10 Concept and Performance Analysis of Virtual Coupling for Railway Vehicles

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10.1 Introduction

Today's operational principles for train headway are based on absolute braking distance (ABD) for collision protection. These train protection systems rely on trackside information and mostly utilize train-to-ground (T2G) communication. The most common national and international systems which are currently applied and in development are fixed and moving blocks [1]:

- Fixed blocks (European Train Control System (ETCS) Level 1 and 2 and most national signalling systems): A track is divided into sections, called blocks, which can only be occupied by one train at the same time. The succeeding train has a maximum movement authority up to the beginning of the next occupied block where it must be able to stop, irrespectively of the position of the train that is currently occupying that section.
- Moving blocks (e.g. ETCS Level 3): The end of authority is directly associated to the rear end of the front train, which allows for shorter headways than in fixed blocks. Each train determines its safe rear end with on-board train integrity and positioning equipment.

Due to the limitation of ABD, the system reaches a state, where it becomes increasingly more complex and less robust to add additional services to the schedule in order to increase the capacity and cover a growing demand in railway transportation. Infrastructural measures can provide additional capacity but are often costly and limited by the available space. Another option to operatively increase capacity in a network is to join trains on a common stretch. This Joining trains is currently enabled through mechanical coupling (MC), which causes additional standstill times during coupling and decoupling and, creatinges a sensitive rendezvous within the timetable, possiblye disrupting operation when one of the trains is delayed. Furthermore, compatibility is a known issue, since many manufacturers utilize different standards.

Virtual coupling combines the best of both approaches, shortening the headway between trains and coupling them to a single train set, by going one step beyond current train protection systems and at the same time avoiding the disadvantages of an MC. The headway between trains is aimed to be further decreased by considering the dynamics of both trains and changing the paradigm to a relative braking distance (RBD) instead of ABD. For this, a fast and secure communication link between trains is required, which can be established with a direct train-to-train (T2T) communication, avoiding a centralized system and reducing delays. A reliable T2T communication together with accurate on-board sensors is the basis of the virtual coupling system. A concept of virtually coupled train sets (VCTS) is developed and analysed in work packages 6 and 7 of X2Rail-3 (Grant Agreement No. 826141[2]), a Horizon 2020 project of the Shift2Rail (S2R) Joint Undertaking, for "Advanced Signalling, Automation and Communication

System". The first results of the concept as well as a preliminary performance analysis are presented hereafter.

10.2 Goals of Virtual Coupling

The main goals VCTS aims to achieve can be summarized as [2]:

- Increasing line capacity by reducing the headway
- Increasing operational flexibility by ensuring interoperability between all railway vehicles
- Improving the use of the existing platforms by utilization of several platform tracks
- Reducing costs by:
    - Utilizing on-board equipment and electronic systems instead of building new tracks or applying major infrastructural changes
    - Reducing maintenance cost in relation to the best use of the line and platforms

Hereby, VCTS tries to take railway operation to the next level, while at the same time keeping the necessary modifications small and cost-efficient. These goals funnel into the overall aim of S2R to increase the competitiveness of the railway with respect to other transportation means.

10.3 The Concept of Virtual Coupling

The concept of virtual coupling is based on the paradigm change called "Breaking the braking wall" [1], which refers to the shift from train protection based on the ABD to an RBD principle. Metaphorically, this wall represents the maximum End-of-Authority, which follows the rear end of the leading train. End-of-Authority is the point where a succeeding train has to be able to stop in any case in an ABD-based system. ABD systems assume that, in the worst case, a train may stop instantaneously, which is justified by the lack of information of the braking capabilities and status of the other trains. By virtually coupling two or more trains of any train type, trains can communicate their braking capabilities and positions in real time, enabling a cooperative movement. The figurative wall can then be removed and the trains can drive closer together at RBD (see Figure 10-1).

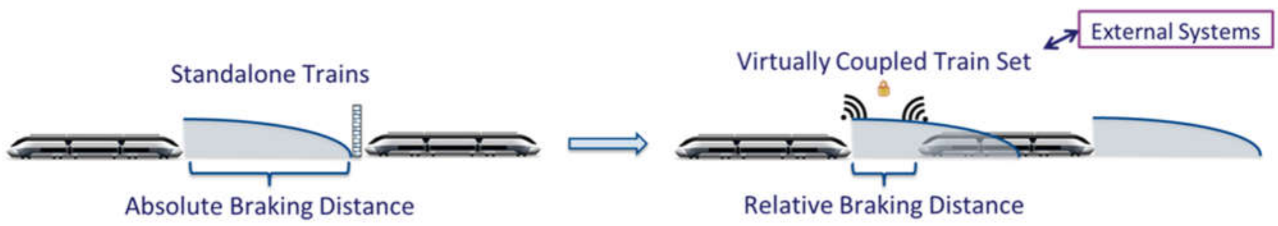

Figure 10-1: Paradigm change "Breaking the braking wall": From absolute to relative braking distance [3] (train graphic by DLR, NGT Project)

Today, when coupling trains mechanically, the distance between them is fixed, and forces are transmitted by the physical link, naturally preventing collision. Additionally, the physical link enables data transfer and a connection of the brake pipes for synchronised braking. The VCTS concept transfers the functions of the mechanical link to an electronic, wireless link. With this concept, fast coupling and decoupling are enabled, even including efficient on-the-fly manoeuvres while driving. Due to the missing mechanical link, the trains inside the platoon may have different dynamic states at any time. Thus, the challenge of virtual coupling is to ensure a safe distance between trains while allowing them to drive closer together than ABD. Therefore, some new elements are required:

- For data transfer, a direct **T2T-communication** needs to be established. It needs to provide a continuous, reliable and safe exchange of critically relevant information such as the current train dynamics, trajectories and braking capabilities. Using different communication technologies for different ranges, this T2T-link is the basis of cooperative platoon movement. Additionally, a VCTS still needs T2G-communication with external systems (e.g. traffic management, signalling).
- The trains forming the platoon need to be aware of themselves and of their environment at all times. Thus, in addition to the odometry system with its estimation of the absolute status for each train, real-time distance, relative speed and relative acceleration between the trains needs to be supervised through **on-board sensors**. Together with the supervision of the absolute state (including braking and acceleration capabilities and weight of train and current track conditions, if available), these values are also exchanged via the T2T-link. These sensors can also ensure safe operation and fast reactions in case the T2T communication fails or is delayed.
- Finally, the actual **distance control** needs to be safely executed on each train. For this, an interface of the VCTS system with traction/braking control units is required.

These three on-board components are the basis for the VCTS **platoon management**. The VCTS concept is aimed to be widely applicable and thus mostly independent from the underlying signalling system. This is possible, as the main components enabling the concept are implemented on-board. To the external systems, a VCTS is then seen as one single train that follows the rules of the underlying signalling system. The distance management below ABD within the platoon is controlled by the on-board VCTS system without interference from the trackside system. Thus, the ABD paradigm is not explicitly violated, which would require a more fundamental change of the signalling system. However, it is necessary to provide additional information (such as current VCTS length, status and number of coupled trains) to the existing trackside system and adjust the corresponding train protection and interlocking functionalities to ensure safe operation with a variable train length and gaps within the VCTS.

10.3.1 Functional Layer Architecture and Main Functions

The elements and interfaces of the VCTS system introduced above provide various functionalities within the VCTS concept. These functionalities can be grouped into different classes. In the proposed concept, these classes are organized in a vertical layer structure, presenting distinct levels of abstraction: from a macroscopic view of the whole railway network down to the microscopic movements of single trains. Four functional layers and their interfaces are defined in X2Rail-3 D6.1 [1], as shown in Figure 10-2.

- **Services**: The top level is in charge of managing service requests and serves as an integrated mobility-as-a-service platform. It provides external interfaces to the users, e.g. individuals accessing the booking systems or platforms for other modes of transportation.

- **Strategic**: Upon service requests, this layer defines the composition, ordering and de-/coupling instructions for a potential VCTS, based on compatibility, destinations and schedules. This layer can provide functionalities to maximise capacity in terms of traffic management by planning and supervising traffic flow, identifying and reacting to conflicts and delays. It furthermore provides feedback to the services layer.

- **Tactical**: On this layer, the actual platoon movements and manoeuvres such as coupling and decoupling are coordinated. It is meant to execute the strategy from the layer above via T2T communication and provides feedback with the current status of a platoon. Unexpected events and degraded modes need to be accounted for within the tactical layer by prearranged, safe procedures. Based on the underlying signalling system, the tactical layer is responsible for defining the speed and acceleration targets and the headway between trains. Here, the coupled operation and connected manoeuvres can be optimised with respect to energy or time consumption.

- **Operational**: The lowest layer, implemented on each vehicle, is in charge of the local control of each unit and has to ensure the safe execution of the commands from the tactical layer. Hereby, the headway is controlled based on target values and safety-limits, while at the same time supervising the stability of the platoon. The safety-critical functions of VCTS on the train level are allocated on this layer.

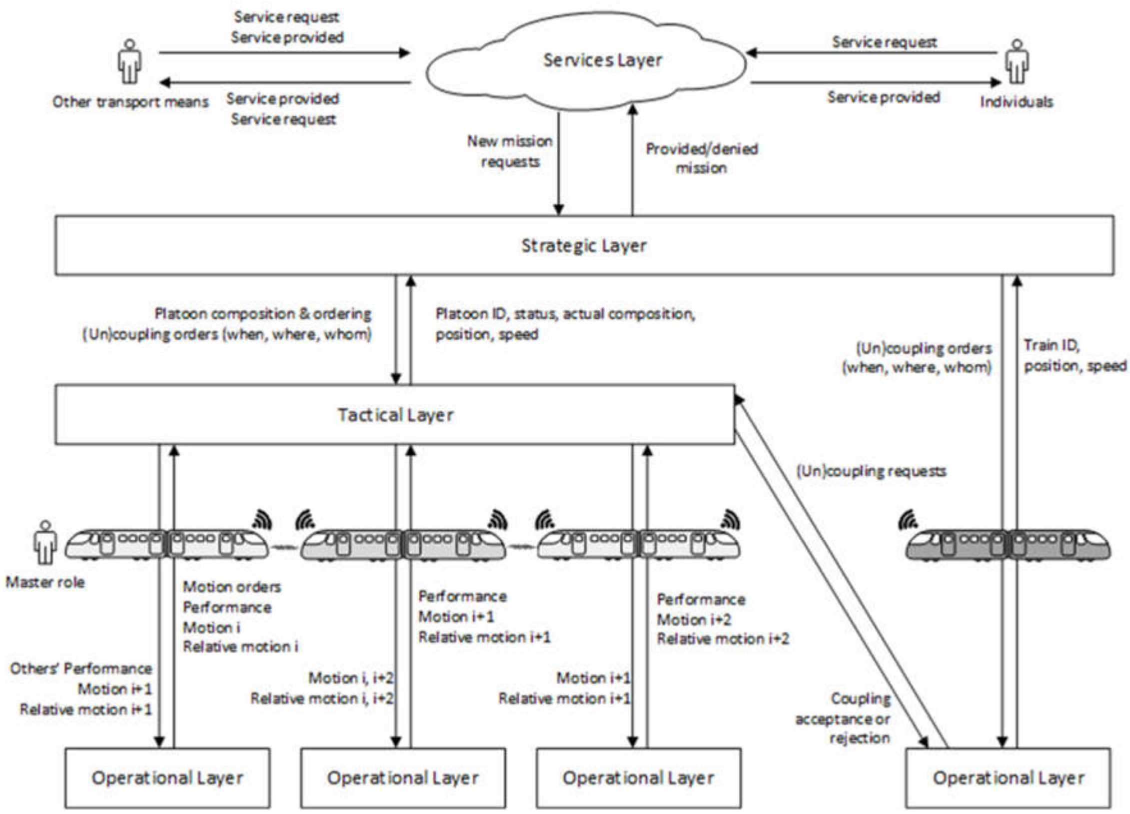

Figure 10-2: VCTS and functional layers [1]

Work packages 6 and 7 of X2Rail-3 are focussed on the operational and tactical layer and interfaces to the strategic layer (highlighted by the dotted box in the Figure 10-2). This is where the main elements of VCTS, as introduced above, are allocated. This part of the functional layer architecture is responsible for five main functions, as shown in Figure 10-3: Protection against collision inside the platoon, VC set-up, coupled driving, VC termination and interaction with external systems. The implementation of these functions is described in the next section.

10.3.2 VCTS Two-Stage Implementation Approach

The VCTS system requires some fundamental changes in railway operation. In order to facilitate the implementation of the concept into existing operation, a stepwise implementation of VCTS functions with increasing complexity is targeted. [4]. Thus, the goal is to provide a VCTS solution that is widely compatible and allows for a near-term introduction with the utilization of two stages. The implementation of the main functions within these two stages is illustrated in Figure 10-3.

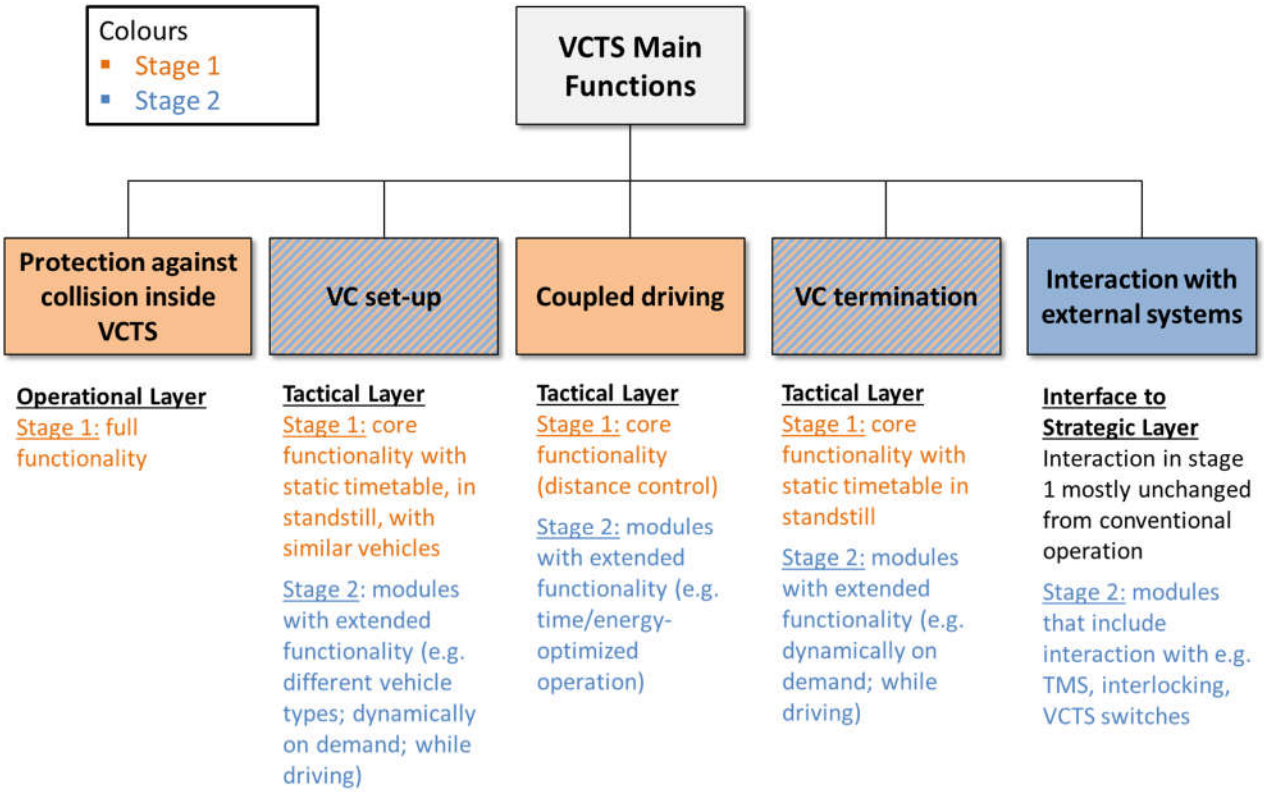

Figure 10-3: The allocation of the five main VCTS functions in the two-stage implementation approach. [4]

- Stage 1: The first step is a minimum-complexity implementation of the core functionality of VCTS. It builds on the established procedure of MC executed in standstill according to the timetable, but with significantly reduced de-/coupling times due to the removal of the mechanical link. This mainly includes the implementation of the safety-critical function to protect the units inside the platoon from collision (full operational layer) and a first, simple distance control during coupled driving with similar vehicles (tactical layer). The interaction with external systems remains similar to a mechanically coupled train (through the lead unit), now including a variable length train set length and gaps in between VCTS units.

- Stage 2: Here, the goal is to provide smaller modules with additional functionalities to the VCTS core that can be added simultaneously or successively. They aim to further utilize the advantages of VCTS with smooth and efficient operation. While the operational layer was fully introduced in stage 1, this concerns the extension of tactical layer and the interfaces with the strategic layer. On-the-fly coupling and decoupling manoeuvres can be introduced as well as calling with one VCTS at multiple platforms, i.e. splitting a long VCTS before a station to stop at different platforms and re-joining the trains behind the station. Furthermore, optimisation of the platoon tactics and additional interactions with external systems can be implemented.

10.4 Performance Analysis

Based on the concept introduced in the previous chapter, a first analysis of the possible VCTS performance was conducted. Following the goals described in the beginning, the VCTS concept has the potential to improve rail operations by combining benefits that usually contradict each other: **Capacity, flexibility and robustness**. The replacement of MC and the reduction of headway in general cannot only lead to a higher network throughput, they also open up possibilities for a more flexible and robust operation. Coupling compatibility issues can be resolved, sensitive MC rendezvous are avoided and some of the capacity gains can also be traded for additional robustness. Additionally, VCTS provides the ability to dynamically arrange and dissolve platoons based on real-time information for more flexibility.

While flexibility and robustness are crucial advantages, in the first analysis, we focussed on a preliminary quantification of capacity gains, since capacity is one of the main S2R key performance indicators (KPIs). Various studies of the IMPACT scenarios [5] for high-speed and regional operation showed that a VCTS Stage 1 implementation (replacing MC), considering only reduced coupling and decoupling times, can lead up to a doubling of the capacity [6]. The exact capacity gains depend on the underlying signalling system, with most cases yielding approximately 10 - 50% improvements compared to MC [6]. However, even more important for capacity improvements than reduced de-/coupling times is the paradigm shift from ABD to RBD as introduced in the previous chapter. In order to quantify possible improvements compared to operation with an ABD protection system, RBD is analysed hereafter.

In general, RBD is the required distance between trains that guarantees safe braking to standstill. In an ideal world without any delays and perfect precision in both measurements and control, the RBD would be zero. In this theoretical case, when both trains travel at the same speed, they could follow the same braking curve and thus never change the distance between them. However, in reality, there are multiple factors of influence that cause deviation from this ideal behaviour and require additional safety margins in the RBD. This can be latencies in communication and control, imprecision in speed and distance measurement, differences in braking capabilities, built-up times or speed levels, etc. For three specific, isolated factors, this behaviour is demonstrated in the following:

- **Reaction delay (RD)**: Δt_{RD} is the elapsed time between brake application of two trains, regardless of the reason for the delay. It may be caused by communication latency, brake build-up time or any other reason that delays brake force application of the rear train. If only this RD is considered, the rear train will travel at initial speed v_0 for Δt_{RD} seconds after the front train started braking and then follow the same braking curve. The required safety margin in the RBD due to this factor is:

$$RBD_{RD} = \Delta t_{RD} \cdot v_0$$

- **Position inaccuracy (PI)**: $\Delta s_{\mathrm{inacc}}$ is the difference between the assumed position of a train (measured or estimated) and its actual position due to the inaccuracy in the determination method. This implies when the front train brakes, it might be closer to the rear train than measurement suggests. The inaccuracy applies for both trains, therefore, the necessary margin covering the worst case results to:

$$RBD_{\mathrm{PI}} = 2 \cdot \Delta s_{\mathrm{inacc}}$$

- **Speed inaccuracy (SI)**: $\Delta v_{\mathrm{inacc}}$ is the difference between the measured speed of a train and its actual speed due to the inaccuracy in the speed determination method. In the worst case, when the front train brakes, it might be slower than measured, while the rear train might be faster. Considering a common brake deceleration of a_brake, the margin is:

$$RBD_{\mathrm{SI}} = 2 \cdot \Delta v_{\mathrm{inacc}} \cdot \frac{v_0}{a_{\mathrm{brake}}}$$

When these effects are combined, they result in a joint headway. This value does not correspond to the pure sum of the margins above, as e.g. SI and RD interact with each other. An algorithm was set up to calculate the RBD, considering RD, PI, SI, different speed levels and braking capabilities. The RBD was determined for the four railway scenarios defined in Table 10-1, considering an additional safety margin of 15%, and compared to the ABD for the same application. The results of this comparison are depicted in Figure 10-4. It is evident that there is a significant reduction in distance. Depending on the scenario the values range from -64 to -81%, which yields an indication for the potential capacity improvements by headway reduction with the paradigm shift from ABD to RBD.

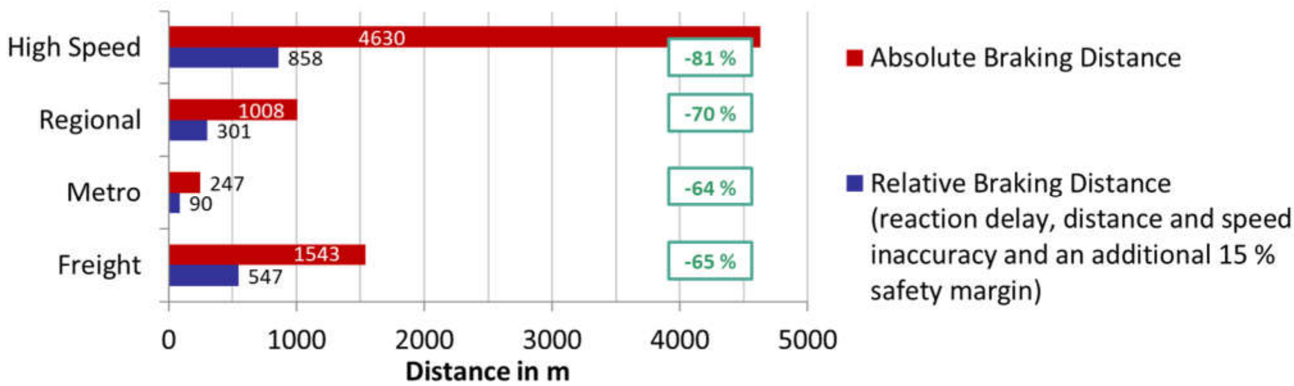

Figure 10-4: Comparison between ABD and RBD for four different railway scenarios [3].

Table 10-1: Railway scenarios based on IMPACT reference cases [5] and additional assumptions.

Service [5]	a in m/s²	v_0 in km/h [5]	Δt_{RD} in s	Δs_{inacc} in m	Δv_{inacc} in km/h [7]
High Speed	-0.75	300	3	20	7.7
Regional	-0.75	140	3	15	4.3
Metro	-1.00	80	1.5	10	3.1
Freight	-0.25	100	8	15	3.5

10.5 Outlook: Development and Migration Roadmap

Together with the preliminary safety analysis in [6], the performance analysis showed that the VCTS has the potential to heavily increase railway network capacity in a safe way. Therefore, a subsequent feasibility analysis was conducted [4]. Here, critical aspects in the VCTS implementation concerning the technological and operational subsystems were identified. The most notable are:

- Precise and safe supervision and exchange of the distance, relative speed and relative acceleration between virtually coupled units,
- variably controllable brakes with fast and precise system response,
- availability of suitable T2T-communication technologies and the respective frequencies and
- reliable supervision of the integrity of each train within the platoon and the platoon length (length of the virtually coupled trains and the current distance between them).

For these aspects, mitigation measures were identified together with S2R experts from the respective domains. For all of the abovementioned points, ongoing developments in other S2R-projects or the industry were identified to provide suitable technologies and systems in the near future [4]. And although additional general, non-technological obstacles exist, such as locked-in effects, these obstacles were not identified as showstoppers. With the demonstration of feasibility, an introduction strategy was developed, proposing the next steps in VCTS implementation [4]. These steps are summarized in a qualitative roadmap in Figure 10-5.

The proposed next steps are grouped into three main categories: Development (I), testing (II) and roll-out (III). This includes the next tasks in the X2Rail-3 project in terms of system requirements specification as well as potential successor projects with the aim of a demonstrator to prove the concept, ultimately leading to a roll-out facilitated by the two-stage approach described in the concept above.

10.6 Conclusions

It can be concluded that VCTS developed in X2Rail-3 provides a concept to increase capacity, flexibility and robustness of a railway network avoiding infrastructural changes by focussing on on-board equipment and operational tactics. VCTS enables decreased headway and coupling times, efficient and dynamic manoeuvres and interoperability by coupling compatibility between any train types. A safe realisation of this concept is possible with the right system design and control mechanisms [6]. Furthermore, the VCTS system is not tailored to a single signalling system, enabling multiple different application cases and avoiding additional barriers in railway operation. In conclusion, VCTS presents a concept to contribute to an increased competitiveness with respect to the road transportation by enabling more efficient freight and passenger transportation over the railway network.

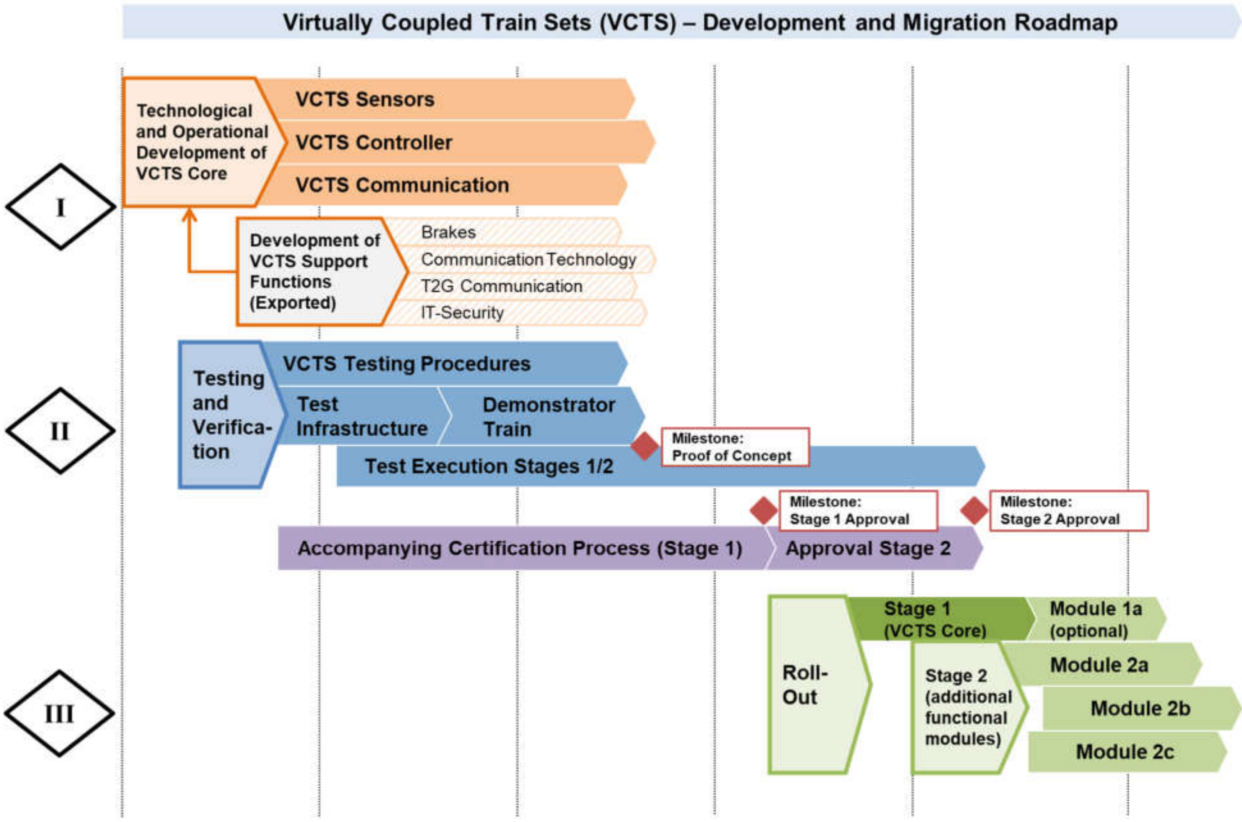

Figure 10-5: Further steps in the VCTS development as a qualitative migration roadmap [4].

10.7 Acknowledgements

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