Virtually Coupled Train Sets - A Comprehensive Analysis

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Abstract

In the X2Rail-3 project of the Shift2Rail Joint Undertaking, a detailed virtual coupling concept is developed and analysed in an extensive theoretical framework. Based on the paradigm shift from absolute to relative braking distance, various operational scenarios and potential hazards are identified. According to these scenarios and the general functional architecture, the project provides a first definition of the system requirements, detailing both the virtual coupling components as well as the interfaces and interactions with external systems. The subsequent analysis shows that virtual coupling can enable multiple performance benefits for railway operation. Beside the significant increase in capacity through shorter headways and reduced coupling times, additional flexibility and robustness are gained with situationally appropriate, dynamic coupling manoeuvres with a free choice of vehicles. Moreover, virtual coupling can contribute to reducing costs and delays by replacing the mechanical coupler. Aiming for technology readiness level 3, the results of the project illustrate that the concept is feasible from a technological and operational point of view, highlighting the most critical implementation parts in sensors, control and communication. A two-stage implementation approach is proposed to facilitate the introduction of virtual coupling. This is based on a minimum-complexity first stage to introduce the core functionalities and a second stage with incremental implementation of additional virtual coupling functionalities to further improve the operation. This stepwise approach is also corroborated by the results of the impact analysis, which shows a reduced impact for the first stage. The impact analysis illustrates that the fundamental principle of the external systems remains untouched and a full rework is not required. This also implies that virtual coupling will not interfere with the progress of the European Train Control System (ETCS) development and deployment. Therefore, the X2Rail-3 virtual coupling concepts provides a feasible, non-disruptive solution for a more efficient railway transport.

Keywords: Virtual coupling, Shift2Rail, vehicle-centric train protection, T2T-communication, efficient rail transport

1. Introduction

Nowadays, typical implementations of train protection systems such as fixed and moving blocks are based on absolute braking distance (ABD). In these approaches, each train takes only its own braking characteristics into consideration to determine its permitted speed, and the following trains are kept at a distance that is larger than what is technically required. The railway system is reaching a limit where the cost and complexity of adding another train into an already heavily occupied network grows exponentially. In order to gain more capacity, this paradigm must be challenged. The concept of virtual coupling proposed within the Shift2Rail (S2R) project X2Rail-3 aims to provide a railway operation concept which allows for shorter headways between trains by forming a virtually coupled train set (VCTS) – or platoon – equipped with direct train-to-train (T2T) communication, suitable on-board sensors and control units.

VCTS specifically challenges the current capacity limit imposed by ABD based automatic train protection (ATP) by enabling trains to drive safely at a shorter distance. The VCTS concept hereby aims to significantly reduce the costs of additional capacity, as it utilizes mostly on on-board equipment instead of introducing major changes to the infrastructure such as the installation of new tracks or signalling systems. However, besides improving the capacity, the VCTS concept particularly targets benefits in operational flexibility and robustness by enabling interoperability between different railway vehicles and replacing sensitive mechanical couplings. Due to the on-board implementation, which is mostly independent from the underlying signalling system, VCTS additionally offers the possibility to be utilized as a highly efficient kind of vehicle-centric ATP for legacy lines without signalling system upgrades. In this contribution, the concept developed and specified within X2Rail-3 is shortly described, followed by an extensive analysis of this concept with regards to performance, feasibility and impact.

2. The X2Rail-3 Virtual Coupling Concept

In the X2Rail-3 project, the expertise of various European partners from the railway domain and research institutes was gathered to find a collaborative and interoperable concept for virtual coupling of railway vehicles. The project started with a concept development phase, setting up the functional architecture, operational scenarios and a two-stage introduction concept. The first stage of VCTS functionality is based on the replacement of mechanical coupling to join or divide trains in standstill. The replacement of the physical by a virtual link will decrease the time required for the coupling processes and increase the robustness of operation. Due to the standardized interface, VCTS can not only replace mechanical coupling, but also allows trains that were previously incompatible to build a coupled train set on common stretches. For further optimized operation, stage two of VCTS includes advanced functionalities such as dynamical de-/coupling processes on-the-fly and optimized platoon behaviour.

During coupled operation, VCTS enables trains to drive at a closer distance than absolute braking distance. This is possible due to fast exchange of relevant train information and dynamics via T2T-communication, the additional supervision through on-board sensors and fast and precise traction and braking control. VCTS hereby presents a paradigm shift that we call “breaking the braking wall”. Utilizing cooperative braking manoeuvres and relative braking distance supervision, the figurative wall for ABD at the rear end of the preceding train can be removed (see Figure 1).

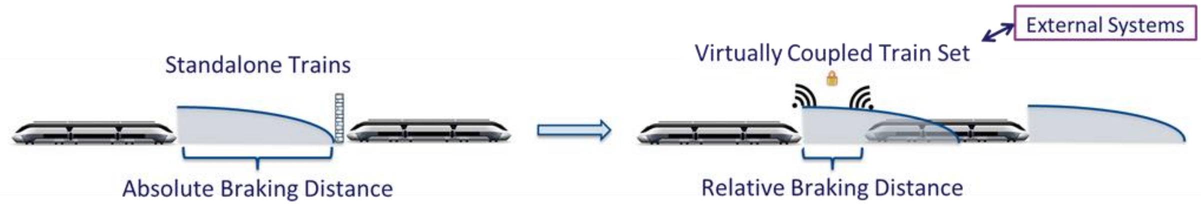

Figure 1: Breaking the braking wall: paradigm shift from absolute braking distance supervision with standalone trains to relative braking distance supervision in a VCTS [1].

In the concept phase, operational scenarios and potential hazards were identified and analysed [2]. The major operational scenarios target the following three phases: coupling set-up, coupled driving and termination of coupling. Possible hazards are linked, amongst others, to interlocking, train integrity, communication and level crossings. This preliminary hazard analysis led to the definition of mitigation measures, which either requires VTCS to implement specific functions or imposes certain requirements on external systems to mitigate these risks.

Based on the operational scenarios and safety evaluations, system requirements were specified following the ARCADIA methodology in the CAPELLA framework [3]. The defined requirements are structured in a hierarchical approach and allocate functions into two main blocks: the on-board and trackside sub-systems [4, 5]. The virtual coupling on-board system includes functional interfaces to other on-board systems and manages the control and communication with the other virtually coupled units for coupled operation. Together with the trackside unit, the coupling and decoupling manoeuvres are coordinated. The trackside part includes interfaces to external systems such as the traffic management system and underlying signalling system, for example through the radio block centres. The resulting system architecture aims to limit the impact on the existing system with an integrated, yet complementary structure, respecting and following the new reference architectures (RCA/OCORA). The specification of requirements, interfaces and derivation of interactions can thus serve as a basis for future demonstrator implementations.

3. The Analysis

The concept described above was evaluated in an extensive analysis framework. First, a performance analysis with different models and simulation approaches was conducted. Afterwards, the concept was further reviewed in a feasibility study. Here, the concept was divided into technical and operational subdomains linked to the implementation of VCTS. For each of these subdomains, interviews with respective experts were performed to evaluate the state-of-the-art technologies as well as ongoing developments and their ability to provide VCTS functionalities. To conclude the set of analyses, a system impact analysis assessed the necessary modifications for VCTS introduction in the external subdomains and their impact on the existing system.

3.1 Performance

Building on the concept, two key operational principles were evaluated in the performance analysis to quantify the improvement potentials: The first key principle is the coupling and decoupling. Here, the goal in the first VCTS implementation step is to remove the mechanical coupler and replace it with virtual coupling in standstill. In this implementation stage, we can already reduce coupling times compare to a mechanical coupling scenario and gain a significant amount of improvement. The evaluation of generic coupling scenarios from the IMPACT project [6] yielded 10 – 50% capacity improvements compared to mechanical coupling operation [7]. The results indicate that the exact improvements depend heavily on the scenario characteristics and the underlying signalling system. In a second stage, dynamic coupling manoeuvres on-the-fly can further improve the effect.

The second key operational principle is the paradigm shift from absolute to relative braking distance. The actual distance between the vehicles is composed by several safety margins that depend on interacting factors such as speed level, braking capabilities, delays, control precision and inaccuracy in position/speed measurement. With the assumption of certain technology goals, an exemplary comparison yields a distance reduction of 60 to 80% (depending on the service category, calculated potential distances at full speed: <100 m for Metro, <900 m for 300 km/h-high speed trains), which illustrates the significant improvement potentials for track occupancy. [1]

Besides these changes in capacity, the performance analysis demonstrated further advantages, which VCTS can enable. While capacity is the most obvious advantage, flexibility in particular can be increased, as virtual coupling allows a free choice of vehicles for coupling, not restricted to any train types and models. Furthermore, situationally appropriate coupling and decoupling can be utilized. VCTS also enables improved robustness, as a reduction of delays due to coupling problems is expected compared to a mechanical coupler. Additionally, VCTS allows for novel procedures of conflict and delay resolution through unscheduled coupling operation.

3.2 Feasibility

After evaluating the performance potentials, we analysed the technical feasibility of the VCTS concept. Therefore, technical and operational VCTS enablers were identified and the VCTS requirements were compared against the state of the art of currently deployed technologies and future developments. An exchange with other S2R technical demonstrators in the form of expert interviews was utilized to evaluate these aspects and discuss general obstacles. The most critical aspects for VCTS implementation were identified as:

- Precise supervision of the distance and relative dynamics between the coupled vehicles
- Fast and accurate brake control with precisely adjustable braking effort
- Availability of suitable T2T-communication technologies and the respective frequencies
- Reliable and continuous supervision of not only the train integrity but also the platoon integrity

Based on the railway application or market segment, the criticality of these issues varies. Therefore, a qualitative assessment for the different market segments has been conducted, and none of these critical aspects were found to be showstoppers. Ongoing developments in other Shift2Rail-projects or the industry were identified to provide suitable solutions or mitigation measures for the potential obstacles [8]. In can thus be stated that the VCTS concept drawn up in these activities is feasible from a technological and operational point of view.

Within the feasibility study, a preliminary introduction strategy was developed, proposing a qualitative roadmap for VCTS (see Figure 2), consisting of the three main steps “Development”, “Testing/Verification” and “Roll-Out” [8]. The first step was already started with the X2Rail-3 system requirements specification. The most important measure identified to facilitate the introduction is the two-stage implementation approach described above.

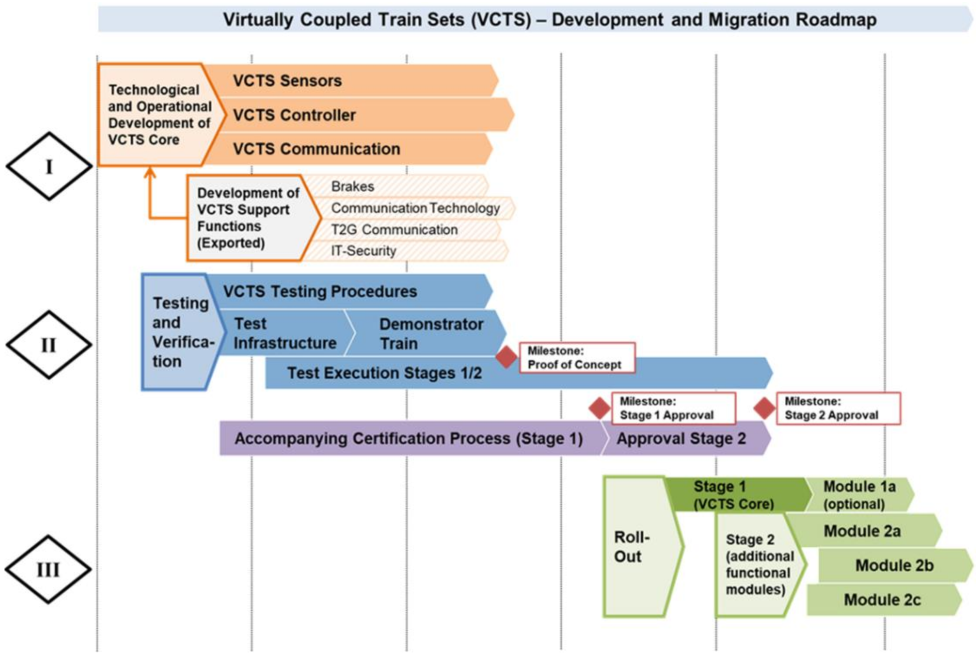

Figure 2: Preliminary qualitative roadmap for VCTS introduction [8].

A quantitative migration strategy was developed during the evaluation of the business model. [9] Here, a strategy and vision for the introduction of VCTS was developed, considering the outcomes of the overall X2Rail-3 analysis and the results of the MOVINGRAIL project [10], which described an extensive business case based on expert interviews, SWOT analyses and simulations. With a technology-open point of view of the VCTS concept, two application cases were analysed: The first scenario is ETCS-based VCTS, focusing on capacity increase and operational flexibility improvements for the whole European railway network, as ETCS is the main S2R application for the Single European Rail Area framework. To facilitate the introduction, a preliminary standalone VCTS application case was evaluated, which can be seen as a stepping stone towards ETCS-based VCTS. It promotes the implementation of this innovative concept and provides an economically-attractive upgrade path for low-traffic lines with legacy systems that are threatened by obsolescence issues and high investment costs needed to upgrade to ETCS. The proactive migration plans for both scenarios target a complete demonstration within 3 to 5 years.

3.3 System Impact

As one of the last activities, the expected impact of VCTS introduction on the existing railway system was evaluated. Here, technical and operational modifications as well as other implications (e.g. on rules, maintenance and training) were analysed. A three-step approach was chosen to assess the impact: Baseline definition, identification and description of the necessary modifications and the quantification of changes in terms of expected range of impact. [11]

In this analysis, particular focus was given to predefined subsystems, such as TMS, ATO, Communication and Cyber Security. It was investigated how these are affected by the introduction of VCTS, for example in terms of software or hardware changes, but also regulation. Again, two baseline scenarios were defined: Application in ETCS L2/L3 and the secondary, low-cost and low-complexity standalone application as a potential first step for this kind of vehicle-centric train protection on low-traffic regional lines. For these scenarios, the necessary modifications in terms of changes, additions and removals were identified. Furthermore, possible architectures for soft- and hardware integration were outlined.

Finally, the possible impact was quantified for each scenario and subsystem. Our evaluation shows that the main effects are allocated in the following categories: communication, train protection and the trains themselves. This is a direct consequence of the VCTS concept, which is vehicle-centric and based on mutual communication between the trains to ensure the train protection in a coupled state. The impact of the implementation of the first stage was found to be lower than in second stage with improved performance, which supports the approach of incremental introduction. Similarly, the impact in the intermediate standalone solution is lower than for a thorough ECTS integration. However, it is also worth mentioning that the introduction of VCTS does not change the fundamental principles of any of the external systems. Therefore, a full rework of any of the systems is not required, the general railway operation will not be completely disrupted and it should also not hinder the progress of the ETCS development and deployment.

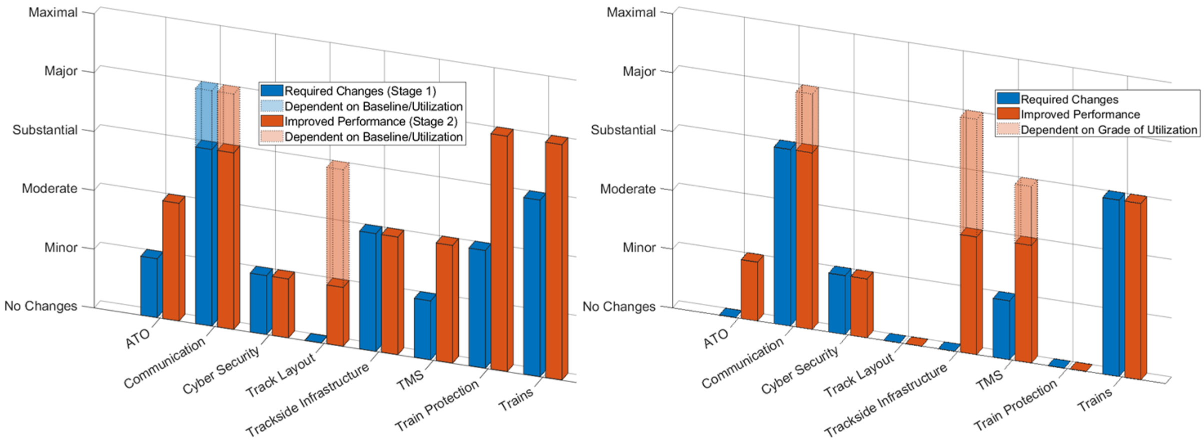

Figure 3: Possible expected range of impact for ETCS application (left) and application in low-traffic regional lines as standalone solution (right), sorted by subsystems and implementation stages [11].

4. Conclusion

The VCTS research in X2Rail-3 illustrates a concept to increase capacity, flexibility and robustness in railway operation. The virtual coupling system requirements were specified, considering interfaces and interactions with external systems. The subsequent extensive theoretical analysis shows promising results. It demonstrates an achievable performance improvement and the feasibility of the concept while taking the impact on external systems into account. Performance-wise, the capacity improvement is realized by significantly reduced headways and coupling times. Moreover, the concept allows for more flexibility due to on-the-fly manoeuvres and free choice of vehicles for coupling. Robustness can be increased with situationally appropriate coupling and the reduction of delays, for example due to a reduction of coupling problems. In the feasibility study, the most critical aspects in implementation are highlighted: the supervision of distance and platoon dynamics, the braking system, T2T communication and the train and platoon integrity. For all critical points, mitigation measures or solutions in development are identified. Furthermore, the criticality differs in between railways services, suggesting a step-wise implementation, starting in a less critical application. Following this proposal, different use cases are analysed with regards to the impact of VCTS introduction on the external systems. It was found that the low-traffic, low-complexity use case has an overall reduced impact and can serve as a first implementation step to gain technological maturity. For a successful and facilitated introduction in ETCS, the step-wise introduction also minimizes the effects alongside the recommendation of implementing VCTS within the RCA and OCORA reference architectures.

The results of this project thereby lay the groundwork for a future demonstration and implementation of VCTS. Due to the independence of the concept from the underlying signalling system, the railway operation could benefit from this concept not only for the main target of high capacity lines, but also to a certain extend as a vehicle-centric train protection to mitigate obsolescence issues on legacy lines as an alternative to major infrastructural upgrades. Hence, VCTS could fulfil many of the common business objectives as an attractive concept for infrastructure managers, railway undertakings, and suppliers. In general, the concept of virtual coupling offers a major performance improvement with minimal infrastructure changes for railway operation. For the first time, an international consortium worked on the concept of virtual coupling to produce an extensive analysis based on a functional architecture and system requirement specifications, and the continuation of such collaborative researches is key for a successful VCTS implementation.

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References

[1] Schenker, M.; Parise, R.; Goikoetxea, J., "Concept and Performance Analysis of Virtual Coupling for Railway Vehicles", 2021, Braunschweig, Germany: 3rd SmartRaCon Science Seminar.

[2] X2Rail-3 (GA No 826141), Canesi, S. (Lead Author), "D6.1 - Virtual Train Coupling System Concept and Application Conditions", 2020, Deliverable: Shift2Rail.

[3] Capella MBSE Tool [cited 2021 November 18] Available from: URL: https://www.eclipse.org/capella/.

[4] X2Rail-3 (GA, No 826141), Iovino, S.D. (Lead Author), "D7.3 - System Functional and non Functional Requirements Specification", 2021, Deliverable: Shift2Rail.

[5] X2Rail-3 (GA No 826141), Iovino, S.D. (Lead Author), "D7.2 - System Functional Architecture Specification", 2021, Deliverable: Shift2Rail.

[6] IMPACT-1 (GA No 730816), "D4.1 - Reference Scenario", 2018, Deliverable: Shift2Rail.

[7] X2Rail-3 (GA No 826141), Canesi, S. (Lead Author), "D6.2 - Performance and Safety Analysis", 2020, Deliverable: Shift2Rail.

[8] X2Rail-3 (GA No 826141), Stickel, S. (Lead Author), "D7.1 - Feasibility Study", 2020, Deliverable: Shift2Rail.

[9] X2Rail-3 (GA No 826141), Damschen, M. (Lead Author), "D7.5 - Business Model", 2021, Deliverable: Shift2Rail.

[10] MOVINGRAIL (GA No 826347), "D3.1 - Virtual Coupling Communication Solutions Analysis", 2018, Deliverable: Shift2Rail.

[11] X2Rail-3 (GA No 826141), Schenker, M. (Lead Author), "D7.4 - Impact Analysis", 2021, Deliverable: Shift2Rail.