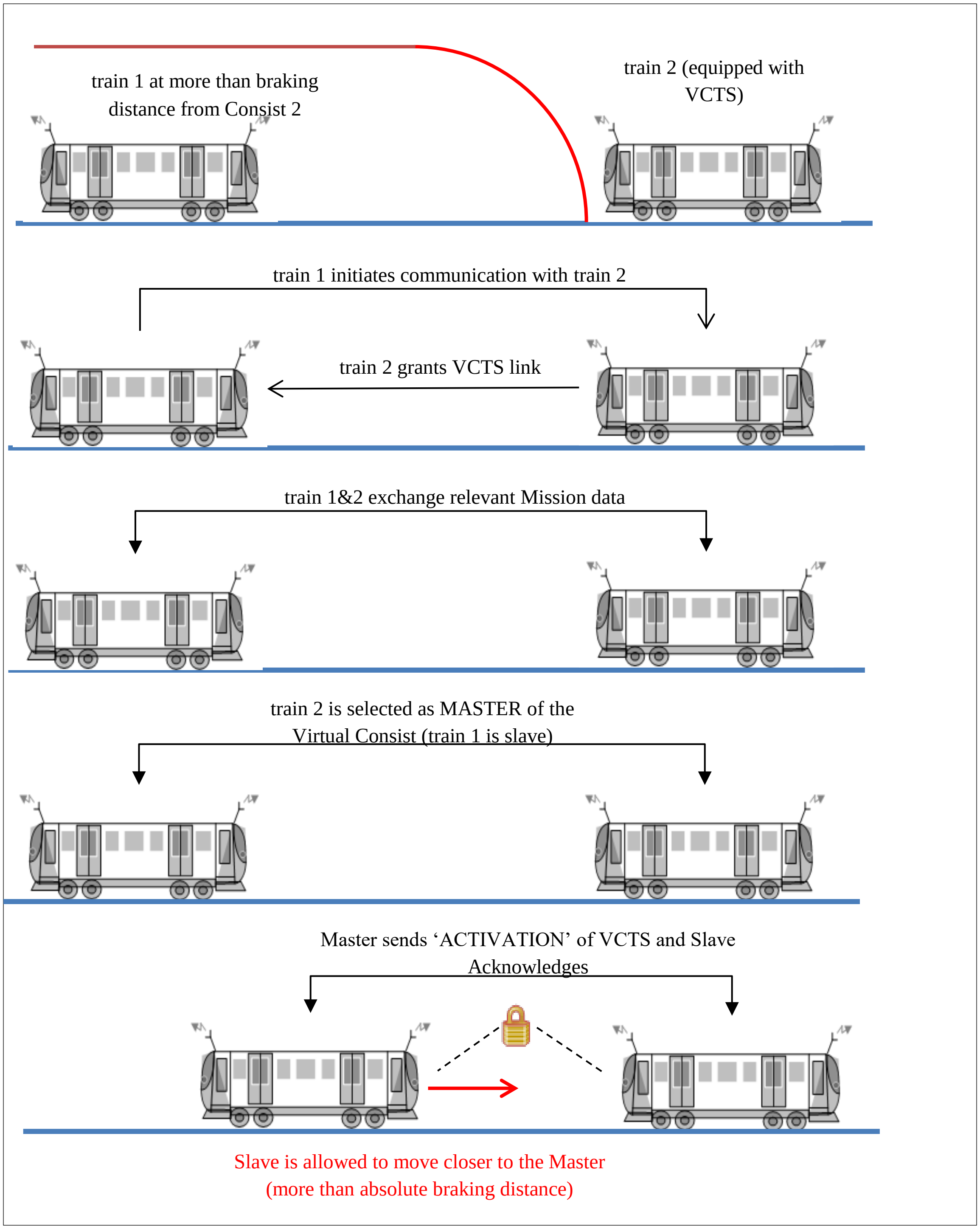

Figure 9-1: Initiation of Virtual Coupling Session by Slave

9.2.2 Coupling of Platoon with more than one Slave

Initial Conditions:

- A platoon is already formed by one master and at least one slave (slave 1). The evolution of the scenario is the same in case of a platoon made of one master and more slaves than 1.
- An additional consist approaches the platoon, maintaining absolute braking distance monitoring from the tail of the platoon (rear end of Slave 1). This scenario is limited to the case in which the new consist is added in rear of the platoon, after the last consist of the pre-formed platoon. The situation in which a new consist has to be added in the middle of the platoon is part of a different scenario description.

Expected Functional Behaviour:

- The new train approaches the Platoon made of Master and Slave 1 and initiates virtual coupling as in other scenarios
- Once connection is granted, the new train and the master of the platoon exchange relevant virtual coupling data. As a remark, this set of data includes all characteristics of all trains in the platoon (not only the ones of master) as the cooperative braking shall be comprehensive of all elements in the platoon.
- Once coupling is granted, the train is allowed to get closer to Slave 1 and is assigned with the role of Slave 2. Slave 2 starts to monitor its virtual coupling distance from Slave 1 and receives data from both Slave 1 and Master to develop its virtual coupling supervision functions. At the same time, Slave 1 starts to monitor its virtual coupling distance from Slave 2 in addition to the distance from the Master.
- The scenario excludes the case of more than one candidate slave inquiring to join the platoon at same time. Slaves shall be added to the platoon one by one, and one at once.

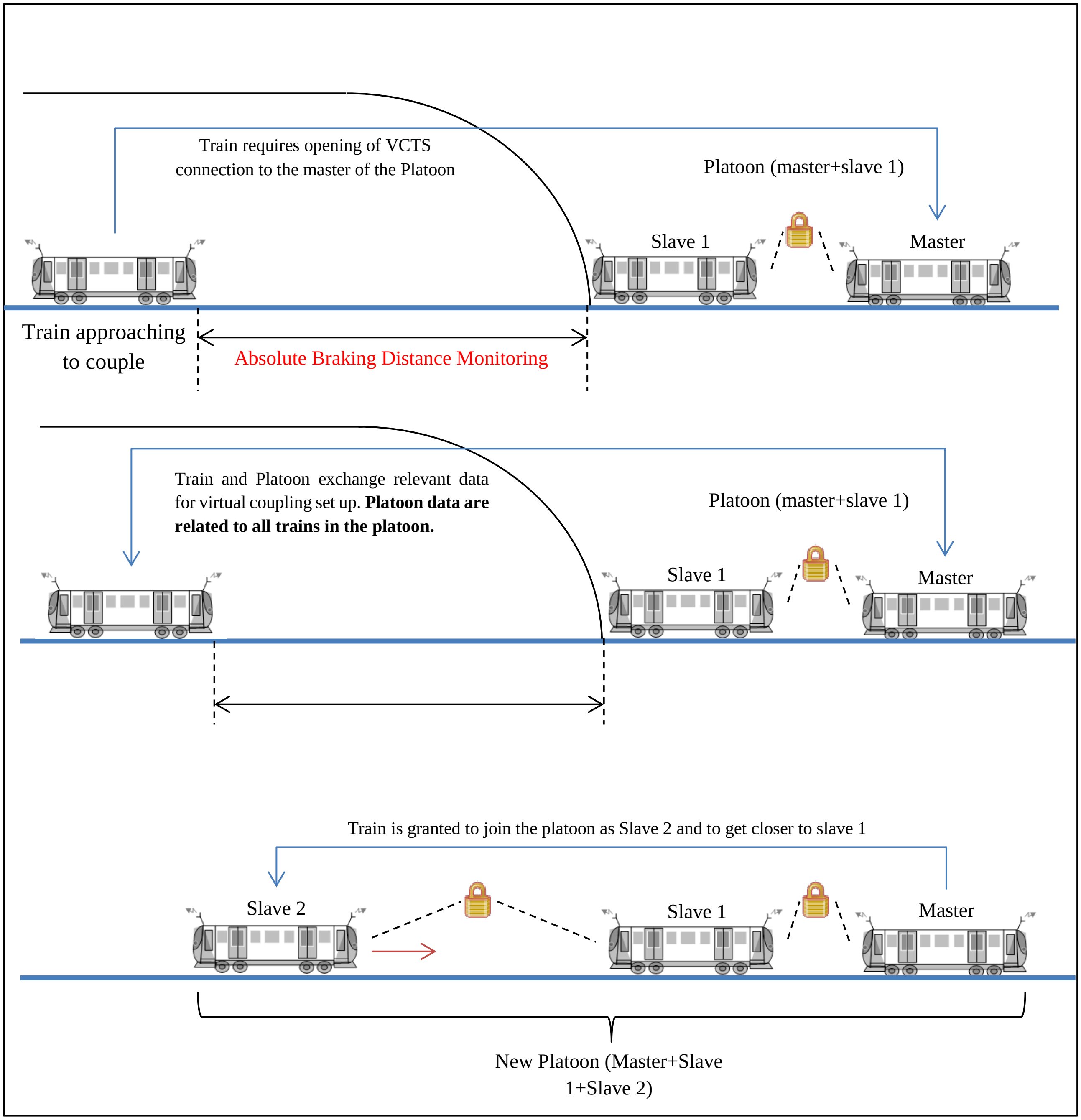

Figure 9-2: Virtual Coupling Set up with more than One Slave

9.3 Coupled Driving

9.3.1 Supervising Train Separation Distance during normal driving

Initial Conditions:

- Consists already virtually coupled
- Consists in the platoon running, not necessarily at same speed. Positioning error may also apply and differences in speed accuracy may apply.
- Slaves monitor relative distance from Master train and from adjacent slaves. The relative distance takes into consideration safety factors due to (list not exhaustive) difference in relative speed and acceleration, latency of the communication channel, positioning error, and different braking capabilities.

Expected functional behaviour:

- Based on the exchanged information, slave trains maintain safe distance from the rear end of the preceding train, and eventually from the following train; this information shall be included in the CAM exchanged between the trains.
- Based on the continuous calculation, the slave train takes action to reduce speed or accelerate in order to adjust its position; the control shall not simply focus on relative distance, but the strategy shall also include intervention steps earlier than the standard distance check, by mean of a dedicated algorithm that checks also differences in acceleration, etc.
- When falling too far behind the preceding train rear end, the slave train takes action to reduce the gap. This correction of position shall follow same principles as before, i.e.: the algorithm shall not only check the distance between the two trains, but shall also anticipate controls by checking speed, acceleration, etc.
- Control algorithms may require monitoring the relative distance and speed between each of the slave trains and the master, in order to assure the platoon stability. Control techniques are not part of this deliverable.

Following figure synthetically describes this scenario in the simplified case of two trains joined by the virtual coupling (for clarity of the figure itself), and can be easily extended to the scenario with more than two trains.

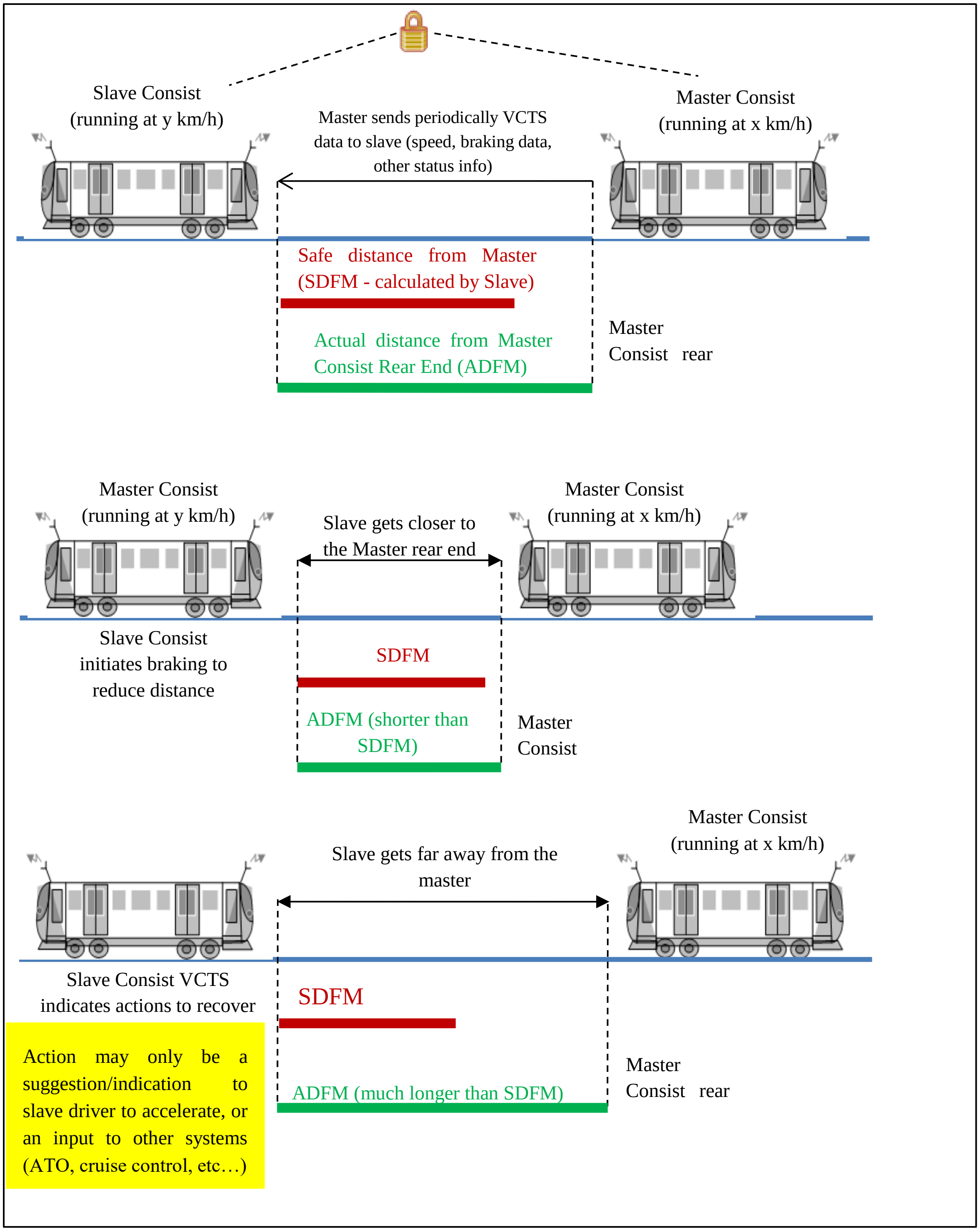

Figure 9-3: Movement Under Virtual Coupling Linkage

9.3.2 Master Train Braking

Initial Conditions:

- Train virtually coupled and running
- Master initiates a braking action (of any type)

Expected functional behaviour:

- Slave trains receive the indication of ongoing braking on master
- The scenario assumes that brake synchronisation has been maintained throughout the whole virtual coupling movements, so that slaves have anyway kept optimal headway distance from the adjacent trains
- Slaves monitor continuously the safe distance from adjacent trains
- Slaves monitors continuously the distance from the master in order to ensure stability of the platoon

Technical Analysis

Braking is a complex procedure which involves electric, eddy current, magnetic shoe and pneumatic brakes, whose reaction time and performance differs. Moreover, braking performances may be affected by other variables as gradient of the track, as well as the adhesion factor. While requirements shall be exported to the brake subsystem to reduce timings, it is also true that in any case the safe state calls for having the slave train going to a brake or pre-brake state, for example by defluxing traction motors, which can be done through coasting or slightly applying the electric brake (depending on the traction architecture).

This means that brake commands/status shall be transmitted across the VCTS. Since it is a cooperative breaking the VCTS shall decelerate homogeneously, at the slowest rate between all trains. Relative distance between trains at the moment of the braking initiation shall be anyway taken into account by the driving logic in order to avoid the slaves to brake too strongly unnecessarily.

The following figures depict synthetically the scenario, simplifying the case of two consists, while the scenario is anyway applicable to N>1 slaves in the platoon.

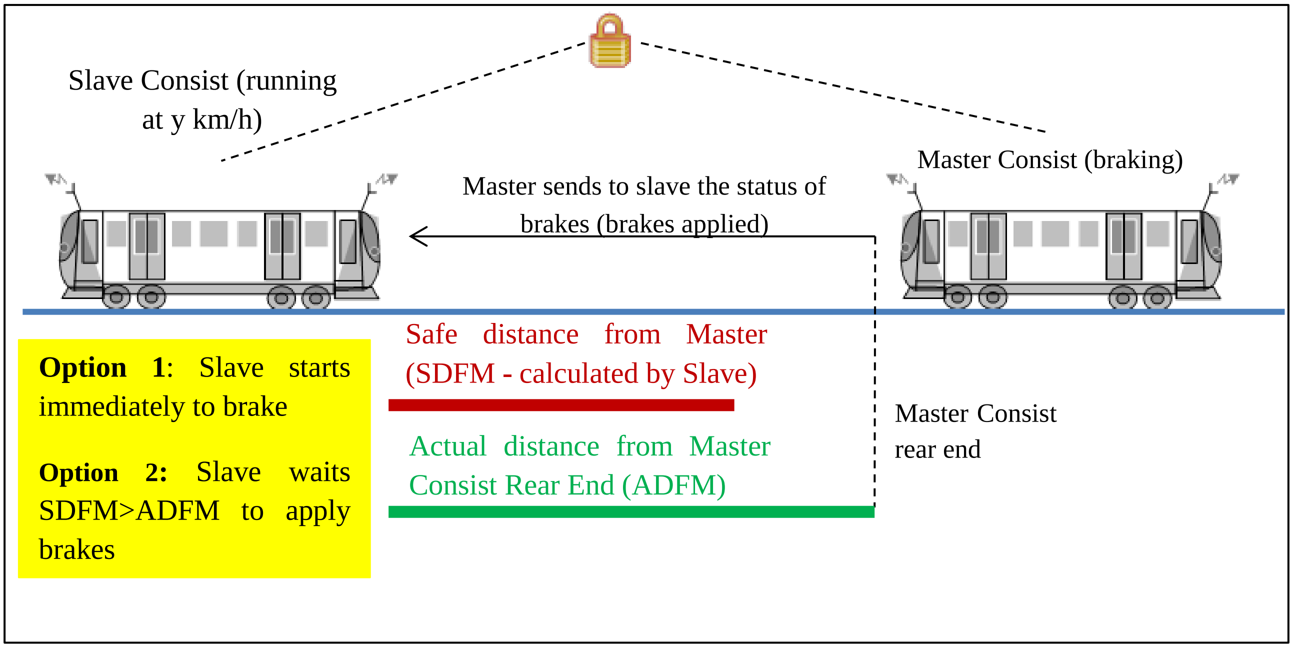

Figure 9-4: Scenario with Master Braking

9.3.3 All Platoon Stopping at Station

Initial Conditions:

- Master train is approaching platform and has reached/about to reach a stop at the stopping signal
- Slave train has not yet reached the platform and it is still safe to go ahead at slow speed, according to braking distance

Expected functional behaviour:

- The slave train is allowed to reach the end of the platform, as long as it is safe
- The slave train shall be allowed to get as close as possible to the master rear end in order to fully occupy the platform

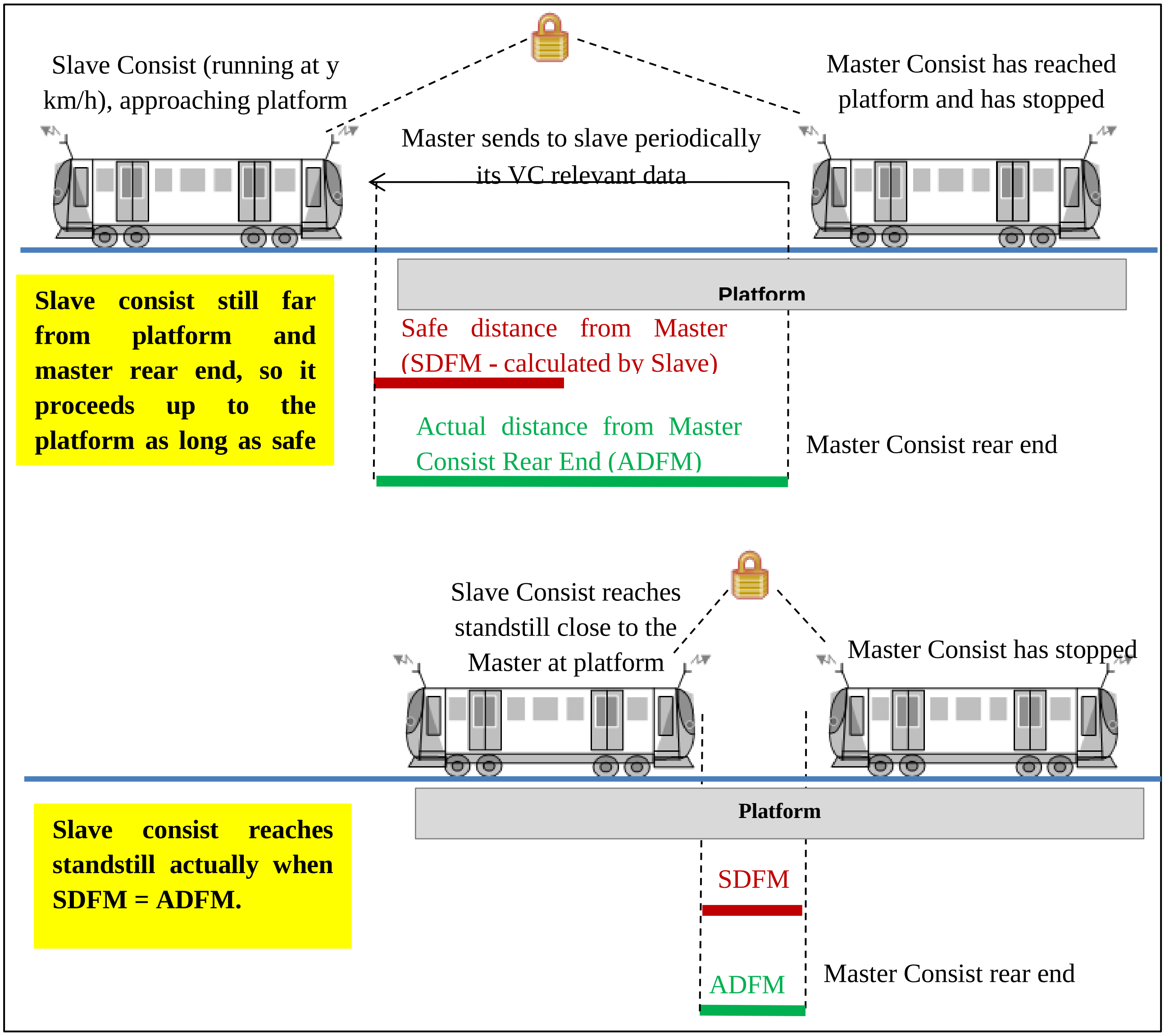

Figure 9-5: Virtual Coupling Train Stopping at Station

9.3.4 Change of Cabin (Master/slave) – Change of Running Direction

Initial Condition:

- Master and slave trains reach standstill
- For human-manned operations, driver in master train closes desk. For driverless operations, ATO in master unit terminates mission.

Expected functional behaviour:

- During change of end (no desks enabled across the whole platoon) all trains maintain active supervision and control of standstill condition (i.e.: avoiding train to roll away)
- As long as no other cabins are enabled, the train with the last enabled cabin remains master

- When another cabin is enabled, adequate mechanism of interaction between slave and master takes place (for example a 3-way handshake) to exchange status of desk and change of role information
- Only once slave unit notify to become master, the former master unit moves to slave role.
- A new inauguration of the platoon shall take place to align virtual coupling data (i.e.: braking characteristics, etc.)

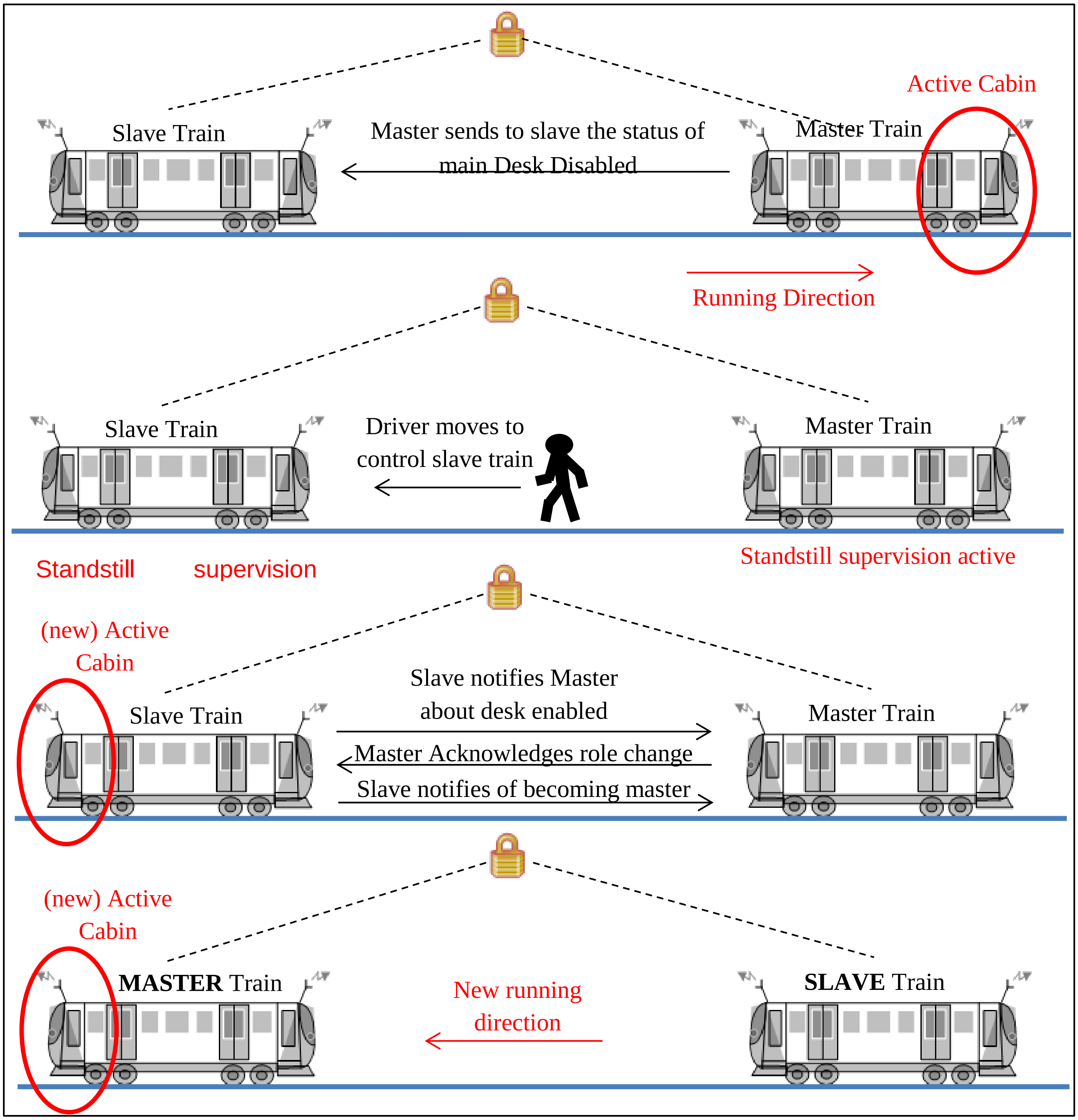

Figure 9-6: Change of Running Direction – Nominal

9.3.5 Virtually Coupled Platoon Coasting at Station

Initial Conditions:

- Platoon virtually coupled, approaching a station, made of N consists (N≥2). The scenario hereafter depicts simplified case of platoon made of 2 virtually coupled consists, but can be replicated to more than one slave;
- Platoon moves according to virtual coupling principles, where the master leads towards the station according to signalling rules and slave(s) follow(s) according to safe virtual coupling distance and platoon stability control

Expected functional behavior:

- Master slows down up to the stopping point of the station; while decelerating, the master sends to all slaves the information about ongoing actions (brakes, traction cut off, etc…).
- Following virtually coupled consist(s) moves towards the station according to master movements, maintaining safe and stable distance from the master. The virtual coupling distance decreases as relative speed with respect to the master decreases, up to reaching standstill position for all consists of the platoon;
- once the master has stopped (i.e.: standstill condition detected by the master), all slaves are allowed to stop as close as possible to the master. **In this case, 'as close as possible' means that:**
    - the fact that the master (or preceding consist) has reached standstill, i.e.: the preceding consist, in the last message sent, has notified the following train that v=0. This actually means that the safe distance of virtual coupling with this consist at standstill may be coincident to the absolute braking distance for the following train.
    - The hazardous scenario (worst case) shall contemplate the case in which, after sending the last message N with v=0, the preceding consist may start to move backward (i.e.: for roll back[3]). This means that while approaching a preceding consist at standstill, the following trains shall consider some safety margin due to the possibility, between the message N and N+1, that the preceding trains may move backwards. In any case, considering the backward movement very limited and happening at very low speed, this is reflected into a minimal margin of safety to avoid contacts between two following consists.

[3] Roll back protection shall be assumed as available on board. On the other hand, typical implementation of roll back protection by ATP foresees X meters of roll back prior to take any protecting action (brakes). For example, typical D_NVROLL parameter (maximum roll back distance) for a ERTMS train is around 2-5 meters, translated then in approximately 3-7 meters of maximum roll back to consider.

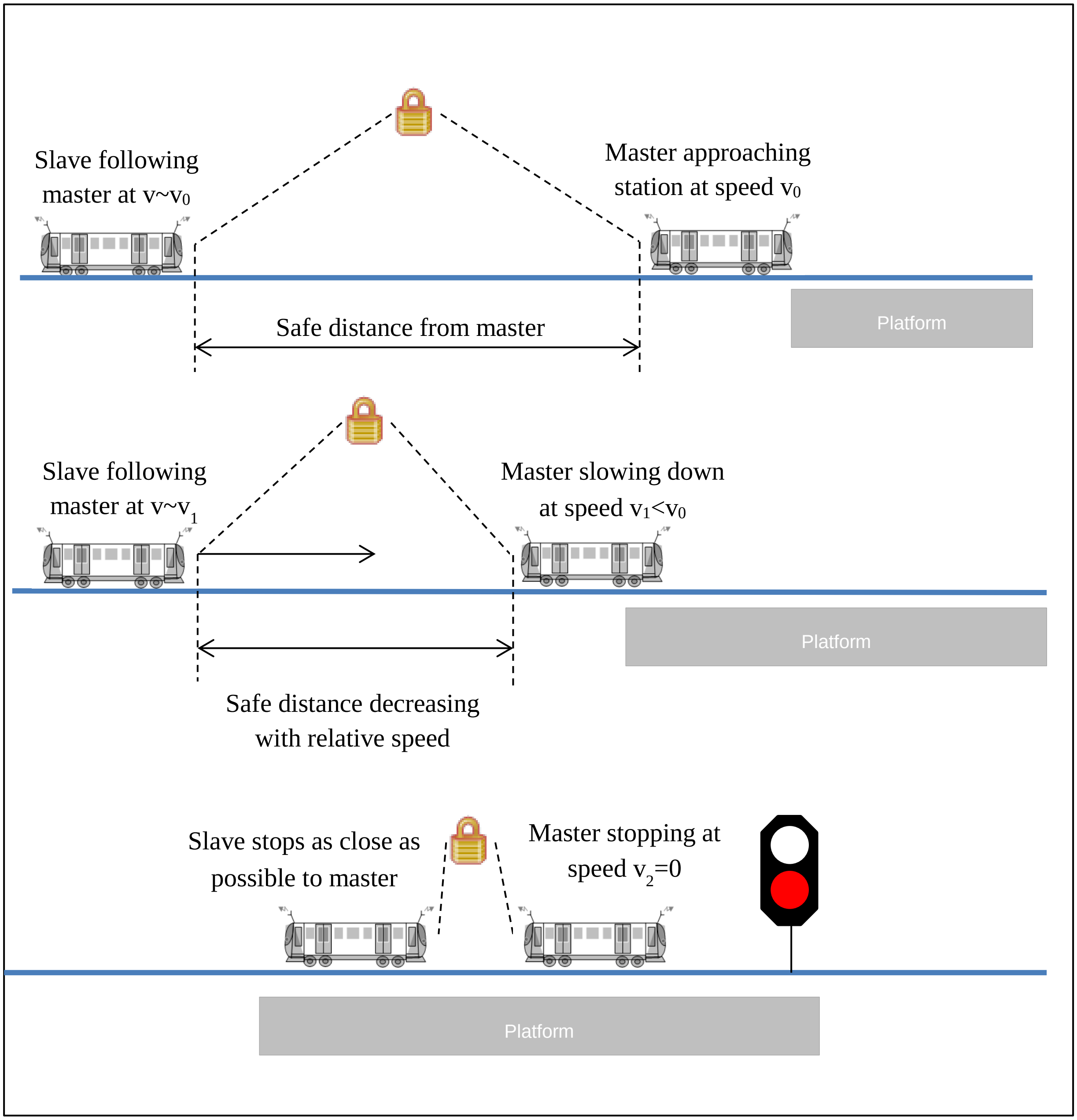

Figure 9-7: Virtually Coupled Platoon Coasting at Platform

9.4 Termination of Virtual Coupling Session

9.4.1 Splitting of a VCTS – Initiated by Slave

Initial Conditions:

- No specific constraints on dynamic conditions. Split can happen at any speed. This specific initial condition is kept to provide the most generic use case possible.
- Once one of the slaves sends message of termination for virtual coupling, the slave units initiate the procedure to become master of the following slave units creating a second platoon (or standalone train in case the slave was the rear unit)
- The master of the newly created platoon should have a driver or autonomous driving capabilities

Expected Functional Behaviour:

- The termination of virtual coupling shall anyway be completed only when it is safe to do so. For instance, as long as the appropriate safety distance is reached, the master shall not be allowed to brake with a braking effort that cannot be achieved by the slave train.
- This means cooperative braking terminates only once the slave has reached a relative distance from master that is sufficient to cope with a braking action from the master that is ‘full effort’ (i.e.: the maximum brake effort achievable by the master train). This is particularly meaningful when master has higher brake effort available than slave.
- Once virtual coupling is terminated, the speed supervision mechanism of the split platoon becomes as based on absolute braking distance. This means, the speed of the new created platoon shall slow down to cope with the new absolute braking distance supervision before actually considering the virtual coupling terminated, i.e.: the rear end of the preceding platoon becoming an End of Authority.
- The evolution of the procedure when the whole platoon is at standstill remains the same, but reasonably, largely simplified.

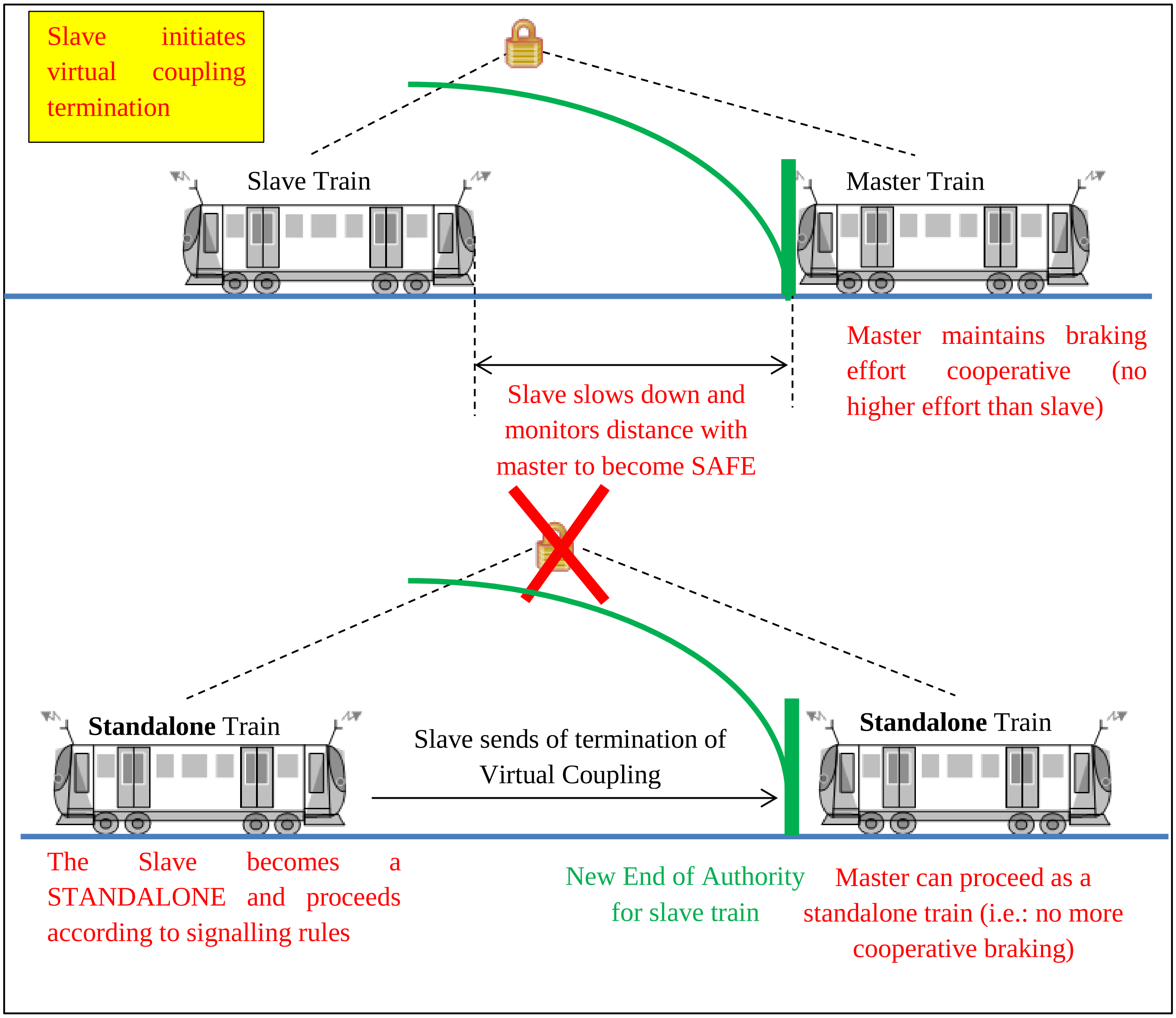

Figure 9-8: Splitting of Virtually Coupled Platoon Initiated by Slave

Considering a simplified scenario, the slave trains may only be required to apply brakes up to standstill as soon as the Virtual Coupling is required to terminate. This means that the expected behaviour of the scenario shall be:

- As soon as virtual coupling termination procedure is initiated, the slaves that initiate the termination shall first reach safe distance from the preceding consist, based on the absolute braking distance. this is mostly aimed to ensure safety once that the communication with the master or the preceding train to allow virtually coupled movements will be terminated (i.e.: the slave will no more be aware of ongoing actions of the trains in front). For this reason, no information on termination is yet sent to master, that keeps on maintaining coordinated braking supervision.
- Once the virtual coupling will be terminated, the master will be allowed to brake with its full effort (especially for scenarios in which slaves have lower braking capability than

masters). This means the slaves monitor the distance from the trains in front and waits that this becomes ‘safe’ to cope with a braking at full effort of the train in front.

In general, determining the safe conditions to terminate virtual coupling is crucial to complete the procedure avoiding safety hazards. Especially, the main hazard which emerges from this procedure is generated by the possibility of the master (or any other slave in front) to carry out a brake application at full effort (i.e.: maximum deceleration achievable). The hazard is also depicted in the simplified scenario in Figure 9-9 where actually:

- The master has an higher braking capability than slave. During virtual coupling, the two trains move along the line at reduced distance, with cooperative braking principles so that for instance, whenever the master is required to apply brakes for any reason, it will not perform braking at full effort as according to the cooperative braking principles, the braking action shall be homogeneous with the braking capability of the slave trains to avoid collision with slaves.
- If virtual coupling terminates, master and slave will no more exchange information regarding their status (speed, brakes, etc.) and the worst case considers the case in which the Master needs to immediately apply full braking effort (for any reason, i.e.: intervention of signalling supervision) to reach standstill after closing the virtual coupling connection. In this case, the slave would not have possibility to reach standstill in time due to its limited braking effort.
- For this reason, prior to terminate virtual coupling, the slave shall separate from the master with sufficient relative distance to allow the slave at least to stop in time, before colliding with the ex-master train. The determination of this *minimum safe distance to terminate virtual coupling* is represented in the following Figure 9-9.

Following figure describes the situation in which master and slave are running at close distance in virtual coupling (simplified scenario with one master and one slave). In Red, the braking curve of the master, while in black the braking curve of the slave is shown (corresponding for both to the maximum achievable deceleration). The figure shows, as standard scenario in virtual coupling, the slave running at closer distance than the one determined by its absolute breaking curve.

In the ‘worst case’ scenario, after termination of virtual coupling the master may initiate immediately a full brake effort action to reach standstill. Considering the virtual coupling terminated, the slave would not be informed about the ongoing braking action of the master in order to take the necessary actions according to virtual coupling principles.

Moreover, after virtual coupling termination the supervision of train movements will be handed back to the signalling system, operating on absolute braking distance. Terminating Virtual coupling at close distance may lead to the signalling system to intervene: in the case of moving blocks, the signalling system may realise that the current (absolute) braking distance falls much beyond the rear end of the preceding train, leading to the brakes intervention.

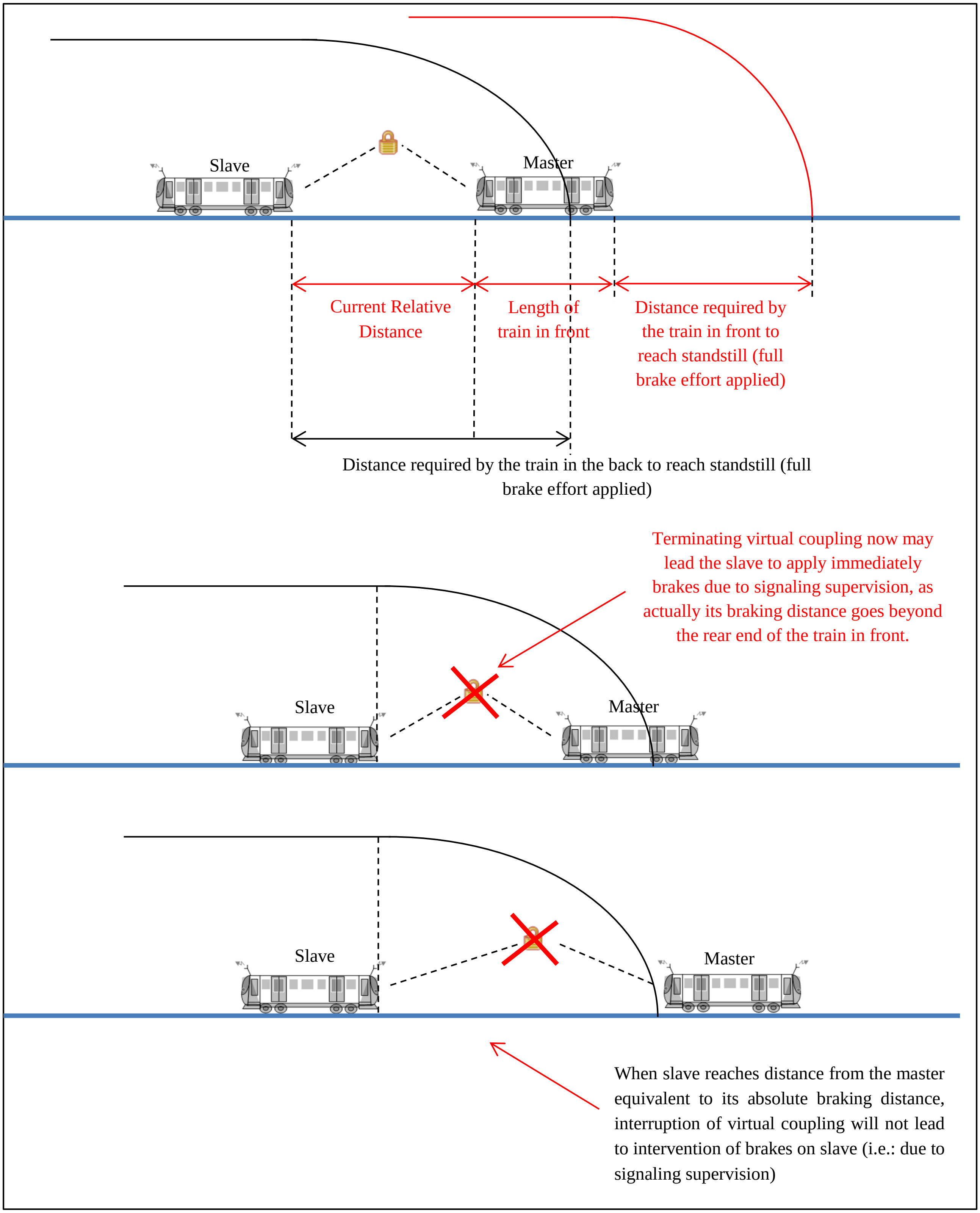

Figure 9-9: Safe Distance to Terminate Virtual Coupling – moving blocks

With fixed blocks, the situation is slightly more complicated than with moving blocks. In order to avoid slave to apply brakes after termination of virtual coupling (due to signaling system taking over the supervision of the train), the slave shall consider the new end of authority that will be generated according to the fixed block and absolute braking distance supervision; this does not correspond to the rear end of the preceding train but corresponds to the beginning of the next occupied section.

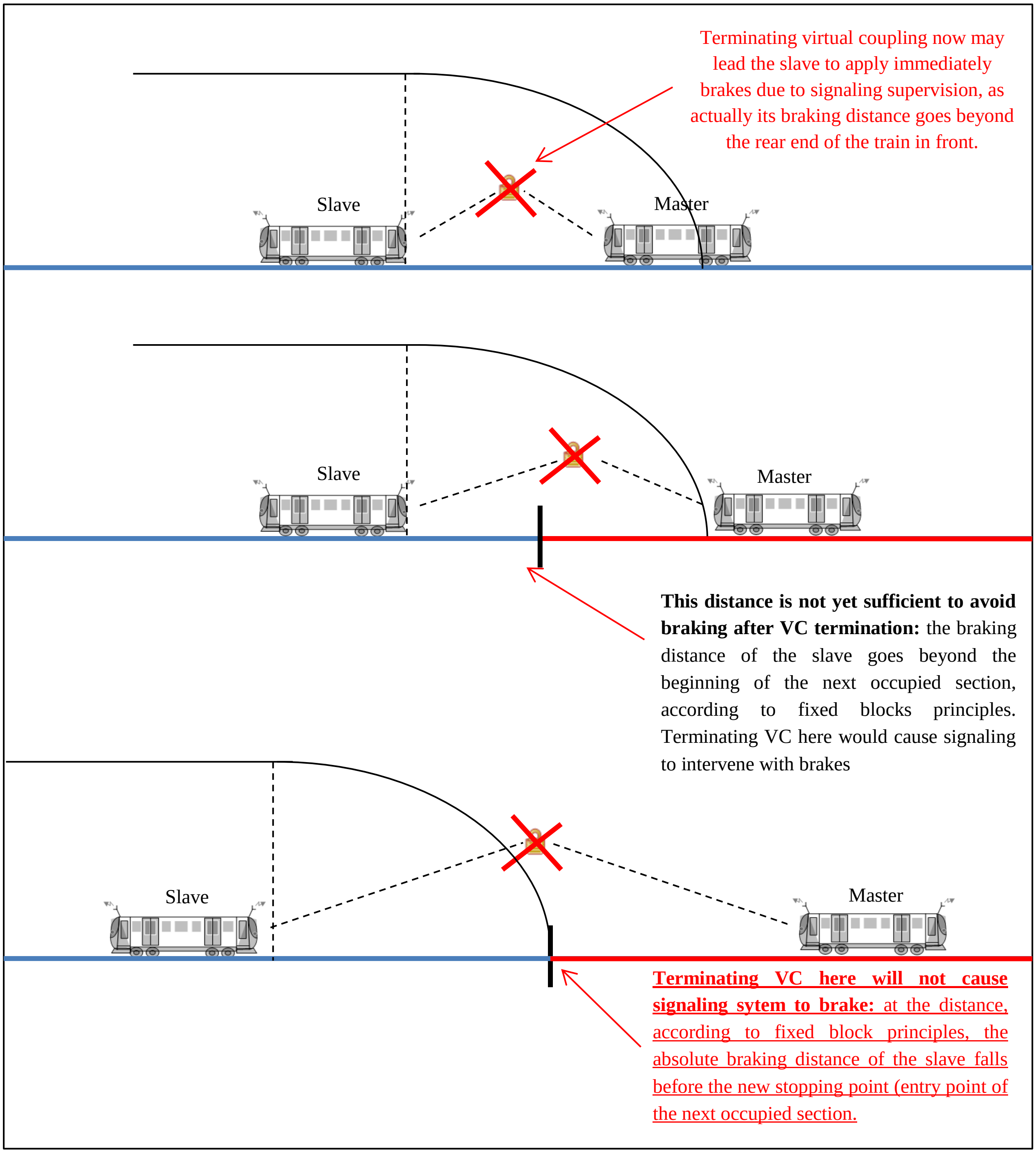

Figure 9-10: Safe Distance to Terminate Virtual Coupling Termination - Fixed Blocks

9.4.2 Splitting of a VCTS – Initiated by Master

Initial Conditions:

- No specific constraints on dynamic conditions. Split can happen at any speed. This specific initial condition is kept to provide the most generic use case possible.
- Once the master sends message of termination for virtual coupling, the slave units initiate the procedure to become an independent platoon, while the master becomes a standalone train.

Expected Functional Behaviour:

- Same behaviour as for splitting initiated by slaves: only when the former slave(s) creating a new platoon have reached a distance which is sufficiently safe to terminate coupling, the actual virtual coupling is considered as terminated and the former master can stop applying cooperative braking supervision (especially when master is provided with higher braking capacity than the new platoon).
- Once termination of coupling is initiated, the new platoon starts to decelerate to reach the safe distance (based on same principles described at previous scenario). As for the previous scenario, two situations are possible:
  - Either the new platoon goes back to the absolute braking distance supervision principles
  - Or it simply applies brakes as soon as VC is requested to terminate. In this case, VC terminates once the relative distance with the trains in front is sufficient to cope with the higher effort of braking of this later ones.

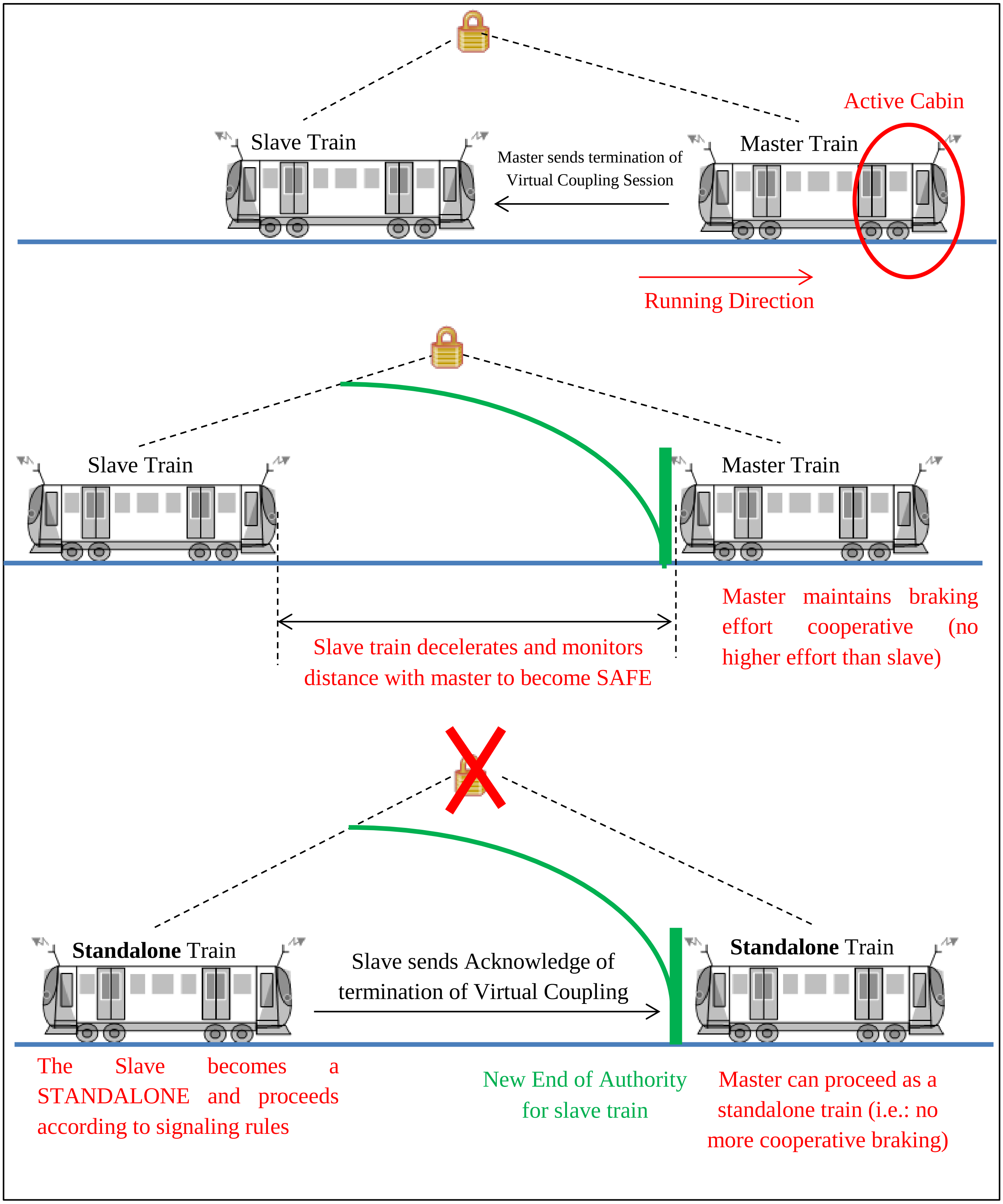

Figure 9-11: Splitting of Platoon Initiated by Master

9.4.3 Loss of Radio Link

Initial Conditions:

- Trains virtually coupled
- At some time, a degradation of the link between master and at least one slave is detected as not efficient (i.e.: loss of connection)

Expected Functional behaviour:

- In general, as long as the connection is not reverted back, the overall platoon shall apply a safe behaviour to maintain appropriate train headway
- During disconnection especially, the slaves cannot be made aware of the speed and other ongoing controls (i.e.: braking actions) of the trains in front. The slave train(s) shall consider the virtual coupling session with master as ceased.
- The slave train takes back autonomous control of its mission based on own data and supervision principles

Technical Analysis

In all cases (either due to a standard disconnection or a degraded condition of the radio link) the slave shall anyway apply the necessary actions to ensure safety of operations as soon as the loss of connection is detected. As a general approach, both master and slave shall proceed according to their signalling rules and information. A separated section shall list events as abnormal operations and build an analysis on consequences of each failure (i.e.: similar to CSM-RA) to then determine the hazards of operations and their mitigations.

Anyway, the following Figure depicts the case in which, after detecting loss of radio link with master, one slave reverts back its mechanism of supervision based on absolute braking distance (i.e.: train movements supervision is reverted back to the signalling system). Depending on the distance at which the event of radio link loss is detected, releasing the control back to the signalling system would allow two options:

- In case the signalling system (i.e.: the on board ATP) realises that the distance from the master is too close, according to absolute braking distance principles, it will apply brakes according to its supervision principles
- In case the signalling system detects that the distance from the preceding train is sufficient, according to absolute braking distance principles, it will simply maintain supervision of the train movements with no braking actions

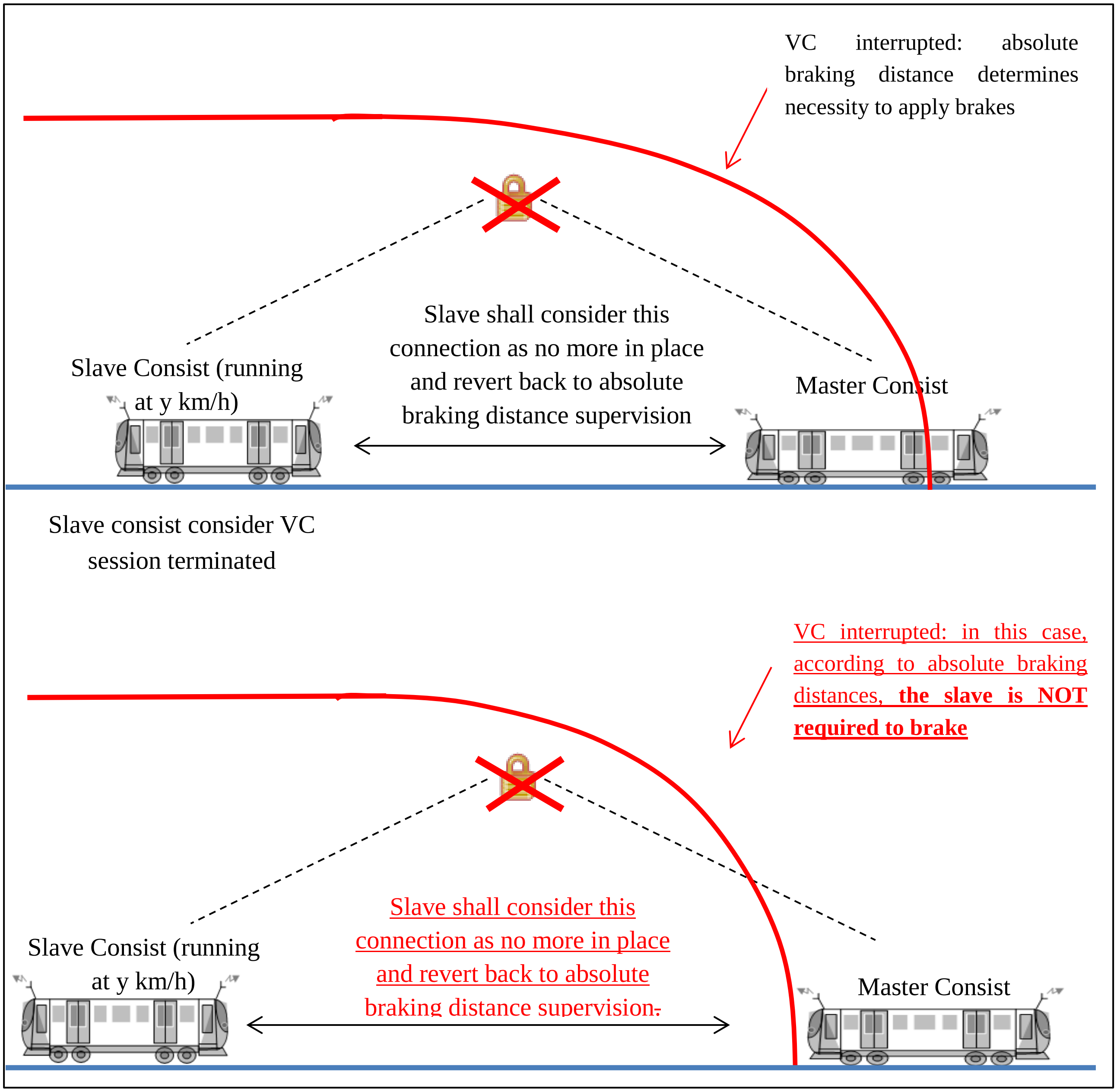

Figure 9-12: Termination of a Virtual Coupling Session

9.5 Additional Scenarios

9.5.1 Platoon in Proximity of Switching Points

The following scenario depicts the case in which a platoon is being formed in proximity of a switch. Especially, the scenario identifies the case in which the point is configured for the conflicting route for some of the trains in the platoon, leading to a potential hazard for safety.

In following Figure 9-13 a platoon is being created with part of the trains (train 1) of the platoon located after a switch (according to the platoon running direction), and part of the trains (train 2) located before the switch. The switch is configured for the conflicting route with respect to train 2.

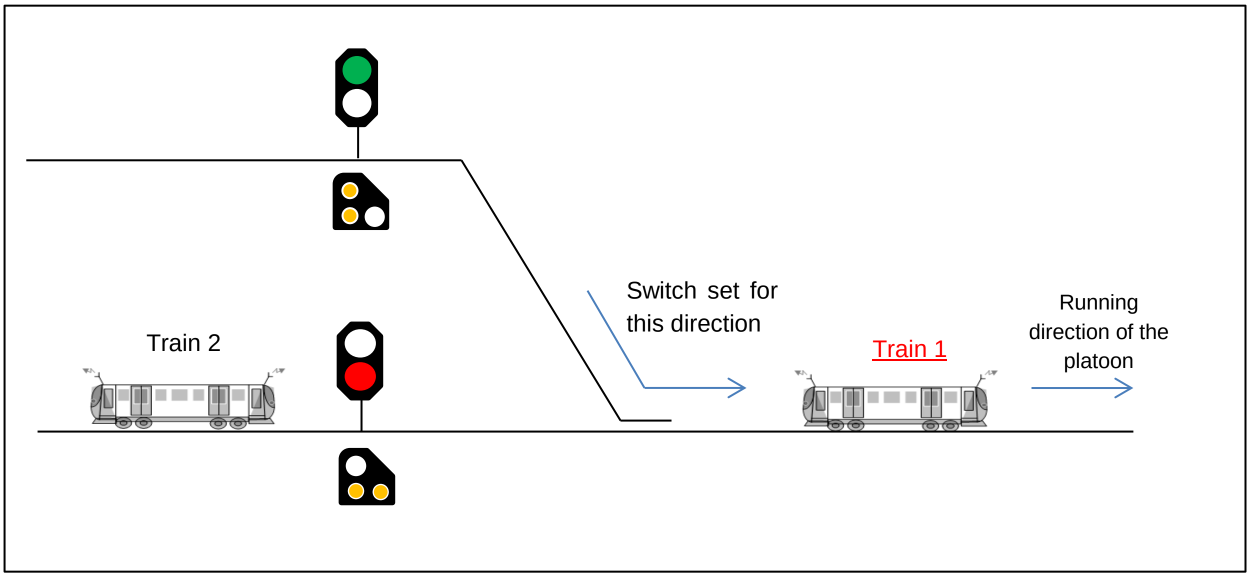

Figure 9-13: Platoon Trains with Conflicting Switch

In this case, countermeasures shall be taken to avoid the platoon to be formed and to proceed in the mission as long as the switch is not configured for the correct route for all trains (e.g.: using signaling terminology, all trains in the platoon shall have same route assigned). Having for instance the train 1 to start running in virtual coupling with train 2, it may lead to the unsafe situation in which train 2 approaches the switch wrongly routed, causing derailment.

In this case, the countermeasures may be that:

- No platoon shall be formed as long as all trains are not associated by a common, continuous route across the whole platoon
- Each train in the platoon shall anyway take into consideration the signalling information available to determine if the trackside is not properly configured (i.e.: route conflicting as in this case). As a matter of example with respect to ERTMS, all trains in the platoon, included the slave, shall anyway be able to distinguish if the Movement Authority assigned by RBC is shorter than the rear end of the train in front (with some tolerance).

In that case, the VCTS on slaves shall anyway allow ATP to protect the train according to absolute distances, and in this case it shall avoid the train 2 to approach the switch.

9.5.2 Route Lock Function and Virtual Coupling

The Route Lock function is a common feature of most of the interlocking (IXL) systems and actually determines the stability of a point (like a switch) as long as a specific route of the track is assigned to a train. In case of mechanically coupled platoons, switches are kept in the correct position as long as the whole train has not been detected as passed across a certain switch. The obvious purpose of this function is to ensure safety of movements once a specific route is assigned to a train, allowing it to calculate its permitted speed and braking curves relying on a stable configuration of the track ahead (e.g.: a sudden change of position of the switch may lead an approaching train not to have sufficient time to stop/decelerate before the switch).

With virtual coupling, the natural gap (despite minimal) between two trains of a platoon may involve the trackside system to determine the train as completely passed over the switch, and to release its lock. In the case of Figure 9-14, train 1 passes over the switch (that is locked by route lock function). In current operations, after train 1 has passed the switch can be again moved as long as the route is not assigned to another following train.

The following train 2 shall have same function of switch locking as long as it has no passed over the same switch. The hazard mitigation shall be thus covered by introducing the functionality in the existing signaling/IXL wayside set of functions, e.g.: the wayside IXL and signaling shall be capable to determine the presence of a platoon and ensure lock of routes accordingly.

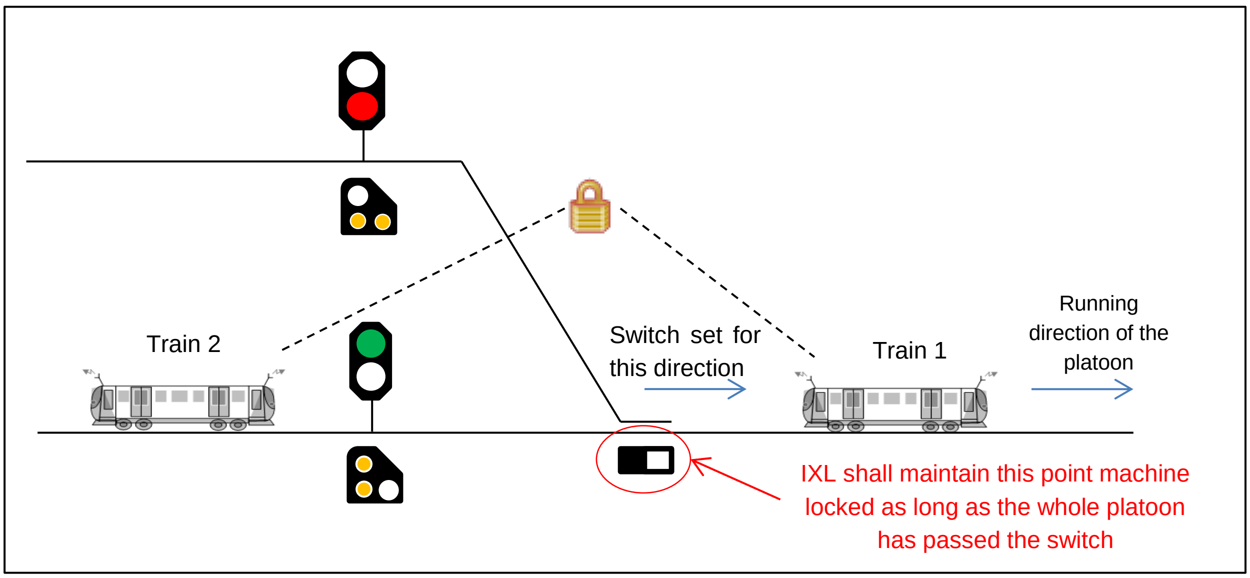

Figure 9-14: Route Lock with Virtually Coupled Platoon

9.5.3 Level Crossings (LX) Management with Platoons

In case of presence of Level Crossings, in similar way to the approach proposed for switches, the system shall foresee adequate solutions for mitigating hazards as the one depicted in following

Figure 9-15 regarding level crossings. According to common implementations of train movement supervision in approach and across level crossings, barriers raising/lowering is often associated to the following policy:

- Approach of trains to LX areas is detected by mean of different solutions (e.g.: axle counters, radio position reports, etc…)
- When a train is detected as approaching a LX, barriers are lowered and locked in order to avoid road traffic or pedestrians to cross the railway line
- Raising of barriers is then enabled once the train has been detected as completely passed across the LX, by mean of similar solutions to the approach detection.

With conventional signaling, e.g.: ERTMS, the barriers of LX would be maintained as 'locked' as long as the section of track is associated to a Movement Authority assigned to a train, so that in the case of Figure 9-15, the LX would not raise barriers as included in a Movement Authority assigned to Train 2 up to the rear end/section of Train 1. Moreover, adequate distance for the detection point in approach to LX shall also ensure enough anticipation to allow both trains to stop before the LX as well as LX area to clear in case of emergency.

With platoons, as in the following figure, train 1 may get detected as completely across the LX, so that barriers are allowed to be raised, while train 2 (virtually coupled) is still to be detected in approach to the LX (this case applies especially when large relative distance applies to the trains in the platoon). The scenario may be mitigated as:

- Having the LX locked as long as the whole platoon has not crossed the LX. This may be implemented, for instance, assigning a movement authority to Train 2, covering the LX and thus maintaining it locked and:
- Having Train 2 to be aware of the presence of a Limit of Authority, associated with the LX, that is closer than the actual limit of authority imposed by relative braking distance monitoring, in order to take the necessary counteractions.

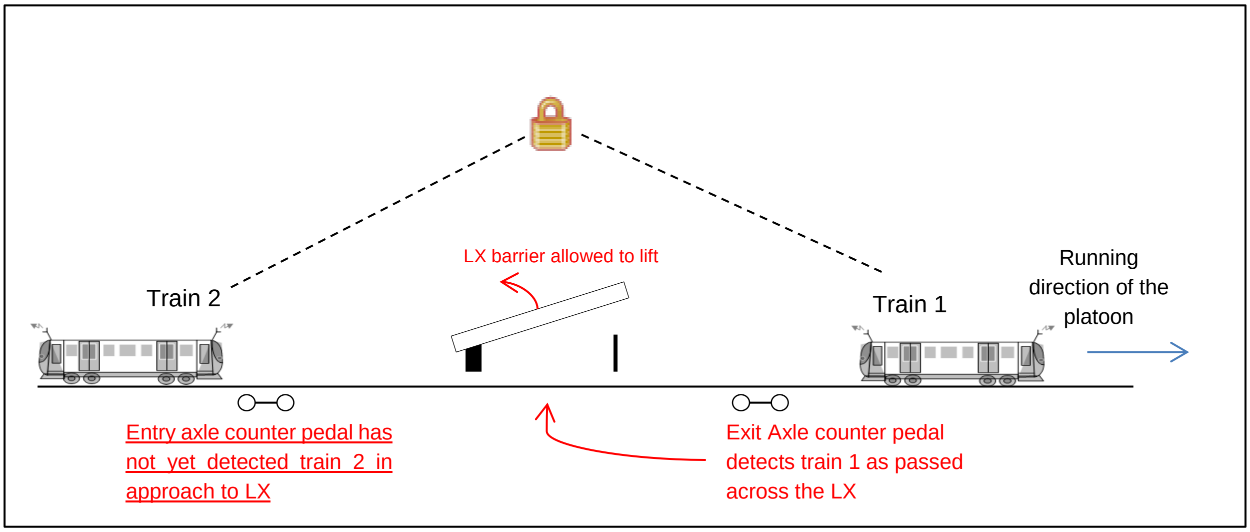

Figure 9-15: Level Crossing Management with Platoons

9.6 Timing Analysis for Platoon Operations

9.6.1 Creation of a Platoon Over Converging Tracks

The creation of a platoon, mapped on real environment conditions, may lead to the definition of exported constraints to the overall railway infrastructure determining actually the efficiency of virtual coupling operations. To support an analysis of this kind, a simple scenario of platoon set up is depicted in following Figure 9-16 where:

- Train 1 is departing from a station, leaving from track 1, routed into the mainline
- Train 2, supposed to form a platoon, is also leaving the station from track 2 into the mainline

According to common principles of operations of a line, a first route will be defined for train 1 by configuring the switch to allow train 1 to exit the station towards the advanced starting signal[4]. In these conditions thus, movements of train 1 will be allowed at least up to the advanced starting signal (or beyond it if track conditions allow it). At the same time, the authorisation for movements assigned to train 2 will be only limited up to the departure signal of track 2 (kept at Red). In this phase, supervision will be still based on absolute braking distances.

In order to allow train 2 to be routed onto the mainline, eventually virtually coupled with train 1, a new route shall be built in order to allow train 2 to follow train 1. This means the switch has to change position creating a path for train 2 up to the advanced start signal or beyond it. Until the new route is not created, train 2 shall not pass the start signal of track 2 (for obvious safety reasons).

This scenario is thus first evidence that the timing to build correct routes for platoons is critical to allow efficiency of the platooning itself. As long as a new route for train 2 is not created, it will not be allowed to proceed beyond the start signal after its preceding train in the platoon (train 1), and so limiting, in this circumstances, the advantages of limited headway which are one of the virtual coupling objectives. Timing for creating a new route is limited by a number of factor as:

- Time required by the previous train to release a specific point/section
- Timing for the point (e.g.: the switch) to actually move in the new position
- Elaboration time for the IXL or the upper signalling infrastructure to detect the new status of the switch and build/assign the new authorisation for movements

[4] Naming of signals and other trackside elements follows the *STD-068-Standard rail signaling naming & symbols*.

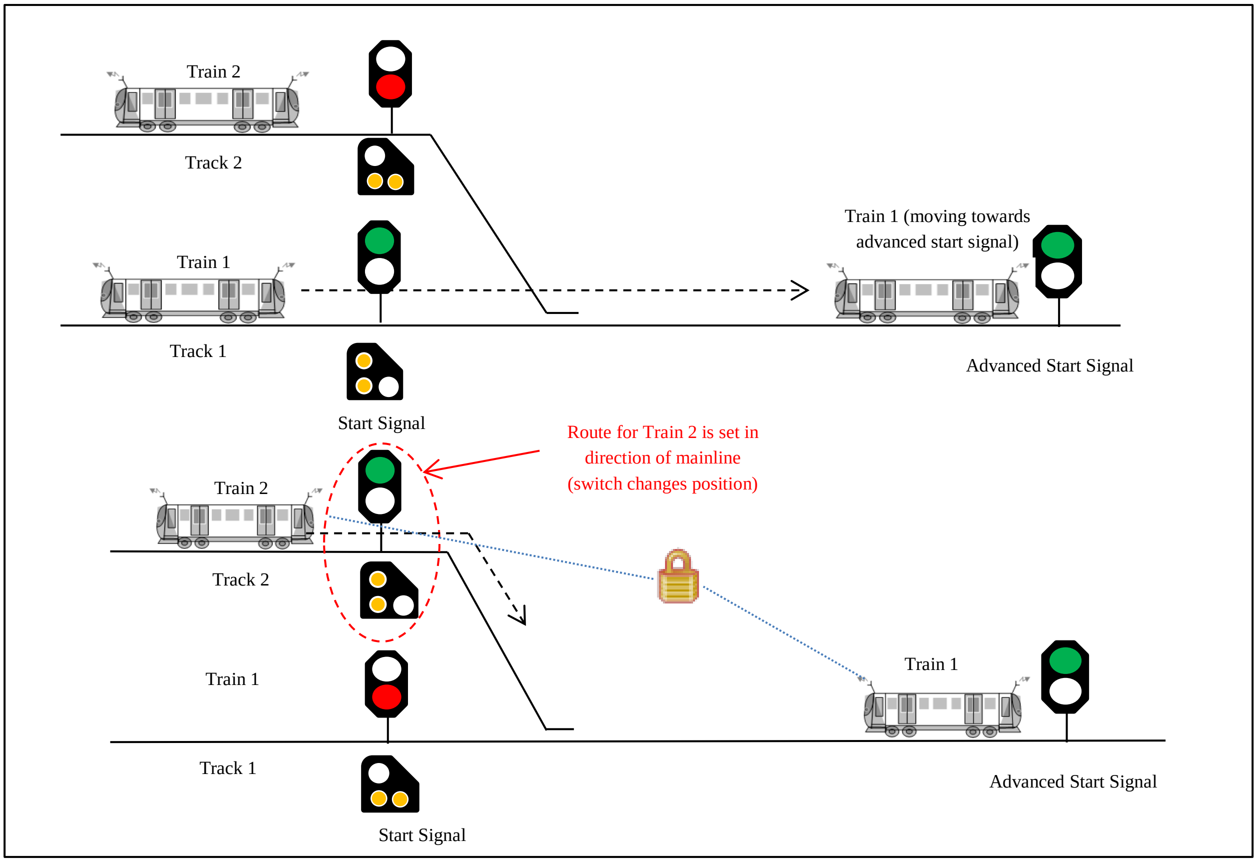

Figure 9-16: Platoon Set Up Over Converging Tracks

9.6.2 Splitting of Platoon at Diverging Tracks

In this scenario, a platoon made of two trains approaches a station and, for any reason, the platoon is required to enter the station split into two or more trains, routed to different platforms of the station. The split may be required, for instance, due to the length of the platoon itself, not compatible with the short platforms in the stations.

The simplified scenario is depicted in following Figure 9-17, where the platoon made of train 1 and 2 approaches a station and initiates a split due to train 1 routed to platform 1, and train 2 routed to platform 2.

As highlighted in the scenarios of Sections 9.4.1 and 9.4.2, splitting of trains inside the platoon requires to maintain, at any time, safety conditions. In this scenario, the splitting requires a sequence of events to take place as follows:

1) The switch is set initially for the route towards platform 1. This means that prior to route train 2 to platform 2, train 1 has to cross the switch and (from an IXL perspective) to release the point.
2) Once the point is released, a new route is created for train 2 up to platform 2. From an IXL perspective, there is thus a limited period of time for the switch to achieve stability of its position (e.g.: to be detected in the correct position as driven by IXL, towards

platform 2), so that the route signal will be set to Red as long as the new route is not confirmed as correctly created. During this period of time, since no route is confirmed as safely determined, **train 2 shall not pass the home signal at red.**

3) Once the new route is created, Train 2 shall be allowed to reach platform 2 according to the speed limitations which are associated to this different track. For example, the switch may be required to be passed at limited speed due to its new position, and this limitation shall be taken into account by train 2 when moving towards the platform.

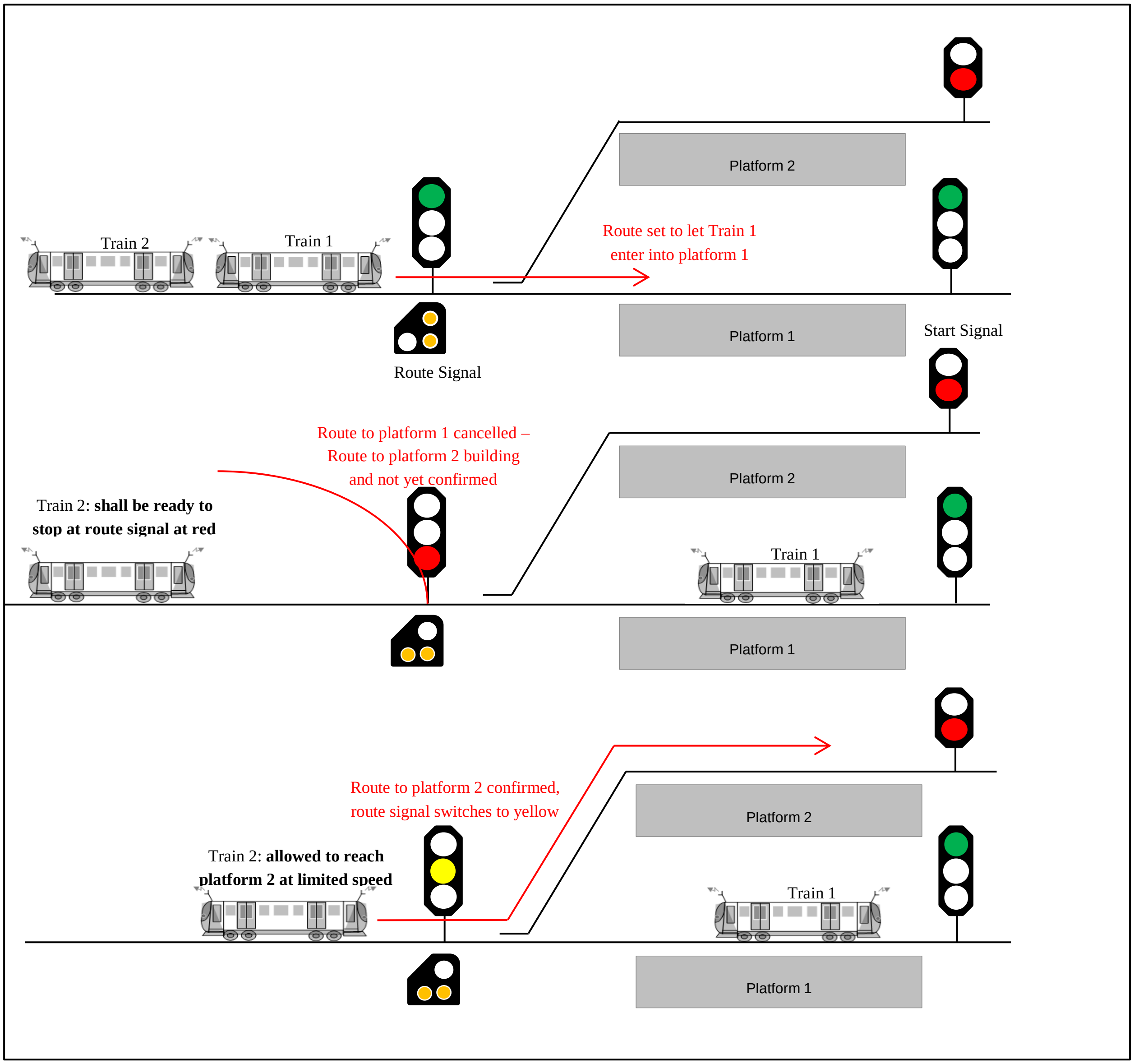

Figure 9-17: Splitting of Platoon in Approach to a Station with Several Platforms

The sequence of events above already highlights some timing and other typologies of constraints imposed by the IXL infrastructure over the virtual coupling system, and namely:

- When cancelling route for platform 1, in order to allow train 2 to reach platform 2, train 2 itself shall approach the station at a speed that is sufficiently low to allow it to respect the home signal at red during the transition period. This introduces a limitation of efficiency (in terms of headway) to the virtual coupling since during the approach of the platoon to station, train 2 shall set its distance from train 1 to eventually cope with this situation.
- Appropriate solutions to implement train protection shall be put in place to allow the whole system, inclusive of ATP and signalling in general, to allow train 2 to respect speed limitations due to the switch or anyway the different route setting.

9.7 Technical Functions

9.7.1 Calculating Relative Distance Between Trains

Initial Conditions:

- Two trains (or existing platoon and standalone train) not yet coupled
- Virtual Coupling is successfully finalised, and the two trains (or platoon and standalone train) become a (longer) VCTS
- The two trains (or platoon and stanalone train) then initiate a mission under Virtual Coupling movements

Expected Functional Behaviour:

- Slave train follows the preceding train (master or slave) at safe distance, while also keeping a safe distance to the following slave
- This means the Slave Train shall know where the preceding train Rear End (and the its own front), and where the front end of the following slave (and its own rear) are located
- Stability of the platoon is achieved by having all slaves to determine their relative distance from the master. Distance to the neighbours is used for ensuring safety, while the distance from the master is mostly used to ensure that relative distances within the platoon are not sujected to large variations, and having all slaves to determine their setpoint of distance from the master ensures stability.

Technical challenges:

- Speed may have uncertainty due to different sensors, accuracy, etc. .so comparing speed between trains may not be sufficient to maintain safe distance; in any case, relative speed shall be checked as it is a key for collision avoidance.
- Similarly, calculated position may be subjected to lack of accuracy; constraints shall be exported to position accuracy. In this concept phase, positioning is anyway considered as a function provided by an external entity/subsystem (i.e.: TD2.4)
- In general, each train shall be able to determine how close, or how far, it is from the adjacent trains (see scenario for approaching station). All trains, slaves and master, should be able to determine the relative distance.

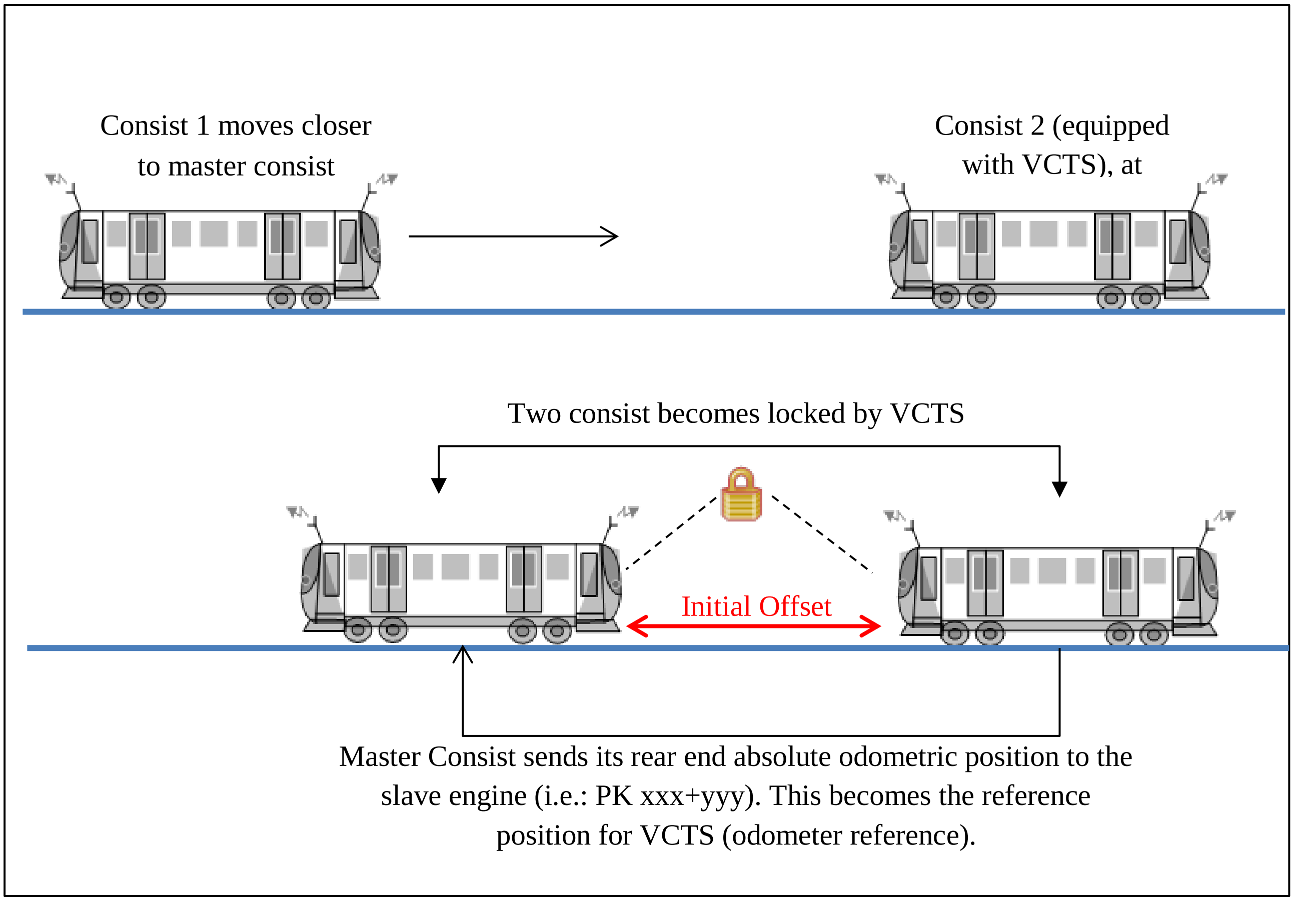

Figure 9-18: Aligning of Virtual Coupling Headway Distance

9.7.2 Maintaining Headway between Trains

The VCTS is based on the principle of two (or more) trains communicating on a dedicated channel (provided with necessary protocol that ensures safety, security and delivery of information). This means that the set of information transmitted between Master and Slave shall be sufficient to:

- Ensure, at all time, that the slave train does not breach the core safety principles, i.e.: it shall not, at any time, enter in collision with the master
- Harmonise the movements of Master and Slave(s), i.e.: the trains shall proceed along the mission together in the most synchronous way possible (i.e. control stability). This means the distance between the train(s) shall not:
  - Avoid controls to maintain headway to be too frequent and fragmented. Relative movements shall be as much as possible harmonised and smooth to ensure highest achievable level of comfort.
  - Similarly, diverge during the mission (i.e.: slave falling far behind the target value)
  - Prevent the virtual coupled train to operate in specific, basic operational scenarios, i.e.: approaching a station platform

The core guideline of this VCTS is concept is thus that the two (or more) trains virtually coupled shall actually operate in the same exact way as a mechanically coupled train. Under this perspective, the VCTS shall be thus improving/simplifying operations of multiple trains, by removing the procedures required to connect two or more trains by mean of mechanical, electrical and pneumatic links, leveraging on the communication channel to transfer the necessary information (commands, data, feedbacks) across the virtual train.

The core of maintaining headway is thus the cooperative braking principle, that actually develops the concept of trains virtually coupled and braking as a single (virtual) platoon. The most relevant aspect is centered on the differences in terms of braking capabilities between trains within the platoon; in a simplified scenario considering a platoon composed of one master and one slave (easy to replicate with N>1 slaves) the two scenarios may be:

- The slave has an higher (or same) braking capability of the master
- The slave has a lower braking capability of the master

The second scenario is clearly the hardest to manage as appropriate solution has to be developed to allow in any case the slave to travel at closer distance to the master than absolute braking principles, but allowing in any case safety margins or solutions to cope with the higher deceleration rate that can be achieved by the master in case of brake application. Two approaches are available:

1) The slave shall calculate its safe distance from master taking into account the difference in braking efforts. This results into an additional safety margin kept to separate master and slave within the platoon.
2) The master shall be able to modulate its braking effort (and thus its supervision braking curves) according to the braking capability of the slave. This results in a shorter relative distance between master and slave within the platoon, but also in a more conservative braking curve supervised by the master (and thus followed by the whole platoon). Moreover, this scenario involves the master to be able to modulate its braking effort (especially the emergency brake), which is not always an available feature on all trains.

As a remark, the case 1) is applicable to all situations in which, for any reason, the distance to stop of the slave becomes actually longer than the master (for instance, when at some time the slave is travelling at higher speed than master, irrespectively from the braking effort). See thus this principle depicted in Figure 9-19 where the calculation of headway distance includes thus a safety gap that shall be taken into account by the slave (as an additional contribution to all other variables like communication network latency, etc.).

With an alternative approach (option 2, Figure 9-20), the master may modulate its braking curves and effort according to the braking capability of the slaves, in order to have an homogeneous deceleration of the whole platoon.

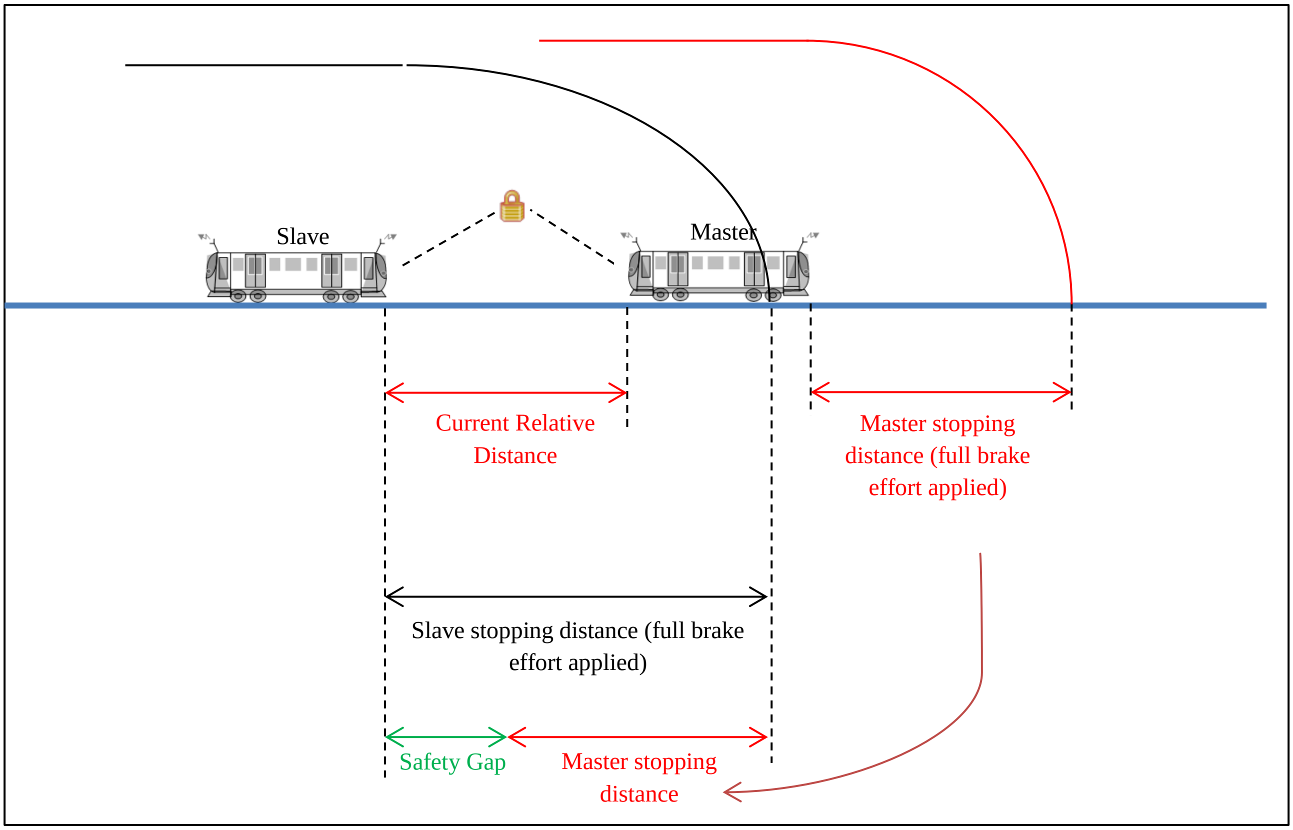

Figure 9-19: Train Headway with Different Stopping Distances

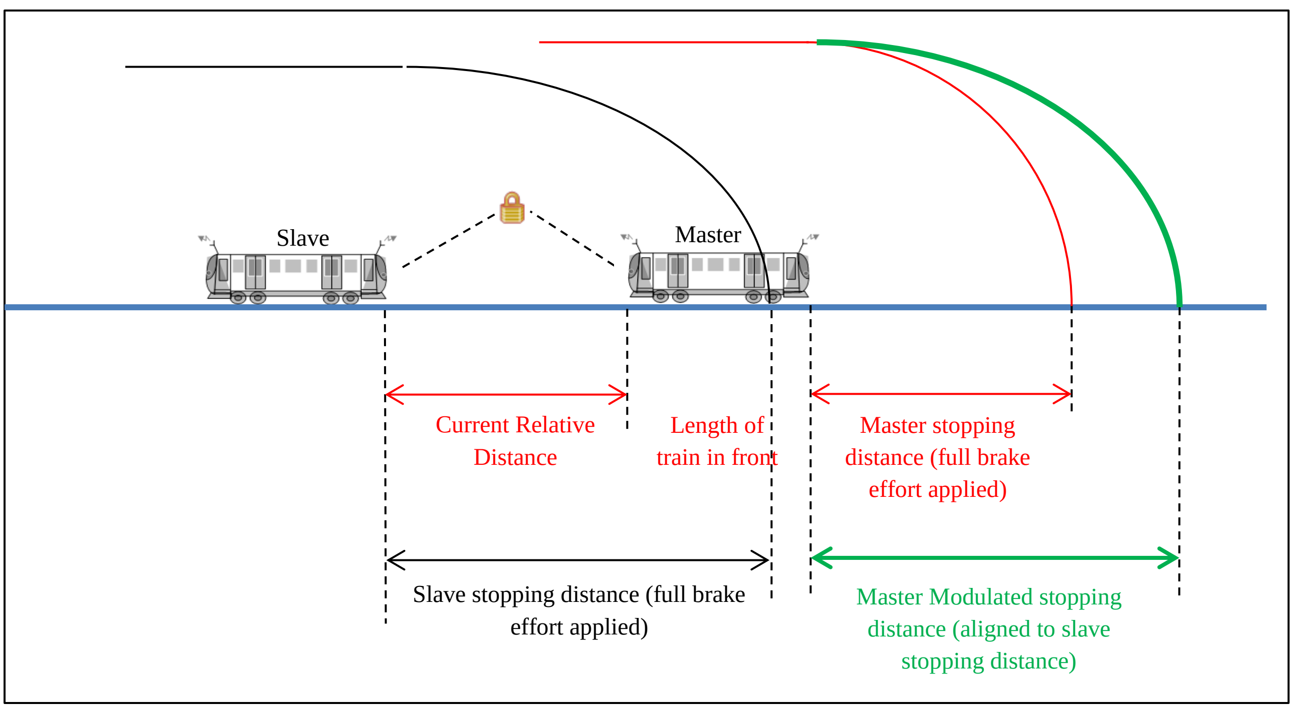

Figure 9-20: Master Modulating Braking Effort to Slave Braking Capability

9.7.3 Managing Train Dynamics

The VCTS concept shall overcome and compensate difference between coupled trains in terms of dynamic behaviour. For instance, the VCTS shall be able to manage:

- Different brake decelerations between trains, including different braking lag; this both refers to different maximum effort achievable when braking, as well as incremental levels of brake effort available; moreover, deceleration also depends on the track gradient at the location in which the train is at any moment, as well as other parameters like track adhesion factor, etc.
- Different acceleration capabilities between trains, including different traction lag; this is typically the case of a master train with high acceleration capability, that shall be harmonised with the slave trains in order to avoid the master to actually ‘run away’ from the rest of the virtual train.
- Different positioning functions (measure of space and speed). Positioning may have different accuracy in each train. This may thus lead to either to availability problems (the slave may fall too far behind the master, see Figure 9-21) or even to a safety hazard (the slave may collide with the master, see Figure 9-22).
- Latency in transmission of relevant data between trains. Delivery of data across an air gap link may be affected by a time to be delivered to destination, as well as a probability of loss (then usually translated in additional delay for retransmission). These delays shall be translated into a safety margin of distance between trains when running virtually coupled. This safety margin (if based on a safety distance) shall be dependent on the current speed of the trains, or better, on the difference of speed between master and slave. In any case there should be controls and techniques in place to minimise the impact of the chained latencies.
- Different local control latencies caused by different computation cycle times, different vehicle bus transmission periods, etc. which lead to additional safety margins.

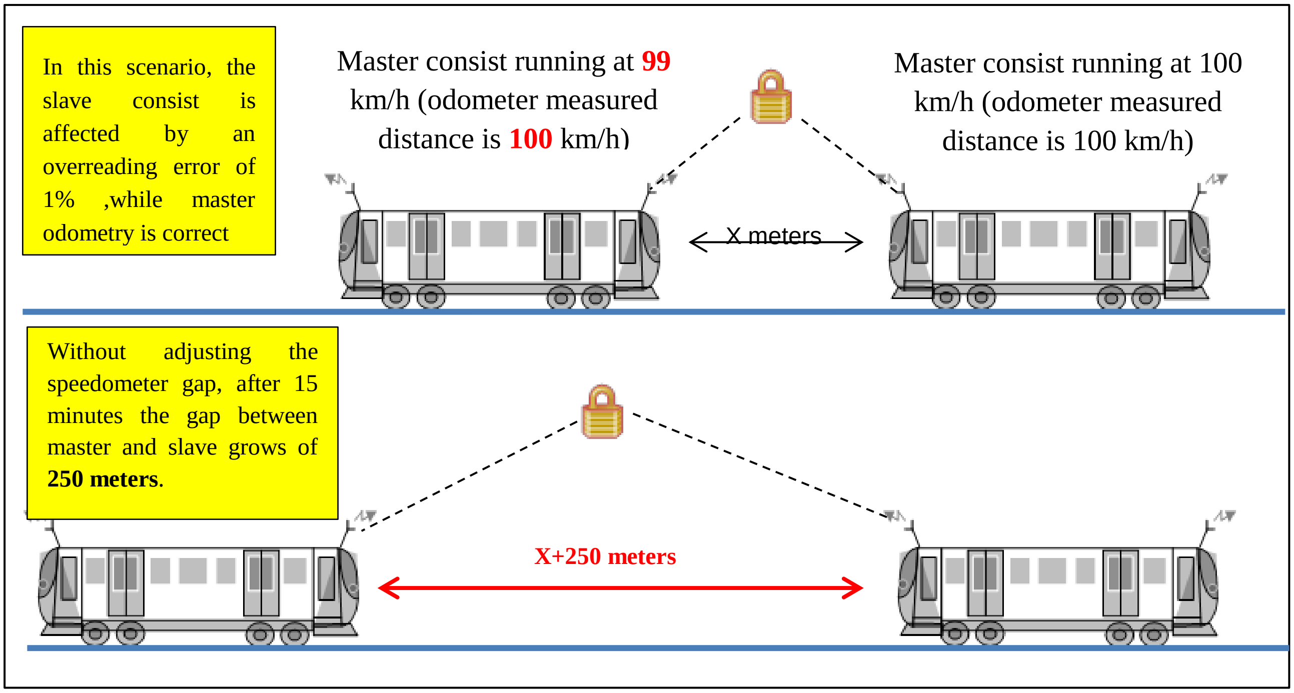

Figure 9-21: VCTS affected by Overreading Positioning Error

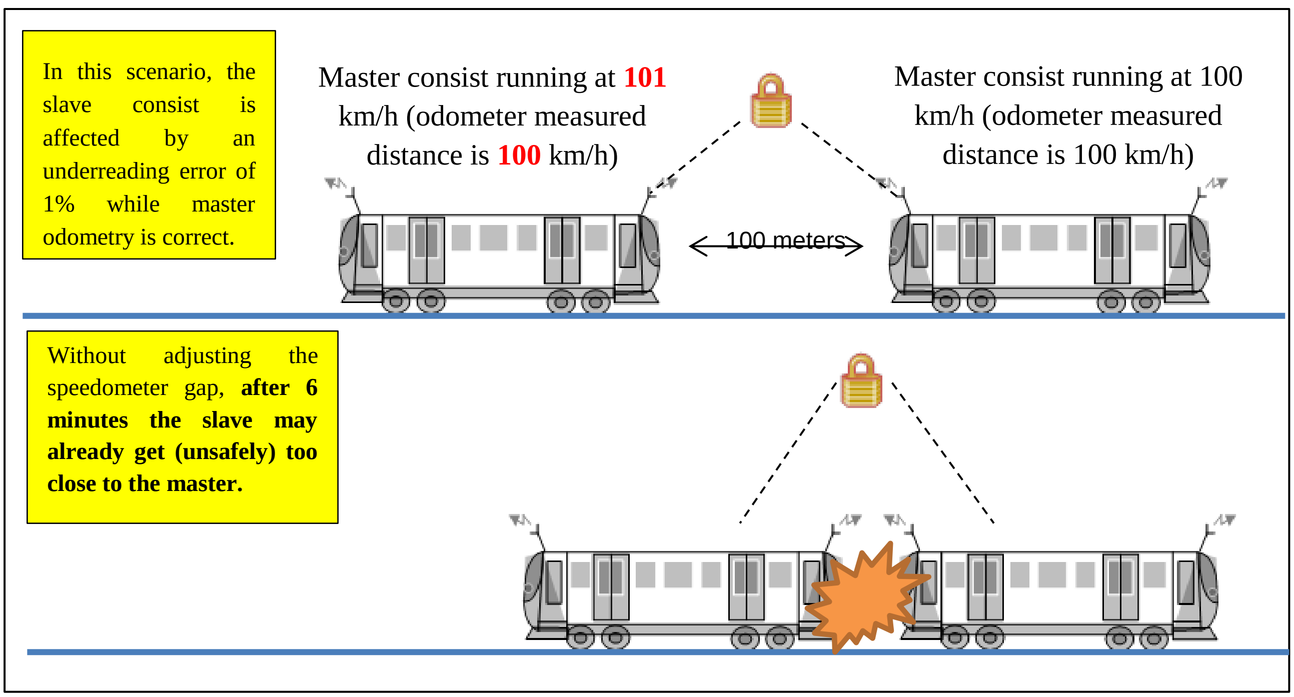

Figure 9-22: VCTS affected by underreading positioning Error

9.7.4 Determining Common Reference for VC Movements Monitoring

If two trains shall monitor the relative distance to determine safety conditions under Virtual Coupling movements, this means some algorithm to determine a common positioning reference system for both of them. Two different trains may calculate their own position and current speed, but there should be a common reference from which to start monitor movements. This means some high level algorithm like the following may take place under VC; as a remark, the following algorithm does not constitute a guideline for implementation, but only a practical representation of how the common reference shall be established, and namely:

- Slave train gets close to the Master or to an existing platoon (at a distance hereafter referred as *vc_initial_offset*, typically few meters or less) and reaches standstill;
- Master and Slave activate the VC session and become a virtually linked train;
- Master sends its (or platoon's) rear end absolute position (hereafter called *master_abs_rear_end*) to slave at the moment of the VC linking finalisation.
- The slave then records the current position as the positioning reference point for virtual coupling. The absolute odometric position of the slave (*slave_abs_front_end*) is set as equal to *master_abs_rear_end*;
- The two trains (or platoon and train) are anyway placed, at the beginning, at a distance (vc*_initial_offset*). Based on the proposed algorithm hereafter, the two trains will never become any closer than initial_offset.
- The slave train, from this point onward, keeps on calculating its safe distance from master based on information exchanged with the master and its braking characteristics (hereafter referred as *safe_distance_from_master*).
- The slave train moves with the master train. At every periodic telegram of VC, the master sends to the slave its updated *master_abs_rear_end*;
- The slave train calculates continuously its travelled distance from the beginning of the VC session (*slave_travelled_distance*). At every cycle of elaboration, *the slave_abs_front_end* is updated with the *slave_travelled_distance*.
- The VCTS shall ensure at every iteration 'i' of the algorithm that:

(master_abs_rear_end(i) - slave_abs_front_end(i)) > safe_distance_from_master(i)

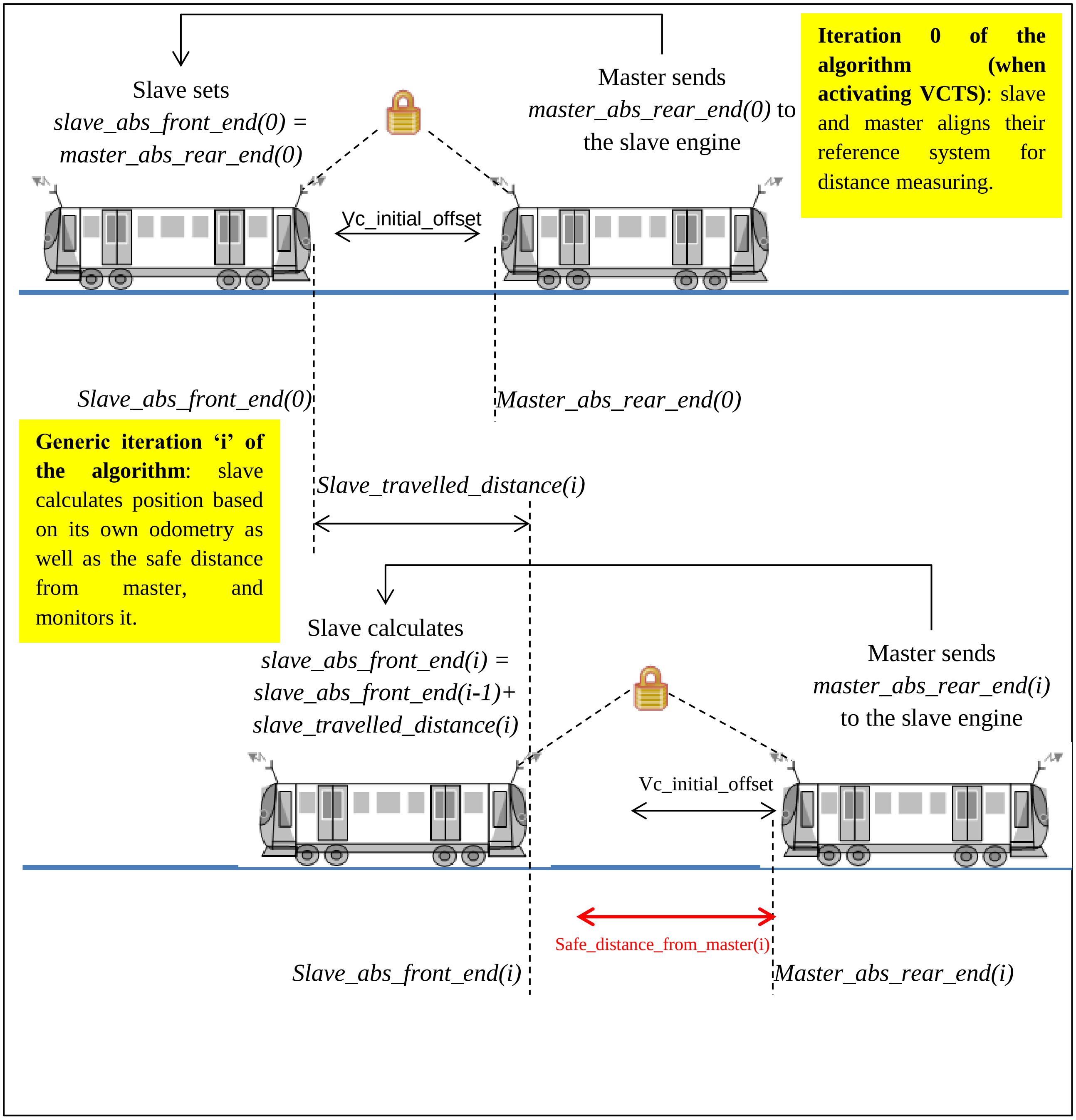

Figure 9-23: Principles of Relative Distance Calculation

At this stage of conceptual definition no specific constraints on the odometry solution, wheel sensors, radars, accelerometers, GPS, etc. is provided. Especially, the odometric system shall be considered as a source of data which is external to the VCTS and that provides input to the VCTS with adequate level of integrity and accuracy. Later stage of design will define the targets (safety and performance) for the odometric function which shall be exported by the VCTS.

9.7.5 Synchronising Position between Master and Slave

Positioning error affects both safety and stability of VCTS. This means some countermeasure shall be applied in order to mitigate this issue, considering that:

- Odometry is prone to accuracy errors that grow with the distance travelled; typical odometric error of wheel sensors is 2% of the measure, leading to approximately 20 meters error over 10 km of distance travelled
- With reference to the previous scenario, even taking into account this error for safety reasons, this means that the Virtual Coupling train headway function may be progressively affected by an odometric error that constantly grows and does not allow the master and slave to get close (actually they progressively fall away from each other with the growth of odometric error)
- In several contexts/applications, solutions are identified to reset the odometric error accumulated during the run, i.e.:
  - Eurobalise in ERTMS: position is always referred to a last relevant balise group
  - CBTC (Communication-Based Train Control): beacons for stopping at platform are used in similar way
  - SCMT (Sistema di Controllo della Marcia del Treno): same as ERTMS, transponders used to reset error

In general, the accuracy of the space/speed measurement shall be considered as a requirement that the VCTS exports to the positioning function (TD2.4), and no definition of positioning algorithms shall be considered within the scope of this analysis.

9.7.6 Establishing/Monitoring Communication across a Platoon

The core of cooperation is the list of Cooperative Awareness Messages (CAMs) which are exchanged through the train-to-train link between virtually coupled trains of the same platoon. CAMs constitute a set of messages exchanged by mean of a protocol with the adequate level of safety and integrity, to allow master and slave consists to implement the necessary controls and supervision functions according to the Virtual Coupling concept.

Whilst the scope of this analysis does not include an inspection of the potential technological solutions of the wireless communication link supporting CAMs exchange, it is possible anyway to determine a preliminary set of requirements applicable to the T2T communication channel as provided in following Table 9-1. In the development of the virtual coupling concept, anyway, performances of the T2T link shall be taken into account as a compulsory input to the computation of the minimum relative distance that can be safely kept within the Virtually Couple Platoon.

Communication Requirement	**Description**
Message delivery	Appropriate protocol mechanisms shall provide guarantee that messages are delivered to destination and/or that eventual loss of messages is detected.
Unique identification of source and destination of messages	It shall be possible to uniquely identify the source of received information (i.e.: it shall be possible to identify the master sending some specific data received by a slave), as well as the destination of transmitted data.
Adequate level of security	Techniques shall be allowed (as Encryption, CRC, etc…) to: • Detect (and eventually correct) corruption of information contained in a message • Intrusion on the communication channel (as aliasing, etc…) aimed to disturb, interrupt or modify the flow of information across the VCC • Separation of data flows; there shall be no possibility that VCTS-related traffic is mixed with other traffic, either safety or non-safety related, but anyway associated to other functions than VCTS
Delivery Time	Adequate protocol shall be arranged to allow precise determination of the worst case time to deliver messages to destination. It shall be possible to determine especially the time required, for a specific message, in the worst case, from the moment it is transmitted by source to reach the destination. An example is the information about the ongoing braking action on the master: the slave shall dimension the safety distance from the master by taking into account the worst case time for a message of ongoing brakes on master to reach the slave itself.
Timestamping/sequencing	The protocol shall allow the destination to determine the time at which the message has been sent and, together with it, the sequence of transmission in order to distinguish/discard older messages.
Status monitoring	It shall be possible to monitor the status of the communication link between master and slaves, in order to determine with predictable timing when the communication is lost/interrupted/degradated and take the necessary safety actions.

Table 9-1: T2T Communication Requirements

The contribution of protocol timing on the safety margins introduced by VCTS is synthetized in the following Figure 9-24:

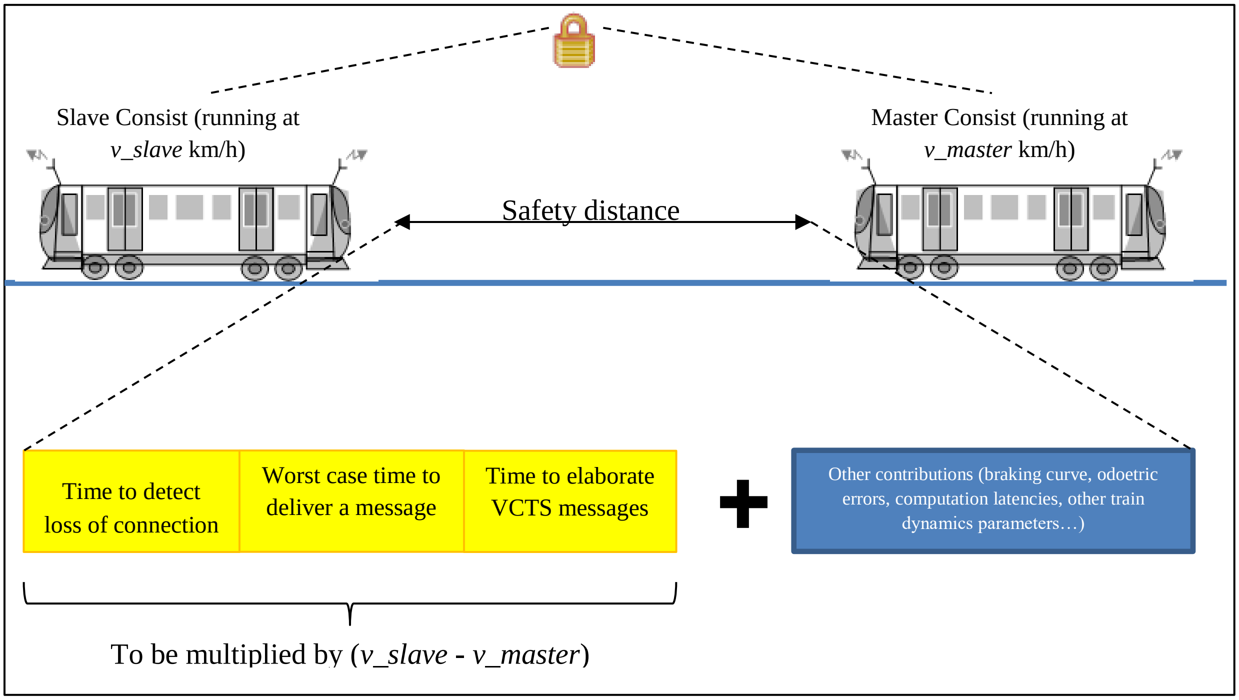

Figure 9-24: Virtual Coupling Safe Distance Contribution of Protocol timing

As highlighted in previous scenarios, one of the key aspects of establishing a safe communication channel between virtually coupled trains is the possibility for the slave to distinguish the master to which connect (or other way around). A sample scenario is depicted in following Figure 9-25, where the train supposed to act as slave approaches a section of track that may allow connection to two master trains (A or B). In this case, reasonably the slave train shall connect only to the master train that is valid for its route, so that appropriate mechanisms of VCTS, either implemented through automatic procedures, shall be implemented. In general, this analysis assumes the presence of a superior hierarchical entity that governs the coupling and determines which trains shall become part of a platoon, see the description of strategic layer as provided in chapter 7.2.2.

Train-to-Train communication requirements will be exported to CONNECTA-2 (TD1.2) in charge of such wireless link, which will be supported by X2Rail-3 WP3 (TD2.1) in defining the suitable technology and protocols.

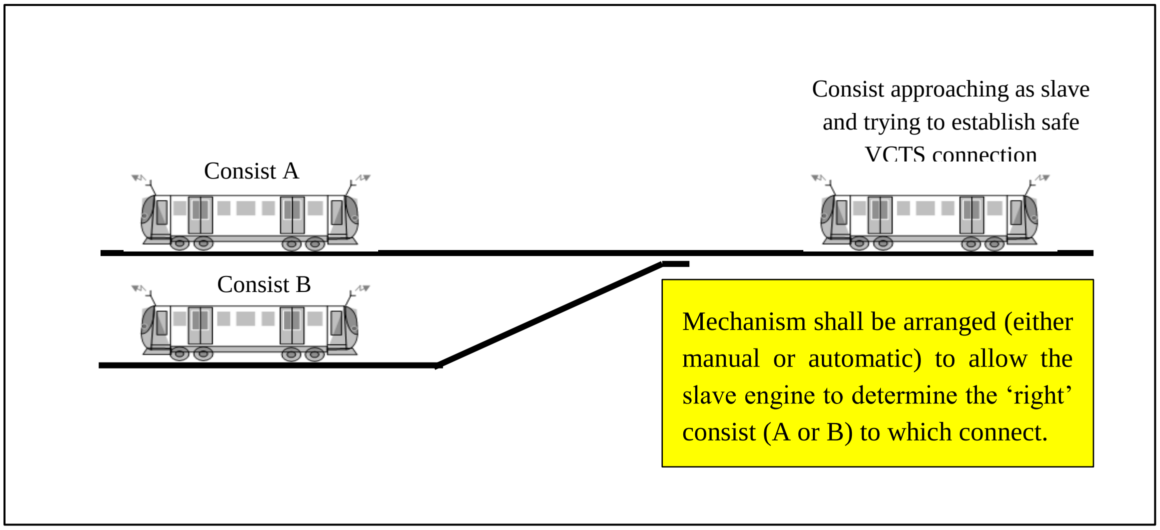

Figure 9-25: VCTS Scenario with Slave Approaching Trains on Different Routes

Following the considerations of this section and previous, it is possible to distinguish different levels of interaction in setting up a VCTS mission, in which different requirements of VCTS are fulfilled. As depicted in **Errore. L'origine riferimento non è stata trovata.**, the implementation of a communication link between two trains of a platoon (in the figure, master and slave communication is represented) goes through different, incremental levels that shall be distinguished as:

- At the beginning, a physical connection (through wireless link) between master and slave, based on any of the available technologies and protocol (i.e.: any wireless data link on which a connection is established based on protocols as TCP/IP, UDP, etc.)
- Once the physical connection is established, a mutual identification takes place in order to allow unique identification of trains in the platoon
- Following the identification procedure, the platoon composition can be determined/checked (eventually against the data provided by the strategic layer)
- Succesfull completion of platoon composition determination allows to proceed with the mission set up procedure, in which all trains exchange the relevant mission data aimed to implement the VCTS functions across the mission
- Having completed the mission set up, it is possible to initiate the Virtual Coupling session by mean of the periodical exchange of messages (CAMs), and thus considering the virtual coupling set up as completed

For this reason, both establishing as well as monitoring of the communication link between trains in the platoon shall consider these layers, and implement adequate mechanisms to regularly check the status of each communication layer. For example:

- In case of temporary loss of wireless communication between one train and the rest of the platoon, a mechanism shall be provided inside VCTS functions to allow, once connection is re-established, that all other layers are still aligned, i.e.: the train composition is remained the same as before the communication loss, as well as the mission data like brake characteristics of any of the trains)

- Similarly, in nominal conditions, a change of train composition shall trigger again the exchange of mission data to align all trains in the consist regarding the dynamic characteristics of the new platoon

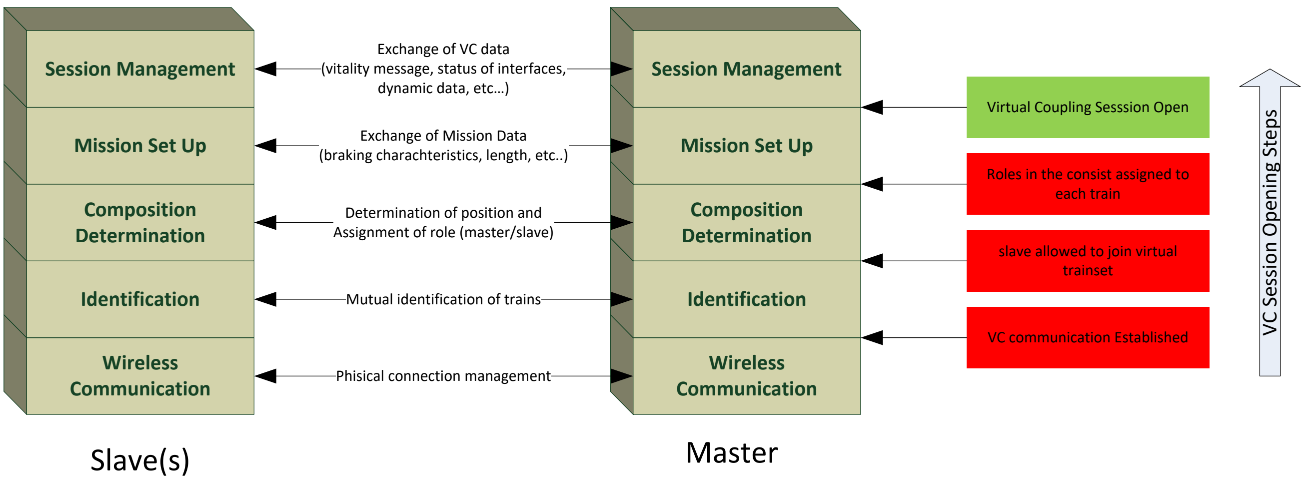

Figure 9-26: Layers of Interaction for VCTS Mission Set Up

9.7.7 Calculating Cooperative Braking Distances

The VCTS shall calculate the coordinated braking distance between two (or more) virtually coupled trains. The relative braking distance/curve shall comprehensively address all braking characteristics of both master and slave(s) and thus take into account:

- Achievable braking deceleration (depending on type of brake applied + brake status)
- Application time (minimum-full brake effort)
- Instantaneous braking curve/stopping distance
- Rotating masses
- Speed
- Gradient profile of the line
- Adhesion factor

As core principle of Virtual Coupling, braking curves shall be developed by each train taking into consideration the braking curve of the preceding train(s) in the platoon. In the example depicted in Figure 9-27, the train identified as ‘slave’ is provided with its own specific braking curve, indicative of the distance required (at the current speed) to reach standstill, based on the current brake capabilities of the train itself (*L_slave_braking*). According to absolute braking distance monitoring, the slave would thus develop its braking curve targeting as stopping point the rear end of the preceding train, at any time (for example as it would happen in moving blocks railways). With relative braking distance monitoring, the approach foresees the slave to also take into consideration the braking information for the train in front identified as ‘master’, e.g.: the space required to the master to reach standstill with the highest rate of deceleration available at the moment. This distance is thus referred as *L_master_braking*. Following a common approach for target distance monitoring, the slave shall thus target as a stopping point (worst case) the position reached by the rear end of the master after a full brake effort application (in the picture: *L_master_braking*-*L_master*).

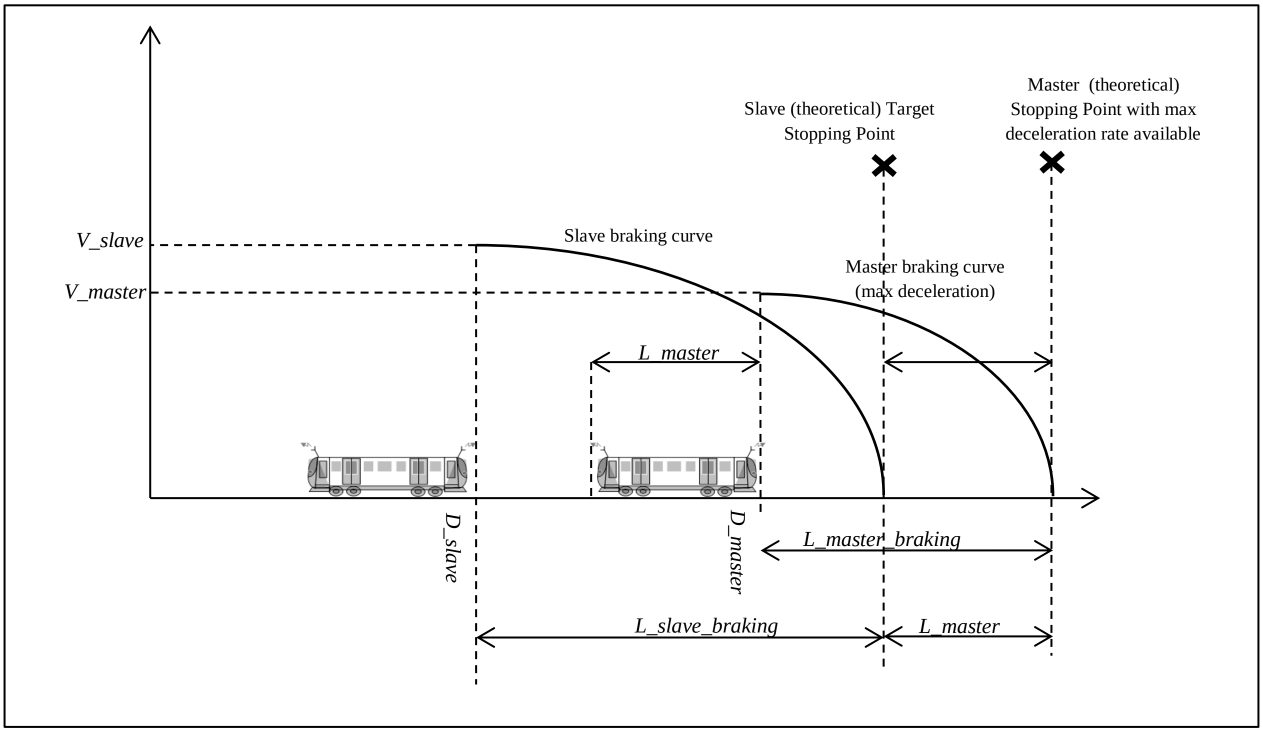

Figure 9-27: Development of Cooperative Braking Curves

9.7.8 Train Movements Protection

The VCTS shall support the functions related to prevent collision between virtually coupled consists (VCT).

Especially, together with the functions aimed to determine the safety margins to be maintained between two VCTs (determining relative distances, synchronising positioning, calculating relative braking distances), it shall also support the implementation of protective actions to limit train movements when necessary (i.e.: trains getting too close).

Protection functions shall be implemented under the perspective of limiting the application of the last line of intervention, which is typically the pneumatic emergency brake, to be used only in case of urgent need. This leads then to the need of defining different, progressive level of intervention based on the actual relative distance between two VCTS, by leveraging for instance on vehicle’s interface functions as:

- Traction cut off/coasting: this shall be the first line of intervention, to avoid slave/master to further accelerate towards each other, reducing their relative distance
- Service brake: when traction cut off is not sufficient to limit the relative braking distance between two VCTs, the service brake shall be triggered. Depending on vehicle's interface, different levels (1…N) of Service Brake may be initiated to progressively provide incremental braking effort.
- Emergency Brake: as last line of intervention, when the Traction Cut Off and Service brake reveal as not sufficient to limit the distance between two VCTs, the pneumatic emergency brake may be triggered

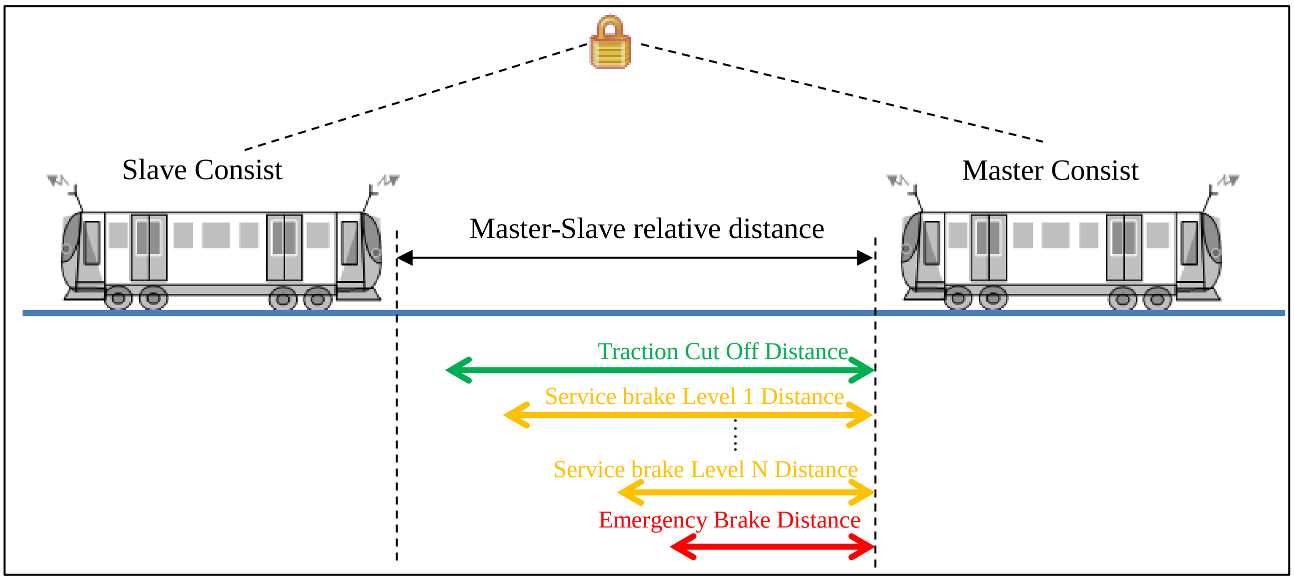

Figure 9-28: VCTS Level of Interventions

As a remark, protection functions do not only apply to the slave trains. Master trains as well shall monitor the relative braking distance, especially to cover cases in which the master train, at some point of the mission, reverts back from its nominal running direction (i.e.: the running direction defined for the mission). This may happen for a number of reasons (see previous operational scenarios), and protection can be achieved:

- Either having the master to implement same protection principles as the slave, based on relative braking distances; OR
- Preventing the master to move backwards, i.e.: roll back protection, or forbidding backwards movement

The second option introduces anyway limitations in the usage of some of the vehicle's system functions (i.e.: it does not allow shunting movements, which are characterised by both directions of movements allowed).

Protection Function	VCTS basic functions involved	Additional functions supporting the protection:	Functions applicable to:
Preventing slave to collide with preceding train	• Determining relative distances • Calculating relative braking distances • Monitoring communication channel with master&preceding train	• Traction Cut Off; • Service brake • Emergency Brake	Slave train(s)
Preventing master to collide with slave	• Determining relative distances • Calculating relative braking distances	• Traction Cut Off; • Service brake • Emergency Brake	Master train

Table 9-2: Protection Functions Allocation

9.7.9 Assisting Train Driving

While protection functions mostly target the prevention of collision, additional functions shall target to maintain harmonised movements (i.e.: Platoon stability) of the virtually coupled platoon. The list of these functions mostly aim to avoid excessive headway between master and slave, which then translates into:

- **Indications on the relative distance between two VCTs.** This indication actually includes the current relative distance between the VCT in front, compared to the actual safe distance to be kept. The VCTS shall thus provide to an external entity (an automatic driving system) the information on how close to the VCT in front the local train can go.
- **Indications regarding the maximum achievable acceleration**, in order to maintain harmonised movements between two VCTs. This applies, for example, when a master train has higher acceleration capabilities than slaves. In order to avoid the master to separate too much from slaves when accelerating, indication of the maximum allowed acceleration shall be provided by the VCT to the driver (human or automatic system).
- **Indications regarding the maximum achievable deceleration**, especially applicable with trains with different deceleration capabilities. For example, trains as the master or the N-1 slaves (in a train with N slaves) shall be prevented to apply strong service brake decelerations if that level of effort is not available for all the following VCTs of the train.+
- **Other status indications,** like VCTS communication/activation status, health status of other trains, interventions notifications (i.e.: indication about the TCO, SB or EB ongoing due to VCTS intervention)

The VCTS shall limit to provide information to an external system more than implementing its own functionality to assist driving. The use of this information shall fall into the accountability of the external driving entity (either driver or any automatic system like Driver Assist system-DAS, cruising control, ATO, etc.) that will then use the indications to implement its driving strategy.

9.7.10 Auxiliary Vehicle Functions

Master trains in a VCTS shall be allowed to drive a set of additional controls on the slave trains, as in standard multiple trains.

- Pantograph management (raise/lower)
- Doors control
- Air tight control
- Air conditioning activation/deactivation/adjust
- Special brakes inhibition/activation (eddy current, magnetic shoe, regenerative, etc…)
- Main switch open/close
- Inhibit passenger's emergency brakes (in specific areas like tunnels, bridges, etc…)
- Traction system configuration (1.5kV DC, 3kV DC, 25 kV AC, etc…)
- CCTV
- Passenger's information system
- Boogie monitoring

An example is provided by the scenario in which a VCTS approaches a change of traction power, in which each train in the platoon shall carry out specific operations to cope with the new power feed available (i.e.: coasting/cutting traction, opening/closing of main switch, lowering/raising pantograph). Each train in the platoon shall individually drive its own vehicle functions at a specific location, according to the track layout.

Referring to a practical example of ERTMS system, ETCS packet 68 provides information to carborne ATPs about the position (beginning) of new traction power area, that is either notified to the driver or automatically managed by the ATP itself, that takes care of operating against vehicle interface to timely configure the traction prior to enter the area.

In a VCTS, the situation becomes more complex as actually all trains in the platoon shall be able to reconfigure traction in time prior to enter the new area, and so appropriate protocol of interaction master/slave shall be allowed. Especially:

- In static Virtual Coupling, the master shall be aware of relative distances, position of pantographs, etc. for each slave train coupled, and operate controls to drive each slave in taking proper actions on the vehicle interface at the right position
- In dynamic virtual coupling, each train in the platoon is aware of its relative position compared to the beginning of the catenary with new traction power, and will operate autonomously the relevant controls to configure the vehicle in advance

This aspect leads to an early consideration of the Virtual Coupling architecture: if the virtually coupled trains require a fully functional WLTB (wireless train backbone) for transmitting TCMS data then each trains behave like normal coupled trains from a TCMS point of view, creating one train. In that case the Functional Open Coupling mechanisms should be applied on top of the WLTB. If the virtually coupled trains are autonomous by themselves and no TCMS data is required then each train behave like independent trains from a TCMS point of view, and a platoon of trains is created.

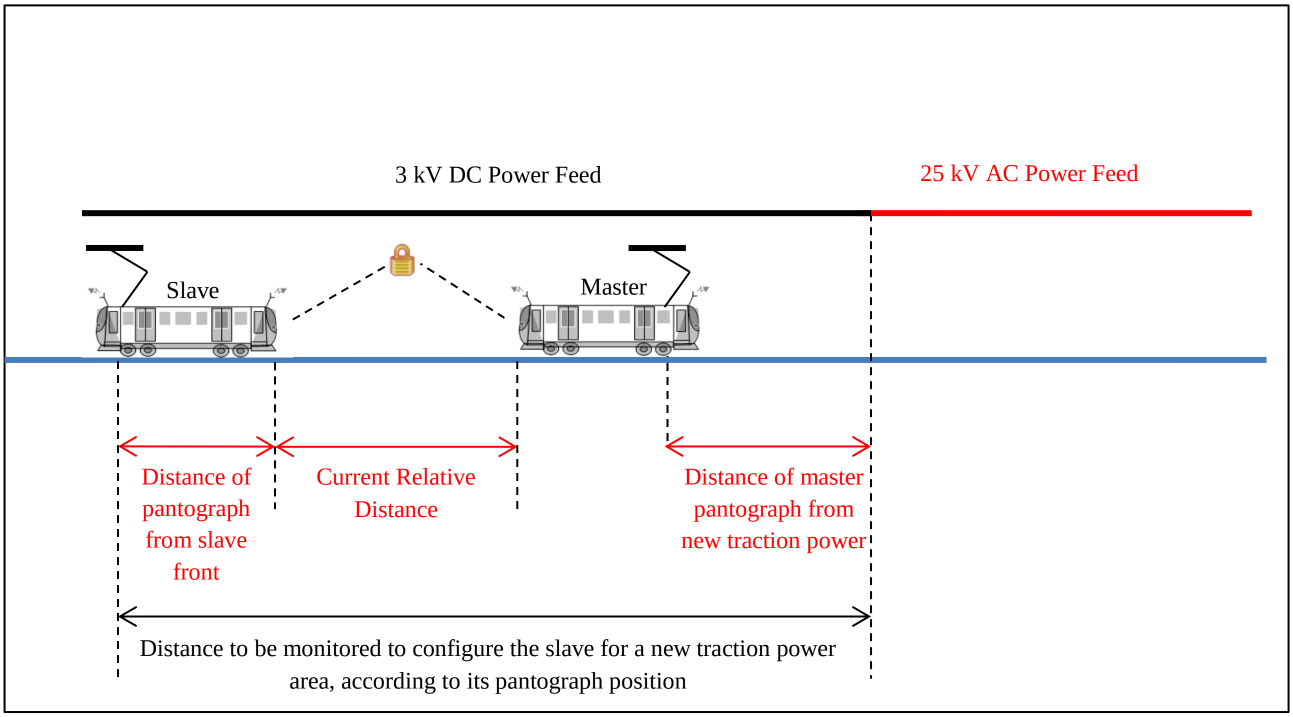

Figure 9-29: Management of Auxiliary Functions for Platoons

10 Future Work

10.1 Key Performance Indicators (KPI) for VCTS

Quantification of KPI will be provided to S2R cross cutting activities in order to determine a tangible, quantifiable indication of the advantages of VCTS. While some KPIs can be quantified for the scenarios mentioned above, the impact on other KPIs will be described textually in a qualitative manner. The main VCTS KPIs are capacity and Life-Cycle-Costing (LCC); the following KPIs have been identified as reasonable to describe the impact of a VCTS system on a railway system:

- **Capacity** (quantify)
    - No of trains (quantify like in TCMS project)
- **LCC** (Capital Expenditure (CapEx) + Operational Expenditure (OpEx))
    - Energy demand in Wh/passenger km (quantify)
    - Train and Infrastructure Equipment (textual description of delta compared to state of the art)
    - Expected impact on Availability, Reliability, Maintenance (textual description, quantification in specific cases) for train and infrastructure
- **Attractiveness** (textual)
    - Total journey time
    - Passenger waiting time
    - Passenger comfort
    - Standstill times during journey
    - Seamless travel
- **Flexibility** (textual)
    - Interoperability in terms of train combinations (textual explanation + specific example with quantification – see TCMS project)
    - New Opportunities (textual) - Lines / connections / point-to-point
    - Scheduling of coupled trains with stops at different stations (selective stopping)

10.2 Input from Other Workstreams

10.2.1 FINE-1 and IMPACT 4-1

This chapter will define and explain the S2R application scenarios that will be used to assess the VCTS potential. The application scenarios represent the context on which the VCTS is expected to be implemented. The scenarios are based on 4 System Platform Demonstrators (SPDs) as defined on the Shift2Rail Masterplan:

- SPD1 High Speed

- SPD2 Regional
- SPD3 Metro
- SPD4 Freight

These four scenarios are based on two sources inside Shift2Rail:

1. The public deliverable 3.1 – "Energy Baseline" [1] of the Shift2Rail CCA project FINE-1 (Future Improvement for Energy and Noise) defines the reference vehicles that should be used in Shift2Rail projects to assess improvements with respect to energy efficiency. Besides vehicles, the Energy Baseline defines typical service profiles as well. Here a service profile is the combination of timetable and track characteristics such as maximum speed, gradients and stations positions. The data available from FINE is thus sufficient to describe how a single train runs on lines without any restriction due to the signalling system. Within the WP6 and WP7 of the X2Rail-3 project, the train and track characteristics are taken from this energy baseline whenever data describing trains and their application scenarios are needed for exemplary calculations.
2. The deliverable 4.1 – "Reference Scenario" [2] of the CCA project IMPACT-1 (Indicator Monitoring for a new railway Paradigm in seamlessly integrated Cross modal Transport chains – Phase 1) adds additional information to the energy baseline from FINE-1 with special focus on operational scenarios. The tracks and vehicles used for the four SPDs in the IMPACT-1 are based respectively on the FINE-1 energy baselines "High Speed 300", "Regional 140", "Metro" and "Freight Mainline". In terms of operational scenarios, IMPACT-1 defines additional data relevant for the VCTS project such as line capacity, train protection system, track layout and track switches positions. In some cases also preliminary cases for (mechanical) coupling and decoupling of trainsets are described.

A summarized description of track and vehicle data is documented in Appendix A, for full details see FINE-1 D3.1 and IMPACT-1 D4.1. The tracks from FINE-1 D3.1 used for the SPD1, SPD2 and SPD3 are considered as flat tracks (without altitude profile or gradients). Only the track used in the SPD4 (freight mainline) provides a gradient profile, however, in IMPACT-1 D4.1 an altitude profile is presented as complementary information for the tracks of the SPDs 1 - 3. For the VCTS concept the data without altitude profile is used as a reference, as intended by these documents, but the consideration of the altitude profiles for SPD1 – 3 is kept as optional; if needed in the further VCTS development.

FINE-1 energy calculations use a backward simulation model, which means the controls and dynamics of the traction system are not defined because in this approach a train is assumed to deliver the required power instantly at the wheels. However, in VCTS the time delays of traction and brake components are crucial for the distance control; therefore additional data has to be defined to describe the dynamic behaviour of the trains in a platoon. Concerning the trains these are at least: a) the reaction times (first order delay) and b) the reaction delays (zero order delay) of traction equipment and brake systems.

In addition to the train characteristics, the VCTS system dynamics are related to other time-dependent characteristics, which depend on the equipment used for communication and sensing of position, speed and acceleration, for example:

- Communication delay probability distribution (as function of distance)
- Maximal range of relative positioning sensor (e.g. radar, LIDAR (Light Detection and Ranging), cameras)
- Update rate of relative positioning sensor (e.g. radar, LIDAR, cameras)
- Positioning error
- Relative positioning sensor error

Concerning the track and signalling infrastructure, further characteristics will have to be defined, for example the switching times of track switches, if trains in a platoon are joined or split using a track switch.

As the VCTS concept should be formulated in a generic way, missing data will be expressed as variable and its impact will be mathematically described in equations. However, numerical examples may be used based on the typical expected values of the variables in order to get tangible results.

Table 10-1 summarizes the operational parameters provided in IMPACT-1 D4.1 for the SPDs 1 to 4.

Table 10-1: SPDs Operational Parameters Overview

Parameter	**Unit**	**SPD1: High Speed**	**SPD2: Regional**	**SPD3: Metro**	**SPD4: Mainline Freight**
Timetable		yes	yes	yes	yes
Stopping time		yes	yes	yes	yes
Maximal couple units		2	3	no coupling	no coupling
Coupling time	min/coupling	2	2		
Theoretical capacity	trains/hour	11	10	12	
Theoretical track capacity	trains/hour	14	14	30	
Existing service	services/hour	6 for A 3 for A’	3 for A 3 for A’ 3 for A’’	12	
Current fleet	trains	24	37	24	
Current signaling[a]		LZB	PZB	LZB	PZB
Acceptable delay	min	5	5	3	
Punctuality	%	90	91	99	70

[a] Both track signalling systems (LZB - Linienzugbeeinflussung and PZB - Punktförmige Zugbeeinflussung) are based on fixed block paradigm. The LZB can in theory provide a shorter headway than the PZB.

Theoretical track capacity is here interpreted as the theoretically maximum capacity of a line operating with block trains, and the theoretical capacity is the theoretically maximum capacity of a line with block trains and taking additionally the amount of couplings and the time needed for coupling into account.

The scenarios of VCTS will be restricted to normal operation, therefore no delays or unpunctuality will be considered on this deliverable. More complex cases can be analysed in further works.

The timetable for SPDs 1 – 3 is presented in the operation table in IMPACT-1 D4.1. The required coupling time for the SPDs 1 and 2 is included in the IMPACT-1 standstill times at stations, thus the IMPACT-1 timetables are slightly different compared to FINE-1 timetables. The switching time in the junctions, however, are not included in coupling time and not defined in these documents.

Furthermore, the above mentioned timetable consider different types of trains in operation, and only trains of the same type (referred to as manufacturer - train type) and some specific combinations are allowed to couple mechanically.

As there are no coupling scenario defined for the SPDs 3 and 4, new scenarios must be created, and there might also be situations where tracks are shared between SPDs 1, 2 and 4.

The SPDs 1 and 2 are analysed in the following sections in details.

10.2.2 SPD1 – High Speed

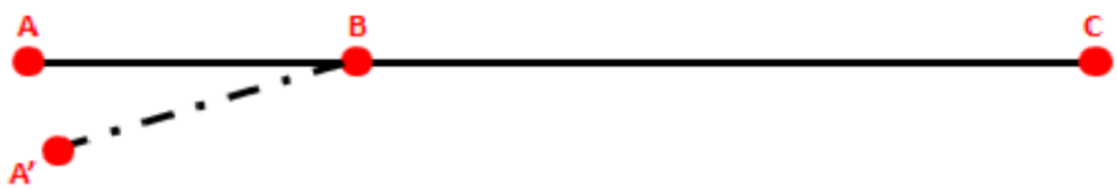

Figure 10-1: Track Layout for SPD1

Figure 10-1 presents the simplified track of the SPD1. The track is 300 km long, with a maximal speed of 250 km/h and 3 (three) stations, and the track is duplicated in identical ramification between stations B and A. The journey of the trains, including the coupling procedure is summarized below:

- Six trains depart per hour from A and three from A'
- At station B, every second train from A will couple mechanically with the train coming from A' and continue driving coupled to the station C
- Trains coming from A' will be merged into the main line from A-B in station B with the following procedure:
    - Train from A stops at coupling position at the platform, after passing the switch
    - Train from A' will merge in the main line using conventional switches and will couple with the train from A
    - The driver from A' steps out is available for a future B-A' service
    - At T=Tc+2min both trains start the passenger boarding
- Passengers cannot embark/disembark during the coupling operation, therefore the coupling time (2min) is added to the required stopping time
- All section (A – B, A' – B and B – C) are considered to be double-tracks, one for each direction
- Shortly before the terminals (stations A and C) there is a switch in order to change the track of the train. This can be done during the arrival or departure of the trains.

10.2.3 SPD2 – Regional Application

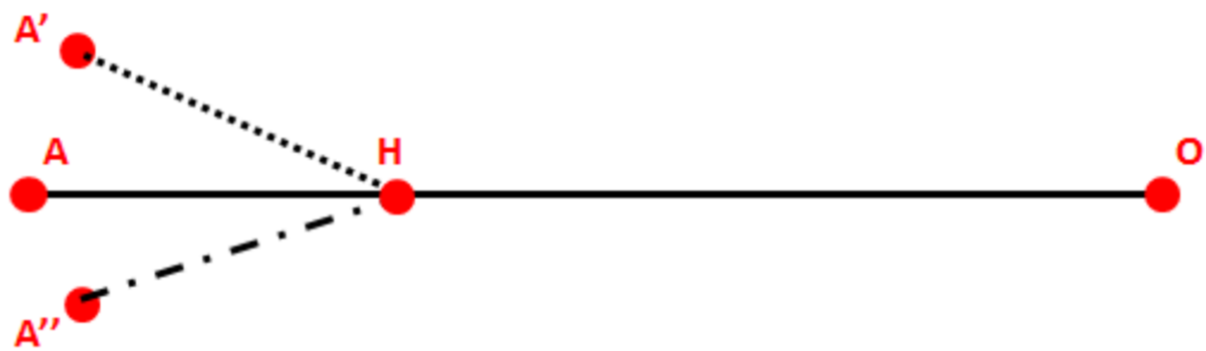

Figure 10-2: Track Layout for SPD2

Figure 10-2 presents the simplified track of the SPD2. The track is 70 km long, with a maximal speed of 140 km/h and 15 stations, and the track is triplicated in identical ramification between stations H and A. The image has been adapted from the original source to omit non-relevant stations. The journey of the trains, including the coupling procedure is summarized below:

- Three trains depart per hour simultaneously from A, A' and A''
- At station H, the trains should couple mechanically and continue driving coupled to the station O
- Trains coming from A' and A'' will be merged in the main in the station H using conventional switches with the following procedure:
  - Train from A stops at coupling position at the platform after passing the switch
  - Train from A' will merge in the main line using conventional switches and will couple with the train from A. The coupling process should take 2 minutes.
  - Train from A'' will merge in the main line using conventional switches and will couple with the coupled train A+A'. This coupling process should take another 2 minutes.
  - All three trains are coupled and start the passenger boarding
  - The driver from A' and A'' steps out is available for future services
- Passengers cannot embark/disembark during the coupling operation, therefore the coupling time (2min per coupling, 4 minutes in total) is added to the required stopping time
- All section (A – H, A' – H, A'' – H, H – K and K – O) are considered to be double-tracks, one for each direction
- Shortly before the terminals (stations A and O) there is a switch in order to change the track of the train. This can be done during the arrival or departure of the trains.

10.2.4 SPD3 – Metro Application

This scenario refers to a line equipped with LZB (signalling system in Germany). This specific application will be further detailed in the overall concept of functions and requirements of VCTS when the entire safety analysis (deliverable 6.2 of VCTS – WP6) will be completed, and so once the overall picture of requirements assigned to each VCTS subsystem is clear.

Especially, it is important to understand the list of safety requirements that shall be assigned to the wayside infrastructure in order to fulfil the overall VCTS concept, and thus to understand what limitations a LZB line provides with respect to a fully automated system ERTMS-like.

10.2.5 SPD4 – Freight Application

Same as for previous SPD3, this scenario includes the case a freight line with PZB. For this reason this scenario will be further developed once full visibility on the assignment of safety requirements to each subsystem will be available.

Appendix A: SPDs Track and Vehicle Overview

The speed profile and station locations of the tracks from the SPDs 1-4 are presented in the following figures.

Track Layouts

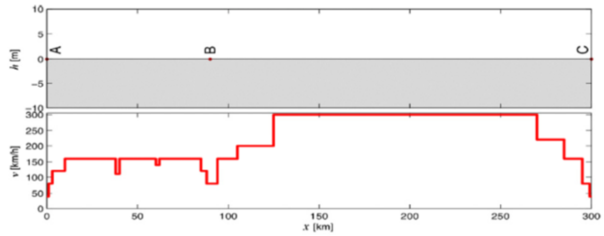

Figure 10-3: Maximal Speed and track layout for SPD1 – High speed Line

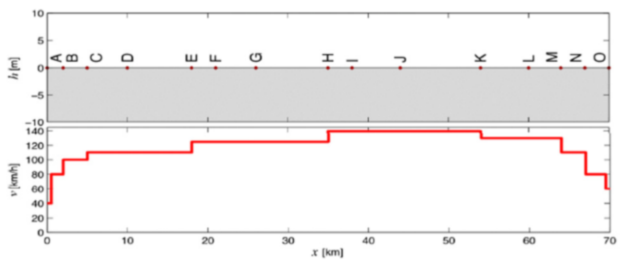

Figure 10-4: Maximal Speed and track layout for SPD2 - Regional Line

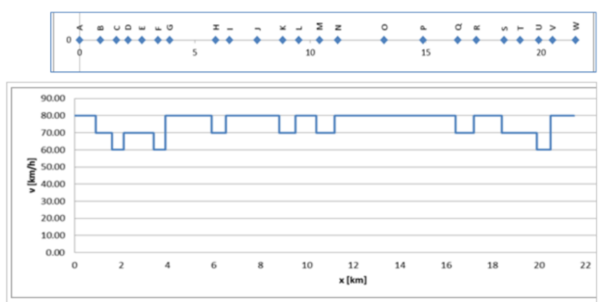

Figure 10-5: Maximal Speed and track layout for SPD3 - Metro Line

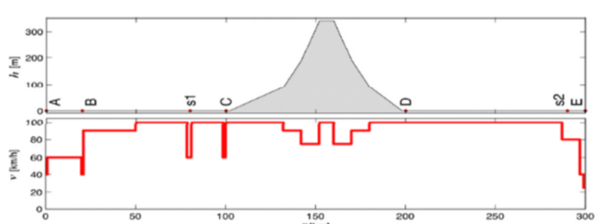

Figure 10-6: Maximal Speed and track layout for SPD4 - Freight Line

Vehicle characteristics

The main parameters of the SPD reference vehicles defined in FINE-1 are summarised in Table 10-2. For the underlying model of the train dynamics see the deliverable FINE-1 D3.1.

Table 10-2: SPDs Vehicle Parameters

Descriptive Parameter	Comments	Unit	SPD1: High Speed	SPD2: Regional	SPD3: Metro	SPD4: Mainline Freight
C0	Specific Rolling resistance	N	3070	1560	5133	24000
C1	Specific running resistance, constant term	N/(km/h)	43.75	16	6.768	256
C2	Absolute running resistance, quadratic term	N/ (km/h)²	0.55	0.4	0.3384	2.6
k0	Coefficient for calculation of resistance force	N	3070	1560	5133	24000
k1	Coefficient for calculation of resistance force	kg/s	157.5	57.6	24.3648	921.6
k2	Coefficient for calculation of resistance force	N/kg	0	0	0	0
k3	Coefficient for calculation of resistance force	1/s	0	0	0	0
k4	Coefficient for calculation of resistance force	kg/m	7.128	5.2	4.385664	33.696
k5	Coefficient for calculation of resistance force	1/m	0	0	0	0
m_tare	design mass in working order acc. to EN 15663	t	450	142	192	80
m_rot	rotating masses (% of m_tare)	%	4	5	13.5	4.2
n_seat	number of seats		460	230	186	0
n_pax	number of passengers (average load)		360	180	1000	0
m_pax	mass per pax	kg	75	75	75	0
m_payload	Waggon mass incl. payload for freight trains	t	0	0	0	1026
v_max	maximum velocity	km/h	330	140	90	120
d_wheel	wheel diameter	mm	1040	815	860	960
v_wind	head wind velocity	km/h	0	0	0	0
f_tunnel	Increase of aerodynamic resistance within tunnels	%	20	80	80	110
a	Coefficient for calculation of curve force				6	
b	Coefficient for calculation of curve force				0	
F_m_traction	Maximum traction force	kN	200	190	350	300
v_1_traction	Begin of maximum power hyperbola traction	km/h	155	55	40	66
v_2_traction	Begin of power reduction traction	km/h	250	160	80	120
F_m_edbrake	Maximum ED-brake force	kN	200	150	305	150
v_1_edbrake	Begin of maximum power hyperbola ED-Brake	km/h	155	73	80	62
v_2_edbrake	Begin of power reduction ED-Brake	km/h	250	160	90	120
F_m_totalbrake	Maximum total brake force	kN	250	150	333	240
v_1_totalbrake	Begin of maximum power hyperbola total brake	km/h	300	160	80	30
v_2_totalbrake	Begin of power reduction total brake	km/h	300	160	90	120
length	Train length	m	200	75	94	326

Timetables

The timetables for the SPDs 1 – 3 are presented in the following tables.

Table 10-3: Timetable SPD 1

Service	Manufacturer - train type	St A. Available	St A. Departure	St B. Arrival	St B. Departure	St C. Arrival	St C. Departure	St B. Arrival	St B. Departure	St A. Arrival	St A. Available
A-B-C-B-A	A	08:00:00	08:03:00	08:45:00	08:50:00	09:52:00	10:25:00	11:27:00	11:30:00	12:12:00	12:45:00
A'-B-C-B-A'	A	08:00:00	08:03:00	08:45:00	08:50:00	09:52:00	10:25:00	11:27:00	11:30:00	12:12:00	12:45:00
A-B-C-B-A	B	08:11:00	08:14:00	08:56:00	09:01:00	10:03:00	10:36:00	11:38:00	11:41:00	12:23:00	12:56:00
A-B-C-B-A	C	08:22:00	08:25:00	09:07:00	09:12:00	10:14:00	10:47:00	11:49:00	11:52:00	12:34:00	13:07:00
A'-B-C-B-A'	C	08:22:00	08:25:00	09:07:00	09:12:00	10:14:00	10:47:00	11:49:00	11:52:00	12:34:00	13:07:00
A-B-C-B-A	D	08:33:00	08:36:00	09:18:00	09:23:00	10:25:00	10:58:00	12:00:00	12:03:00	12:45:00	13:18:00
A-B-C-B-A	A	08:44:00	08:47:00	09:29:00	09:34:00	10:36:00	11:09:00	12:11:00	12:14:00	12:56:00	13:29:00
A'-B-C-B-A'	A	08:44:00	08:47:00	09:29:00	09:34:00	10:36:00	11:09:00	12:11:00	12:14:00	12:56:00	13:29:00
A-B-C-B-A	B	08:55:00	08:58:00	09:40:00	09:45:00	10:47:00	11:20:00	12:22:00	12:25:00	13:07:00	13:40:00
A-B-C-B-A	C	09:06:00	09:09:00	09:51:00	09:56:00	10:58:00	11:31:00	12:33:00	12:36:00	13:18:00	13:51:00
A'-B-C-B-A'	C	09:06:00	09:09:00	09:51:00	09:56:00	10:58:00	11:31:00	12:33:00	12:36:00	13:18:00	13:51:00
A-B-C-B-A	D	09:17:00	09:20:00	10:02:00	10:07:00	11:09:00	11:42:00	12:44:00	12:47:00	13:29:00	14:02:00
A-B-C-B-A	A	09:28:00	09:31:00	10:13:00	10:18:00	11:20:00	11:53:00	12:55:00	12:58:00	13:40:00	14:13:00
A'-B-C-B-A'	A	09:28:00	09:31:00	10:13:00	10:18:00	11:20:00	11:53:00	12:55:00	12:58:00	13:40:00	14:13:00
A-B-C-B-A	B	09:39:00	09:42:00	10:24:00	10:29:00	11:31:00	12:04:00	13:06:00	13:09:00	13:51:00	14:24:00
A-B-C-B-A	C	09:50:00	09:53:00	10:35:00	10:40:00	11:42:00	12:15:00	13:17:00	13:20:00	14:02:00	14:35:00
A'-B-C-B-A'	C	09:50:00	09:53:00	10:35:00	10:40:00	11:42:00	12:15:00	13:17:00	13:20:00	14:02:00	14:35:00
A-B-C-B-A	D	10:01:00	10:04:00	10:46:00	10:51:00	11:53:00	12:26:00	13:28:00	13:31:00	14:13:00	14:46:00
A-B-C-B-A	E	10:12:00	10:15:00	10:57:00	11:02:00	12:04:00	12:37:00	13:39:00	13:42:00	14:24:00	14:57:00
A'-B-C-B-A'	E	10:12:00	10:15:00	10:57:00	11:02:00	12:04:00	12:37:00	13:39:00	13:42:00	14:24:00	14:57:00
A-B-C-B-A	E	10:23:00	10:26:00	11:08:00	11:13:00	12:15:00	12:48:00	13:50:00	13:53:00	14:35:00	15:08:00
A-B-C-B-A	E	10:34:00	10:37:00	11:19:00	11:24:00	12:26:00	12:59:00	14:01:00	14:04:00	14:46:00	15:19:00
A'-B-C-B-A'	E	10:34:00	10:37:00	11:19:00	11:24:00	12:26:00	12:59:00	14:01:00	14:04:00	14:46:00	15:19:00
A-B-C-B-A	E	10:45:00	10:48:00	11:30:00	11:35:00	12:37:00	13:10:00	14:12:00	14:15:00	14:57:00	15:30:00
A-B-C-B-A	E	10:56:00	10:59:00	11:41:00	11:46:00	12:48:00	13:21:00	14:23:00	14:26:00	15:08:00	15:41:00
A'-B-C-B-A'	E	10:56:00	10:59:00	11:41:00	11:46:00	12:48:00	13:21:00	14:23:00	14:26:00	15:08:00	15:41:00
A-B-C-B-A	E	11:07:00	11:10:00	11:52:00	11:57:00	12:59:00	13:32:00	14:34:00	14:37:00	15:19:00	15:52:00
A-B-C-B-A	E	11:18:00	11:21:00	12:03:00	12:08:00	13:10:00	13:43:00	14:45:00	14:48:00	15:30:00	16:03:00
A'-B-C-B-A'	E	11:18:00	11:21:00	12:03:00	12:08:00	13:10:00	13:43:00	14:45:00	14:48:00	15:30:00	16:03:00
A-B-C-B-A	E	11:29:00	11:32:00	12:14:00	12:19:00	13:21:00	13:54:00	14:56:00	14:59:00	15:41:00	16:14:00
A-B-C-B-A	E	11:40:00	11:43:00	12:25:00	12:30:00	13:32:00	14:05:00	15:07:00	15:10:00	15:52:00	16:25:00
A'-B-C-B-A'	E	11:40:00	11:43:00	12:25:00	12:30:00	13:32:00	14:05:00	15:07:00	15:10:00	15:52:00	16:25:00
A-B-C-B-A	E	11:51:00	11:54:00	12:36:00	12:41:00	13:43:00	14:16:00	15:18:00	15:21:00	16:03:00	16:36:00
A-B-C-B-A	E	12:02:00	12:05:00	12:47:00	12:52:00	13:54:00	14:27:00	15:29:00	15:32:00	16:14:00	16:47:00
A'-B-C-B-A'	E	12:02:00	12:05:00	12:47:00	12:52:00	13:54:00	14:27:00	15:29:00	15:32:00	16:14:00	16:47:00
A-B-C-B-A	E	12:13:00	12:16:00	12:58:00	13:03:00	14:05:00	14:38:00	15:40:00	15:43:00	16:25:00	16:58:00
A-B-C-B-A	E	12:24:00	12:27:00	13:09:00	13:14:00	14:16:00	14:49:00	15:51:00	15:54:00	16:36:00	17:09:00
A'-B-C-B-A'	E	12:24:00	12:27:00	13:09:00	13:14:00	14:16:00	14:49:00	15:51:00	15:54:00	16:36:00	17:09:00
A-B-C-B-A	E	12:35:00	12:38:00	13:20:00	13:25:00	14:27:00	15:00:00	16:02:00	16:05:00	16:47:00	17:20:00

Table 10-4: Timetable SPD 2

Service	Manufacturer - train type	St A. Available	St A. Departure	St H. Arrival	St H. Departure	St K. Arrival	St K. Departure	St O. Arrival	St O. Departure	St K. Arrival	St K. Departure	St H. Arrival	St H. Departure	St A. Arrival	St A. Available
A-H-K-O-K-H-A	A	08:00:00	08:02:00	08:36:25	08:42:25	08:56:50	09:00:50	09:17:00	09:34:00	09:50:10	09:52:10	10:08:35	0.424016	10:49:00	11:06:00
A'-H-K-O-K-H-A'	A	08:00:00	08:02:00	08:36:25	08:42:25	08:56:50	09:00:50	09:17:00	09:34:00	09:50:10	09:52:10	10:08:35	10:10:35	10:49:00	11:06:00
A''-H-K-O-K-H-A''	A	08:00:00	08:02:00	08:36:25	08:42:25	08:56:50	09:00:50	09:17:00	09:34:00	09:50:10	09:52:10	10:08:35	10:10:35	10:49:00	11:06:00
A-H-K-O-K-H-A	B	08:19:30	08:21:30	08:55:55	09:01:55	09:16:20	09:20:20	09:36:30	09:53:30	10:09:40	10:11:40	10:28:05	10:30:05	11:08:30	11:25:30
A'-H-K-O-K-H-A'	B	08:39:00	08:41:00	09:15:25	09:21:25	09:35:50	09:39:50	09:56:00	10:13:00	10:29:10	10:31:10	10:47:35	10:49:35	11:28:00	11:45:00
A''-H-K-O-K-H-A''	B	08:58:30	09:00:30	09:34:55	09:40:55	09:55:20	09:59:20	10:15:30	10:32:30	10:48:40	10:50:40	11:07:05	11:09:05	11:47:30	12:04:30
A-H-K-O-K-H-A	C	08:39:00	08:41:00	09:15:25	09:21:25	09:35:50	09:39:50	09:56:00	10:13:00	10:29:10	10:31:10	10:47:35	10:49:35	11:28:00	11:45:00
A'-H-K-O-K-H-A'	C	08:58:30	09:00:30	09:34:55	09:40:55	09:55:20	09:59:20	10:15:30	10:32:30	10:48:40	10:50:40	11:07:05	11:09:05	11:47:30	12:04:30
A''-H-K-O-K-H-A''	C	09:18:00	09:20:00	09:54:25	10:00:25	10:14:50	10:18:50	10:35:00	10:52:00	11:08:10	11:10:10	11:26:35	11:28:35	12:07:00	12:24:00
A-H-K-O-K-H-A	D	08:58:30	09:00:30	09:34:55	09:40:55	09:55:20	09:59:20	10:15:30	10:32:30	10:48:40	10:50:40	11:07:05	11:09:05	11:47:30	12:04:30
A'-H-K-O-K-H-A'	D	09:18:00	09:20:00	09:54:25	10:00:25	10:14:50	10:18:50	10:35:00	10:52:00	11:08:10	11:10:10	11:26:35	11:28:35	12:07:00	12:24:00
A''-H-K-O-K-H-A''	D	09:37:30	09:39:30	10:13:55	10:19:55	10:34:20	10:38:20	10:54:30	11:11:30	11:27:40	11:29:40	11:46:05	11:48:05	12:26:30	12:43:30
A-H-K-O-K-H-A	A	09:18:00	09:20:00	09:54:25	10:00:25	10:14:50	10:18:50	10:35:00	10:52:00	11:08:10	11:10:10	11:26:35	11:28:35	12:07:00	12:24:00
A'-H-K-O-K-H-A'	A	09:37:30	09:39:30	10:13:55	10:19:55	10:34:20	10:38:20	10:54:30	11:11:30	11:27:40	11:29:40	11:46:05	11:48:05	12:26:30	12:43:30
A''-H-K-O-K-H-A''	A	09:57:00	09:59:00	10:33:25	10:39:25	10:53:50	10:57:50	11:14:00	11:31:00	11:47:10	11:49:10	12:05:35	12:07:35	12:46:00	13:03:00
A-H-K-O-K-H-A	B	09:37:30	09:39:30	10:13:55	10:19:55	10:34:20	10:38:20	10:54:30	11:11:30	11:27:40	11:29:40	11:46:05	11:48:05	12:26:30	12:43:30
A'-H-K-O-K-H-A'	B	09:57:00	09:59:00	10:33:25	10:39:25	10:53:50	10:57:50	11:14:00	11:31:00	11:47:10	11:49:10	12:05:35	12:07:35	12:46:00	13:03:00
A''-H-K-O-K-H-A''	B	10:16:30	10:18:30	10:52:55	10:58:55	11:13:20	11:17:20	11:33:30	11:50:30	12:06:40	12:08:40	12:25:05	12:27:05	13:05:30	13:22:30
A-H-K-O-K-H-A	E	09:57:00	09:59:00	10:33:25	10:39:25	10:53:50	10:57:50	11:14:00	11:31:00	11:47:10	11:49:10	12:05:35	12:07:35	12:46:00	13:03:00
A'-H-K-O-K-H-A'	E	10:16:30	10:18:30	10:52:55	10:58:55	11:13:20	11:17:20	11:33:30	11:50:30	12:06:40	12:08:40	12:25:05	12:27:05	13:05:30	13:22:30
A''-H-K-O-K-H-A''	E	10:36:00	10:38:00	11:12:25	11:18:25	11:32:50	11:36:50	11:53:00	12:10:00	12:26:10	12:28:10	12:44:35	12:46:35	13:25:00	13:42:00
A-H-K-O-K-H-A	E	10:16:30	10:18:30	10:52:55	10:58:55	11:13:20	11:17:20	11:33:30	11:50:30	12:06:40	12:08:40	12:25:05	12:27:05	13:05:30	13:22:30
A'-H-K-O-K-H-A'	E	10:36:00	10:38:00	11:12:25	11:18:25	11:32:50	11:36:50	11:53:00	12:10:00	12:26:10	12:28:10	12:44:35	12:46:35	13:25:00	13:42:00
A''-H-K-O-K-H-A''	E	10:55:30	10:57:30	11:31:55	11:37:55	11:52:20	11:56:20	12:12:30	12:29:30	12:45:40	12:47:40	13:04:05	13:06:05	13:44:30	14:01:30
A-H-K-O-K-H-A	E	10:36:00	10:38:00	11:12:25	11:18:25	11:32:50	11:36:50	11:53:00	12:10:00	12:26:10	12:28:10	12:44:35	12:46:35	13:25:00	13:42:00
A'-H-K-O-K-H-A'	E	10:55:30	10:57:30	11:31:55	11:37:55	11:52:20	11:56:20	12:12:30	12:29:30	12:45:40	12:47:40	13:04:05	13:06:05	13:44:30	14:01:30
A''-H-K-O-K-H-A''	E	11:15:00	11:17:00	11:51:25	11:57:25	12:11:50	12:15:50	12:32:00	12:49:00	13:05:10	13:07:10	13:23:35	13:25:35	14:04:00	14:21:00
A-H-K-O-K-H-A	E	10:55:30	10:57:30	11:31:55	11:37:55	11:52:20	11:56:20	12:12:30	12:29:30	12:45:40	12:47:40	13:04:05	13:06:05	13:44:30	14:01:30
A'-H-K-O-K-H-A'	E	11:15:00	11:17:00	11:51:25	11:57:25	12:11:50	12:15:50	12:32:00	12:49:00	13:05:10	13:07:10	13:23:35	13:25:35	14:04:00	14:21:00
A''-H-K-O-K-H-A''	E	11:34:30	11:36:30	12:10:55	12:16:55	12:31:20	12:35:20	12:51:30	13:08:30	13:24:40	13:26:40	13:43:05	13:45:05	14:23:30	

Table 10-5: Timetable SPD 3

Station	Distance	Speed limit	Stop (min:sec)
(km)	(km/h)		
Station A	-	80	00:00
Station B	0,900	70	00:30
Station C	1,600	60	00:30
Station D	2,100	70	00:30
Station E	2,700	70	00:30
Station F	3,400	60	00:30
Station G	3,900	80	00:30
Station H	5,900	70	00:30
Station I	6,500	80	00:30
Station J	7,700	80	00:30
Station K	8,800	70	00:30
Station L	9,500	80	00:30
Station M	10,400	70	00:30
Station N	11,200	80	00:30
Station O	13,200	80	00:30
Station P	14,900	80	00:30
Station Q	16,400	70	00:30
Station R	17,200	80	00:30
Station S	18,400	70	00:30
Station T	19,100	70	00:30
Station U	19,900	60	00:30
Station V	20,500	80	00:30
Station W	21,500	80	00:00