Application Roadmap for the Introduction of Virtual Coupling

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Application Roadmap for the Introduction of Virtual Coupling

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Executive Summary

This document constitutes MOVINGRAIL Deliverable D4.3 'Application Roadmap for the Introduction of Virtual Coupling' in the framework of TD2.8 of IP2 according to the Shift2Rail Multi-Annual Action plan (MAAP). This deliverable moves forward the current state of the railways by developing a long-term strategy that will enable a smooth, gradual transition towards the implementation of Virtual Coupling for various market segments.

The scope of Virtual Coupling is analysed together with the impact on the technical and operational railway system components of interlocking, communication structures, automatic train protection, automatic train operation, railway traffic planning, and railway traffic management. For each of these components main research and development challenges are derived providing an overview of knowledge gaps and critical step-changes for the development of Virtual Coupling. A clear distinction must be made between VCTS train protection and cooperative train operation, similar to ATP and ATO but then for virtual-coupled trains. A convoy or VCTS is a vital safety system concept that allows virtual-coupled trains to follow each other up to relative braking distances. A convoy can additionally form a platoon, which is a non-vital multi-train control concept that enables (virtually-coupled) trains to move synchronously and stable together. The cooperative train operation system guarantees stable operation in a platoon, while the VCTS train protection system supervises the relative braking distances.

A Swimlane roadmap is developed to group step-changes into different themes and categories. This is achieved by means of a quantitative-qualitative gap analysis between current and future states in the operational, technological and business domains. A survey was distributed to stakeholders to collect priorities and time orders for each of the defined steps within the Swimlane roadmap. Optimistic and pessimistic scenarios are defined for each market segment using the SWOT analysis from MOVINGRAIL D4.1 and the cost-effectiveness analysis from MOVINGRAIL D4.2. Optimistic scenarios are based on the estimates made in the 'White Paper on Transport' of the European Commission (EC) regarding travel demand and CO_2 emissions. Pessimistic scenarios consider a lower growth in the railway demand as well as a higher increase in CO_2 emissions and capital and operational costs when compared to the optimistic scenarios (specifically a 50% less increase in rail demand and 50% more increase in CO_2 emissions and costs).

Scenario-based roadmaps are developed to fulfil the EC's vision of a more competitive, capacity-effective and sustainable railway by 2050. This deliverable is based on the assumption that the strategic goals set by the EC in terms of railway demand, capacity and emissions could be met if Virtual Coupling (VC) operations will be implemented within the target year 2050. Results show that all the considered scenarios and railway market segments could achieve the timely deployment of Virtual Coupling except in the pessimistic scenario for mainline railways where VC could be deployed not earlier than 2054. Critical issues are here the longitudinal motion control systems of the Virtually Coupled Train Sets and the integrated traffic management and cooperative train operation complexity for heterogeneous trains. These scenario-based roadmaps can be used as an efficient tool for stakeholders to identify and solve potential criticalities/risks to the deployment of Virtual Coupling as well as to plan necessary investment/development actions.

The developed roadmaps provide a long-term transition strategy defining for each rail market segment a sequence of progressive upgrades to connected and automated railways that will eventually lead to the deployment of Virtual Coupling and enable a significant increase in infrastructure capacity and operation efficiency.

Abbreviations and Acronyms

Abbreviation/Acronym	Description
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CAV	Connected and Automated Vehicle
CBTC	Communications-Based Train Control
CSM-RA	Risk Assessment according to Common Safety Method
D4.1	MOVINGRAIL Deliverable 4.1
D4.2	MOVINGRAIL Deliverable 4.2
EMUs	Electric Multiple Units
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EU	European Union
EVC	European Vital Computer
GSM-R	Global System for Mobile – Railway
HS	High Speed
IM	Infrastructure Manager
L1, L2, L3	Level 1, Level 2, Level 3
MA	Movement Authority
MAAP	Multi-Annual Action Plan
MB	Moving Block
MOVINGRAIL	MOving block and VIrtual coupling New Generations of RAIL signalling
MS	Market Segment
OD	Origin - Destination
RAMS	Reliability, Availability, Maintainability and Safety
R&D	Research and Development
R&I	Research and Innovation
RU	Railway Undertaking
S2R	Shift2Rail
SIL	Safety Integrity Level
TCMS	Train Control and Management System
TIM	Train Integrity Monitoring
TUD	Delft University of Technology
V2V	Vehicle-to-Vehicle
VC	Virtual Coupling
VCTS	Virtually Coupled Train Set

1. Background

1.1. Scope

This document constitutes Deliverable D4.3 "Application Roadmap for the Introduction of Virtual Coupling" from MOVINGRAIL, which contributes to Task 2.8.1 Virtual Coupling concept of the Technology Demonstrator TD2.8 Virtually Coupled Train Sets of IP2 according to the Shift2Rail Multi-Annual Action plan (MAAP).

This deliverable is part of MOVINGRAIL WP4 Business Analysis of Virtual Coupling, and builds on the previous deliverables

- MOVINGRAIL D4.1 Market Potential and Operational Scenarios for Virtual Coupling
- MOVINGRAIL D4.2 Cost-Effectiveness Analysis for Virtual Coupling

and is closely related to

- MOVINGRAIL D4.3 Business Risk Analysis of Virtual Coupling.

Moreover, this deliverable uses the results from

- MOVINGRAIL D3.1 Virtual Coupling Communication Solutions Analysis
- MOVINGRAIL D3.2 Advances in Automated Vehicle Technology and Applicability to Railways
- MOVINGRAIL D3.3 Proposals for Virtual Coupling communication Structures
- X2RAIL-3 D6.1 Virtual Train Coupling System Concept and Application Conditions.

The aim of this deliverable is to provide a roadmap for the introduction of Virtual Coupling. Figure 1 illustrates the workflow of WP4. Steps 1 to 4 were reported in Deliverable D4.1 that aimed to assess market needs and possible VC operational scenarios based on the outcome of a SWOT analysis. Step 5 was reported in D4.2 on a Cost-Effectiveness Analysis (CEA) for Virtual Coupling where a hybrid Delphi-AHP technique has been used to weigh the criteria in a Multi-Criteria Analysis (MCA). Step 6 is the topic of the present deliverable D4.3, while step 7 corresponds to D4.4 on Business Risk Analysis of Virtual Coupling. The stated travel preferences survey of D4.1 was expanded in D4.2 where the scenario of increased frequency and cost was not only applicable to VC but also to ETCS L3 Moving Block (MB). Deliverables D4.3 and D4.4 are inter-related and were executed simultaneously to get a better understanding on the business risks that may affect or impose new steps in the application roadmap for the introduction of Virtual Coupling.

In the remainder of this chapter D4.1 and D4.2 are briefly recaptured, followed by an outline of the deliverable.

1.2. Market potential for Virtual Coupling

In Deliverable 4.1 "Market Potential and Operational Scenarios for Virtual Coupling" we focused on a SWOT analysis that identified main strengths and weaknesses of the Virtual Coupling concept and corresponding opportunities and threats to each specific railway market segment. The research relied on a Delphi method with an extensive survey of expert opinions and stated travel preferences assuming Virtual Coupling has been implemented. The survey involved subject matter experts of the wide European railway industry including infrastructure managers, railway undertakings, system suppliers, transport authorities, railway institutions, private consultants and academics.

The main strengths that were identified for VC are a substantial increase in capacity and flexibility with respect to Moving Block while mitigating delay propagation and improving reliability of ground/train communication. Weaknesses identified for the Virtual Coupling concept refer to the fact that capacity gains at diverging junctions equipped with current switch technologies might be marginal, since trains would still need to be separated by an absolute braking distance at the switches. Also, the implementation of VC operations would require investments to upgrade the overhead line system, platform lengths (to allow platoons of trains to stop) and possibly the switch technology to facilitate higher train frequencies. Significant opportunities will be brought about Virtual Coupling such as potential increase in the profit of infrastructure managers and railway undertakings as well as a deregulation of the current railway market which could be opened also to smaller railway undertakings due to the increase of available train paths and the decrease of operational costs by fully automated trains. In addition, the train-to-train communication could lead to the institution of cooperative consortia of railway undertakings, which can be more economically beneficial than the current competitive market model. This would also provide a chance to migrate obsolescent command and control systems towards future-proof digital railway architectures. Possible threats to the introduction of this concept mainly relate to potential increase of train control complexity and associated enlarged risk of approval from the railway industry. The need for an initial investment might not be received well by infrastructure managers and local governments. In addition, there is a necessity of partially changing policies, operational procedures and engineering rules currently in place. When overcoming such challenges, Virtual Coupling has potentials to fully revolutionise and improve current train operations so to induce a sustainable shift to railways.

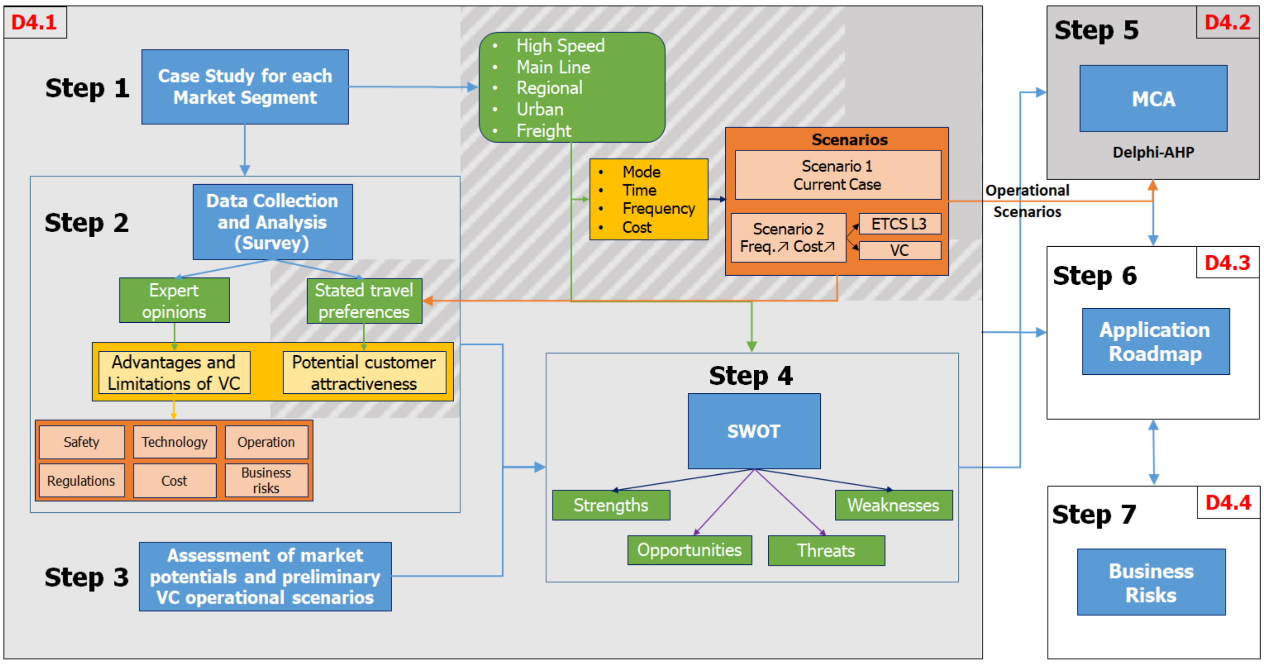

Figure 1: Overview of Work Package 4

1.3. Cost-effectiveness for Virtual Coupling

In Deliverable 4.2 "Cost-Effective Analysis for Virtual Coupling", a comprehensive multidimensional impact assessment advanced the current state of knowledge on Virtual Coupling by identifying the market segments where such a signalling system would be worth being considered within strategic investment plans of the European Commission and the railway industry. Eight criteria were considered to assess and compare the effectiveness of both moving block (MB) and virtual coupling (VC) signalling by means of a hybrid Delphi-Analytic Hierarchy Process (AHP) technique for the different railway market segments identified by the Shift2Rail Multi-Annual Action Plan (S2R MAAP, 2015). Five quantitative criteria were defined: total costs, infrastructure capacity, system stability, travel demand and energy consumption. In addition, three qualitative criteria were defined related to safety, public acceptance and regulatory approval. Consolidated mathematical techniques and engineering methods were used to assess each of the quantitative criteria while a Delphi approach gathered values for the qualitative criteria based on extensive Subject Matter Expert (SME) interviews and workshops. The results of D4.2 showed that VC can outperform MB for all the market segments if the level of technological maturity is achieved (i.e. acknowledged safety).

1.4. Outline

This deliverable develops a roadmap for the implementation of Virtual Coupling taking into account uncertainties represented by scenarios for each market segment. Chapter 2 presents the objectives of this deliverable. Chapter 3 focuses on fundamentals of Virtual Coupling operations and introduces necessary changes to current operational rules and technologies to be included in a migration roadmap. Chapter 4 explains the applied roadmapping approach and presents a Swimlane roadmap for the phased deployment of Virtual Coupling. Chapter 5 describes scenarios for the various market segments, while Chapter 6 derives corresponding scenario-based roadmaps. Conclusions and recommendations are provided in Chapter 7.

2. Objective

This document has the objective of developing a roadmap to the implementation of Virtual Coupling for each of the rail market segments identified by the Shift2Rail MAAP. To achieve this objective, the following steps have been performed in this deliverable:

- Identification of the main railway system components that will be affected by Virtual Coupling.
- Development of a gap analysis between current and future states of the operational, technological, and business domains for the introduction of Virtual Coupling.
- Identification of the main business and market actions that will enable migration to Virtual Coupling.
- Identification of the technological and operational step-changes that will lead to Virtual Coupling implementation.
- Definition of optimistic and pessimistic scenarios for each market segment.
- Collection of potential timelines for the identified step-changes in consultation with key stakeholders.
- Derivation of scenario-based roadmaps for the introduction of Virtual Coupling for each of the market segments.

3. Virtual Coupling Scope and Directions

3.1. Introduction

With the roll-out of ETCS level 2, guiding trains by cab signalling is going to become the new train control standard in Europe. While ETCS level 2 is still based on fixed block sections, the braking curves are calculated onboard depending on the current speed and the braking performance of the train. On lines with optimised block lengths, the impact of the fixed block system on the line capacity is marginalized. In particular on lines with mixed traffic, the capacity improvement that could be achieved by moving block is rather limited. Therefore, there is currently not much interest among European railways to upgrade from ETCS level 2 to ETCS level 3, which would allow trains to be controlled by moving block. To achieve a significant capacity improvement, the idea of combining moving block and virtual coupling was developed. By combining individual trains into virtually coupled train sets or train convoys, the moving block principle is only used to keep these train convoys apart. This is expected to lead to a significant capacity improvement. It will also reduce the impact of speed differences on capacity by assembling trains of the same speed class into virtually coupled train convoys or platoons reducing speed differentiation between individual trains. Since the virtual coupling and decoupling can be done on the run, the system has a very high flexibility.

Moving block is based on the principle of spacing trains in absolute braking distance. In a moving block system, the rear end of a train is considered as a moving danger point to be protected against a following train. That means that the minimum distance between two following trains equals the braking distance of the second train plus a supplementary safety distance, see Figure 2.

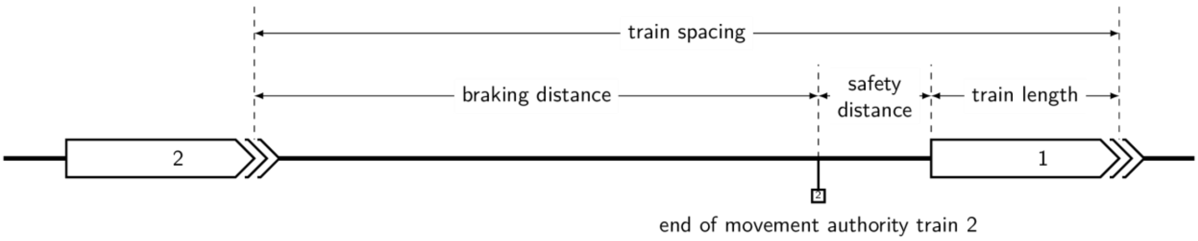

Figure 2: Train separation by moving block

The braking distance equals the movement authority. The supplementary safety distance runs from the end of authority to the danger point provided by the rear end of the train ahead. That supplementary distance is an equivalent to the block overlap in a traditional fixed block system. It is the minimum safety distance kept between the two trains if the second train stops behind the first train. If points are going to be moved between two trains following each other in moving block, an additional time window for moving the points is needed. When passing through a complex point zone, that time window depends on the point control principle.

Virtual coupling is based on the principle of spacing trains in relative braking distance. That means that the distance between two following trains equals the difference of the braking distances of the trains plus an additional safety distance. If the braking distance of the second train equals the braking distance of the first train or is shorter than the braking distance of the first train, that safety distance is kept as a minimum distance between the two trains, see Figure 3.

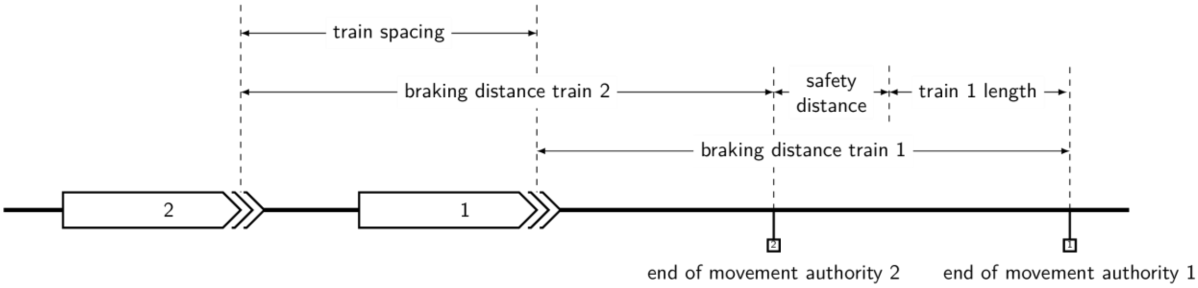

Figure 3: Train separation by relative braking distance

With all trains having the same braking performance, virtual coupling means that two trains running at the same speed are kept apart just by this minimum distance. For this, the second train must reach the same braking deceleration as the first train. When two successive trains are being coupled on the run, the second train will be following the train ahead at a greater speed until having reached the relative braking distance forcing the second train to slow down to the speed of the first train. Then, both trains are just kept separated by the minimum safety distance. For decoupling trains on the run, the second train will slow down until having reached the full braking distance enabling the train to follow the first train by the moving block principle. When having reached this point, the speed of the second train may be increased again up to the speed of the first train.

The following terminology will be used throughout this deliverable.

- **Virtual Coupling (VC)** is a railway signalling concept that enables trains to follow each other at a relative braking distance while keeping a safety margin to the rear of the predecessor even when this predecessor executes an emergency braking.
- A **Train Convoy** or **Virtual Coupled Train Set (VCTS)** is a formation of virtually coupled trains based on Vehicle-to-Vehicle communication that is viewed as one train by the interlocking systems. Coupling to or decoupling from a train convoy can occur at stations or on-the-run.

The introduction of Virtual Coupling into railway operations will require the implementation of new technology and adaptation of existing technology. In particular, the following railway system components will be affected by the introduction of Virtual Coupling:

- Interlocking
- Communication structures
- Cooperative train protection of train convoys
- Cooperative train operation of train convoys
- Railway traffic planning and management.

Other technology essential for the introduction of virtual coupling includes train integrity monitoring and accurate train positioning, which are already existing developments within Shift2Rail and not further considered here.

This chapter gives an overview of these railway system components and how they will be affected by the introduction of Virtual Coupling. The main challenges will be discussed and summarized as input to a roadmap for the introduction of Virtual Coupling. This chapter starts with the principles of interlocking to give an understanding on how train convoys will change the operation of the railway traffic and the control of routes over the railway infrastructure. Then the innovative communication structures are considered that are needed for communication with and within a train convoy. Next the automatic train protection of a train convoy and within the train convoy is considered, followed by the automatic train operation of virtually coupled train within a convoy. Last the changes to capacity allocation and traffic management are considered as well the planning of train convoys.

3.2. Interlocking

3.2.1. The structure of the traffic flow under virtual coupling

The traffic flow with virtual coupling consists of train convoys of virtually coupled trains that are separated by moving block. The train convoys are somehow treated like traditional trains, in which the mechanical coupling is replaced by virtual coupling. Here, the first train of such a convoy is called the leading train. That term also applies to a train that is not virtually coupled with other trains, since it can be treated as a convoy consisting of just one train. The virtual coupling allows a very high degree of flexibility, since the train convoys may be coupled and decoupled on the run. When coupling, the units to be coupled switch from moving block to virtual coupling, when decoupling, they switch from virtual coupling to moving block. When a train or a train convoy is joining a line from a converging line, it may couple with other trains or train convoys on that line, see Figure 4. When a train convoy is approaching a junction where the paths of individual trains of that convoy split, the convoy is decoupled to allow the separated units to take different routes, see Figure 5. Later, these units may be coupled with other trains or train convoys.

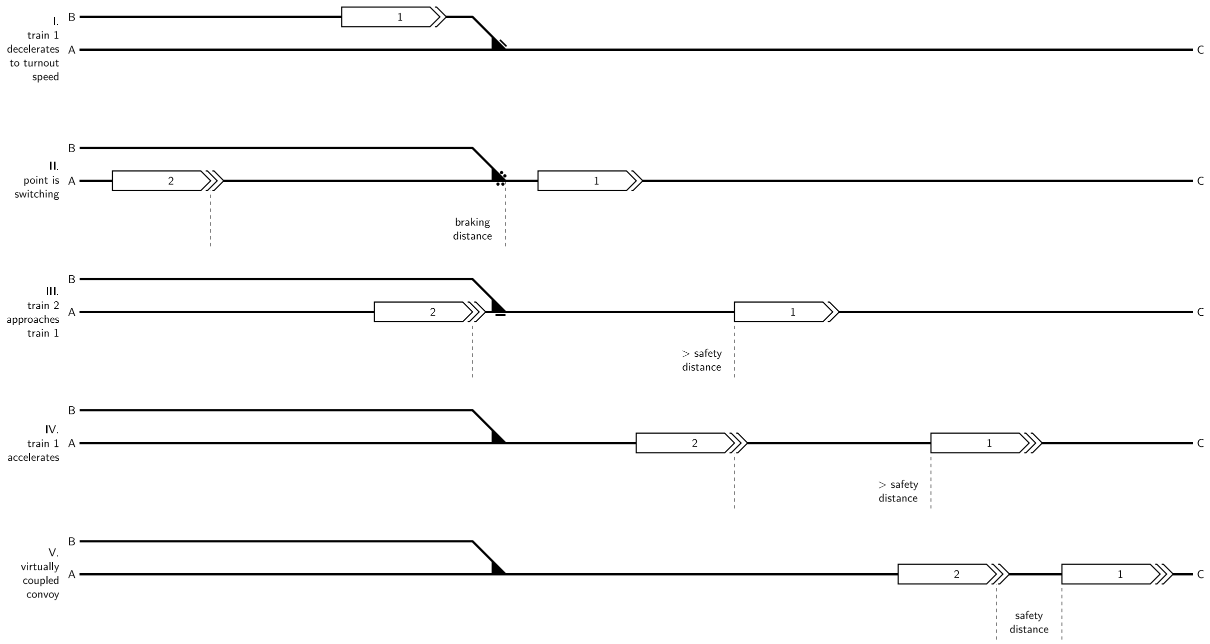

Figure 4: Coupling train convoys on the run when passing through a junction

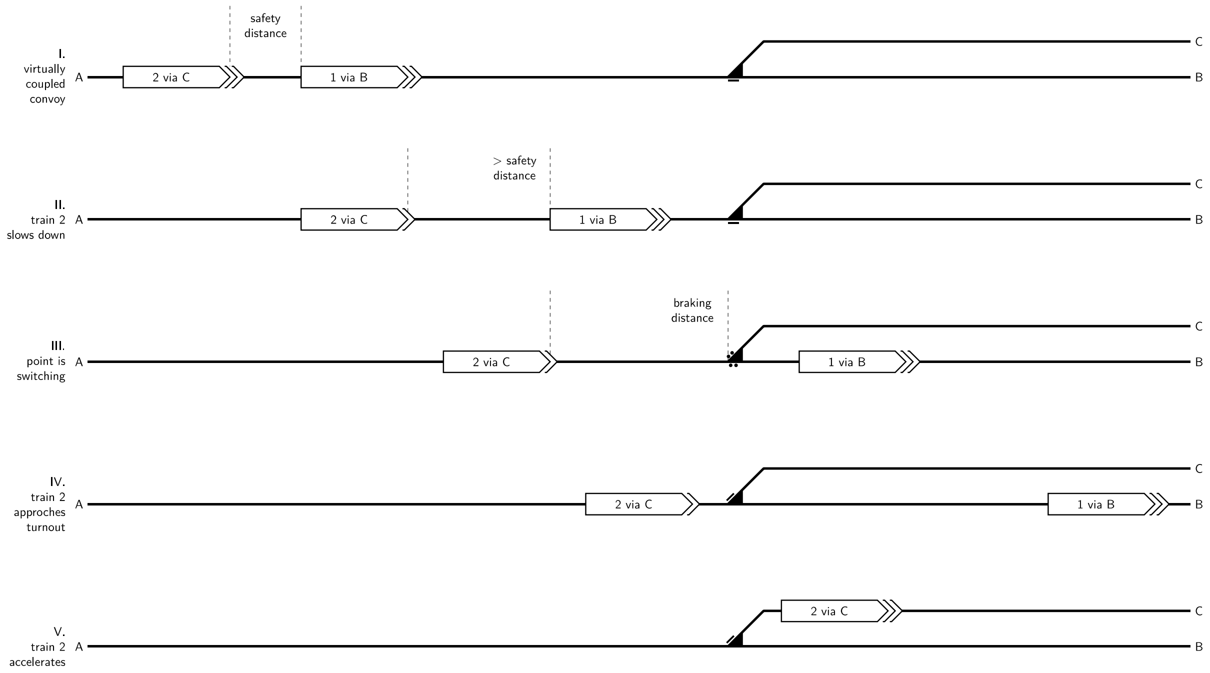

Figure 5: Decoupling train convoys on the run when passing through a junction

The same procedure is used in station areas where the individual trains of a train convoy have to be distributed to several station tracks and re-joined to a train convoy when leaving the station.

3.2.2. Direction control on lines with bidirectional traffic

Besides the safe separation of movements following each other in the same direction, the protection of opposing movements on lines with bidirectional operation is a key function of safe train control. In a traditional fixed block system, this is effected either by direction locking (usually on lines outside of station areas where trains cannot reverse) or by locking out opposing routes on station tracks by the interlocking system. In a moving block system, the leading train will always check that the braking distance ahead of the leading vehicle is available, see Figure 6.I. When the braking distance overlaps with the danger point ahead of the braking distance of an opposing train, the end of authority will stop moving and the train will be brought to a stop. Since the same procedure also happens for the opposing train, both trains will stop at the opposing danger point keeping the minimum safety distance between them, see Figure 6.II. While this is a safe situation, it must be avoided on line sections where trains cannot reverse. This applies to most lines outside station areas. A train must not enter such section as long as any opposing movements are travelling through that section or have authority to enter that section from the next location where the train sequence may be changed, see Figure 6.III. If it desired that two opposing trains can enter the same track section, the track section has to be divided into two logical units with separate direction controls. Trains can then only leave these track section by reversing, see Figure 6.IV.

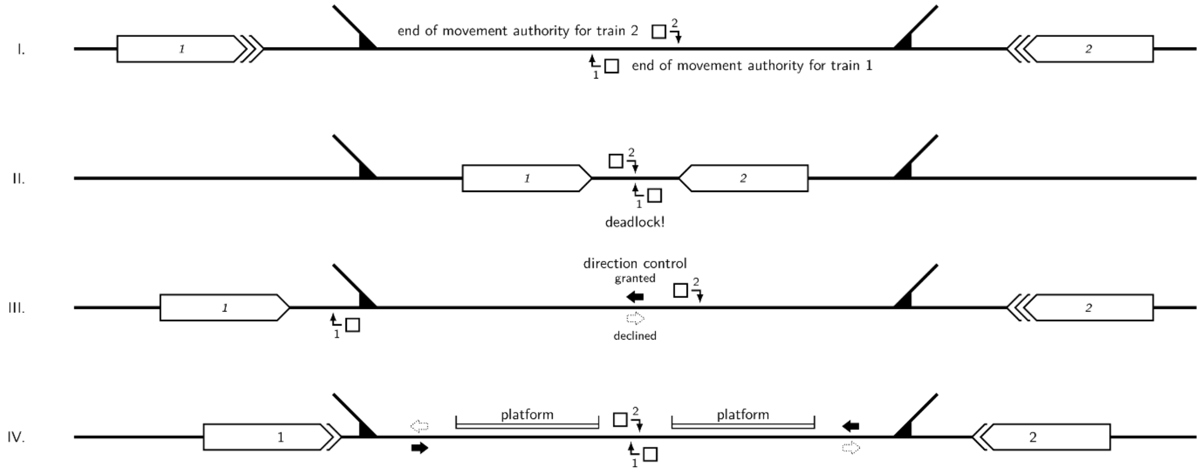

Figure 6: Comparing the two solutions of direction control

3.2.3. Principles of controlling and locking points

When a train convoy is travelling through a point zone, the points must be kept locked until they have been cleared by the entire convoy. Thus, from the viewpoint of point locking, a train convoy is more or less treated like a traditional train. Moving points is only possible in the gaps provided by the moving block principle between the train convoys. For this, a time window must be established ahead of the danger point to provide the control time for moving points, see Figure 7. The control time contains the time to request the points, the time to get the points assigned, and the time to move the points.

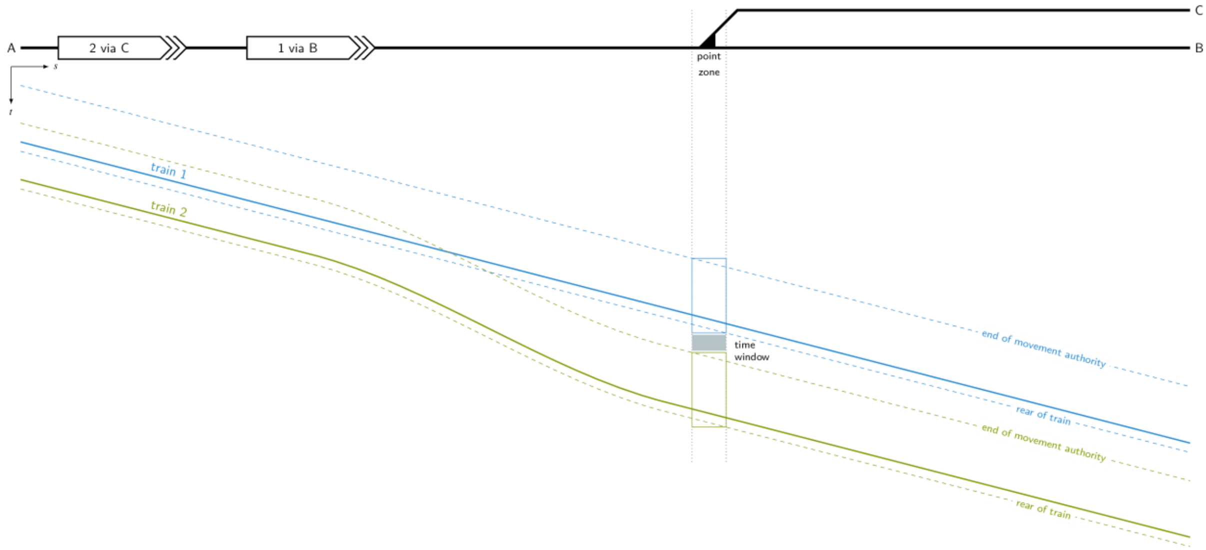

Figure 7: Time window for point control between trains separated by moving block

Points are requested by the leading train according to the route data in the onboard unit. The points must have reached the proper position in front of the danger point of an approaching train. The locking of points is effectuated by the principle that after points have been assigned to a train, the requests of other trains will be declined. Assigning points to a train means that the train gets the exclusive right to control and occupy the points. If that train is the leading train of a train convoy, the assignment applies to the entire convoy. The same procedure also applies to crossings without movable points to lock out conflicting moves. Points that are locked for flank protection to protect another train may be assigned to a train but cannot be moved by that train. The train the points were assigned to, would usually need those points in the same position the points are locked in to provide flank protection to another train. Otherwise, there would be a conflict with a train that is currently protected by these points, so the train will have to wait anyway, see Figure 8. In such a situation, after the points have been assigned to the train, the train will have to wait with moving the points until they are no longer called for flank protection. As explained later, assigning points to the leading train cannot be done in a pure train-centric manner but requires action from a traffic control centre.

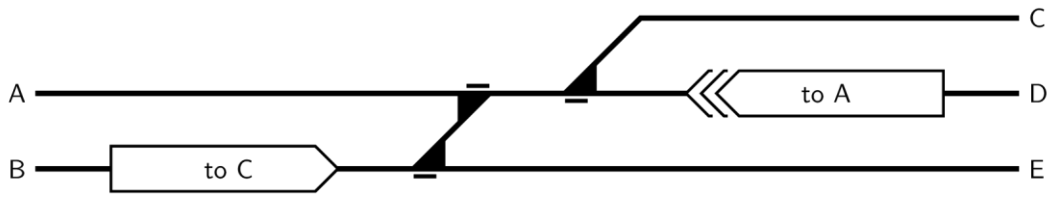

Figure 8: Train waiting in front of points locked for flank protection

Point control can be made either by dynamic routes or by fixed routes. A dynamic route means that the points are assigned individually to the leading train. So, a route through a point zone is extended step by step ahead of that train. A fixed route means that the leading train requests all points providing a route through a point zone at once. That principle is similar to an interlocking route as used in traditional interlocking system. The fixed route principle will reduce capacity by requiring a longer time window ahead of the danger point of the leading train and thus a greater distance between trains separated by moving block. On the other hand, in case of a route conflict, point control based on dynamic routes may force the leading train to stop somewhere in the middle of a point zone and block the paths of other trains, see Figure 9. This may also seriously harm capacity.

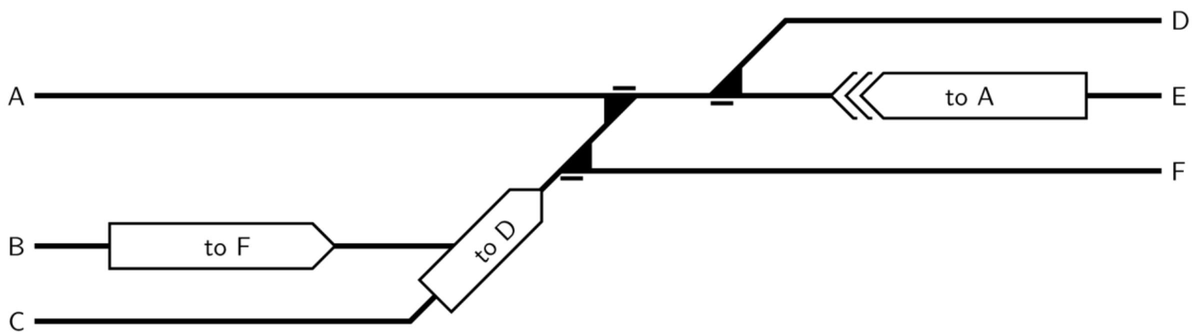

Figure 9: Trains blocked by a train stopping within a point zone

So, the decision whether to use dynamic or fixed routes depends on the capabilities of the traffic control system. For the use of dynamic routes, the traffic control system must be able to handle complex conflicts in point zones with more than two trains involved to prevent a train from stopping at a location where it would cause serious delays by blocking the paths of other trains. If the traffic control does not provide that functionality, using fixed routes is more appropriate.

Finding the optimum balance between fixed and dynamic routes is a key challenge concerning the control of the interlocking system: For a train that is following another train in moving block mode, the route could be assigned and locked elementwise in accordance with the release of locked route elements behind the rear end of the train ahead according to a dynamic route. While this reduces the headway between trains following each other through a point zone on the same path, a train may come to a stop in the middle of a point zone. Each route element that can separately release may act as an authority limit for the next train. While stopping at such an authority limit, a train may block the paths of other trains through the point zone. From the viewpoint of interlocking, this is still safe. However, it may lead to a significant loss of capacity by increased waiting times which could be avoided by having the train waiting in front of the point zone. That effect is described in Pachl (2018, chapter 4.6), and already more than 20 years ago in the 1st edition of this textbook from 1999. There, the suggestion was to avoid stopping positions at which the train would block crossing paths of other trains. On the other hand, blocking a converging path leading into the same direction would not be a problem since a train on that path would also be blocked by the train ahead. So, from the viewpoint of traffic management, there might be situations in which a train should enter a point zone only after the entire route to pass through this point zone has been set. In Pachl (2018), this principle is called 'virtual routes', which equals the fixed route principle. So, the challenge is to overlay the interlocking control system by a traffic control system that can make that decision based on the current situation.

Another key challenge is the route release procedure for trains separated by relative braking distance: When two trains are following each other in moving block mode, i.e., separated by absolute braking distance, the route elements will release behind the rear end of the first train and then lock for the second train. This is not possible if two trains are following each other at relative braking distance. When two trains are following each other at relative braking distance, route elements must not be released after having cleared by the first train. Instead, the route must remain locked until cleared by the last train of the convoy. This corresponds with the traditional interlocking principle that a route element is exclusively assigned to just one train and thus must be released before it can be locked for another train. The concrete procedure will depend on how the interaction of convoys and interlocking will be modelled. In particular, if successive virtually-coupled trains in a convoy maintain separate movement authorities then they will overlap each other, which leads to a situation that a route element may be locked for multiple trains simultaneously, which is a total break with the traditional interlocking principle.

If two trains are virtually coupled, the entire convoy should be treated by the interlocking system as if being one single train. Since the movement authority is issued only to the leading unit of the convoy, there are no overlapping authorities. Also, a route element is never locked for several trains at the same time (trains in the sense of a train convoy). However, the normal route release procedure, which is based on occupying and clearing route elements, must not be applied. This traditional procedure is based on the constraint that the minimum length of a route element that may individually release, must exceed the maximum distance between two axles within a train. By that constraint, a route element will never accidently release under a moving train. For virtually coupled trains, this constraint is not sufficient because the distance between two virtually coupled trains may significantly exceed the length of a route element that may individually release. Thus, the interlocking control system has to know which trains are virtually coupled. Then, for a convoy consisting of virtually coupled trains, cleared route elements are kept locked until the entire consist has passed.

3.2.4. Principles of flank protection

The problem of flank protection does not depend on the principle of train separation. The basic requirements of how to protect a train against flank hazards from converging and crossing tracks does not differ between traditional interlockings and point zones on which trains are controlled by moving block and virtual coupling.

The flank hazard from conflicting trains can be handled by bringing trains to a safe stop when the danger point ahead of the limit of authority is touching the flank zone of a train to be protected. This is not different from traditional systems in which flank protection against conflicting train moves is provided by main signals or the authority limit of cab signalling (e.g., in ETCS level 2). In point zones where shunting and parking of equipment is not permitted, no other means for flank protection are needed. However, points that could be brought into a protective position should be moved to that position.

The critical flank hazards do not result from conflicting train moves but from shunting moves and parked equipment that could get into motion unintentionally. In areas, where shunting and parking of equipment is allowed, trains can be protected against these flank hazards by these flank protection elements:

- shunting signals
- flank points
- derailers.

Shunting moves that may reverse or pick up or leave vehicles cannot be controlled by cab signalling. Consequently, if an ETCS onboard unit is switched to shunting mode (mode SH), there is no authority limit protected by the ETCS. It wouldn't make sense since a shunting unit with the locomotive at the rear end would violate an authority limit. In shunting mode, the driver simply has to stop at a shunting signal or another location given by the control centre. For controlling shunting moves, shunting signals are still a practical solution even in areas where all regular train movements are controlled by cab signalling or automatically. As long as a shunting signal provides flank protection to a train move, shunting movements using that signal as a destination point should also be locked out, see Figure 10.

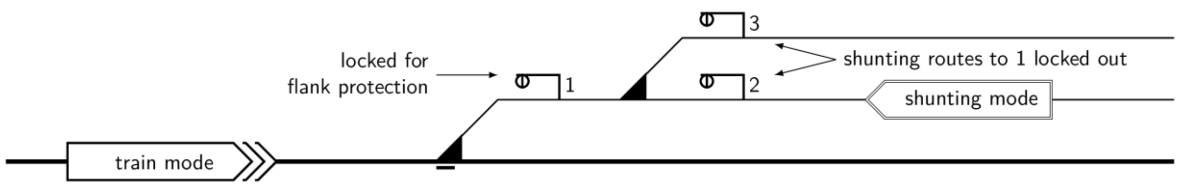

Figure 10: Locking out a shunting move against a shunting signal protecting a train move

On tracks with heavy shunting or where vehicles are parked, shunting signals are not sufficient for flank protection. On most railways, the use of derailers is limited to sidings. On main tracks, flank points must be provided. Most railways also require flank points to protect tracks on which trains pass at a high speed (usually exceeding 160 km/h).

If a train is protected by flank protection elements, the so-called flank area between the fouling point of the train path and the protective elements must be kept clear of any vehicles. In particular, this is important in cases where flank protection is provided by remote elements with flank transfer points located between these elements and the fouling point of the train path, see Figure 11. Thus, while track clear detection technology is no longer needed for train separation, they might still be needed to check the clearance of the flank areas.

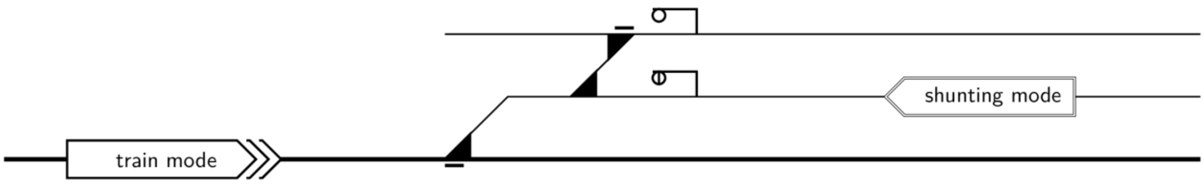

Figure 11: Example of a flank area with remote flank protection

In a train-centric control system, the control of flank protection elements is not effected by a centralised control logic but by communication between track elements. That means, all controllable track elements have not just have a point machine in the sense of a drive but some kind of local intelligence enabling them to communicate to each other. Flank protection is initiated by the point that was assigned to a train. After being assigned to that train and having received the control command to move to the position needed for the passage of the train, the point would initiate a search for flank protection into the track diverging from the path of the train. The flank search procedure could be based on the same rules as developed for traditional interlocking systems based on a geographical control model, see Figure 12.

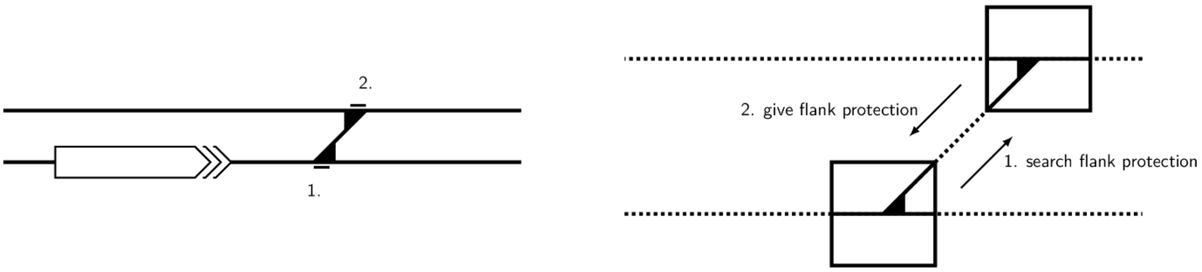

Figure 12: Principle of flank search by communication between track elements

When having found the relevant protecting elements, they are moved to the protective position. When having reached the protective position, it is confirmed to the point requesting the protection. The point requesting the protection is also checking the clearance of the flank areas.

3.2.5. Principles of level crossing control

While level crossing control shows some similarities with point control, there is also an essential difference. After a train convoy has passed through a level crossing, the level crossing is not necessarily released. The level crossing is only released if between two train convoys that are separated by moving block a gap is available that equals the minimum approach time for the level crossing, see Figure 13.

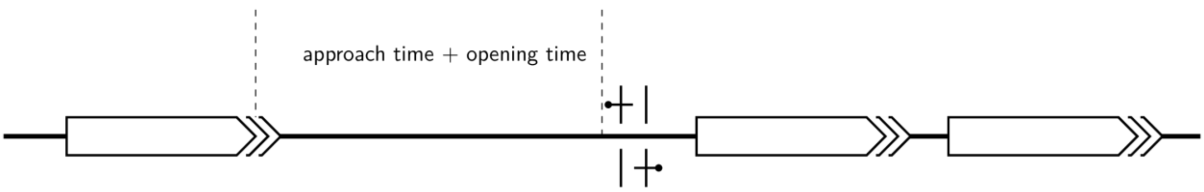

Figure 13: Time window to open a level crossing between trains separated by moving block

3.2.6. The role of traffic control

While in a train-centric operation, most of the safety functions for train separation and point control are performed onboard the trains, a traffic control centre is not obsolete. Different from a traditional interlocking, the function of traffic control is not to provide safe routes for train movements but to regulate the train sequence to avoid or minimise delays in case of conflicts. When a train convoy is passing through a point zone, the task of the control centre is to assign points and crossings on the request of the leading train, see Figure 14.

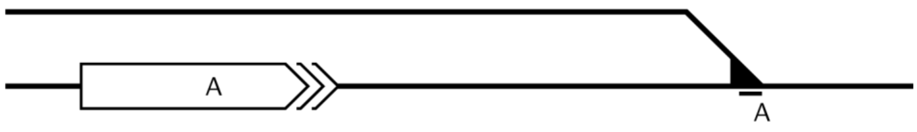

Figure 14: Assigning points to a train

In case of a conflict between two trains, there are competing requests the control centre has to handle. When having made a decision on the sequence of the two trains, the request of the inferior train for the relevant elements is declined, so this train will have to wait until these elements have been released by the superior train. Another conflict to be avoided by the control centre is to lock out opposing moves on stretches of line with bidirectional operation on which trains cannot reverse, see Figure 15.

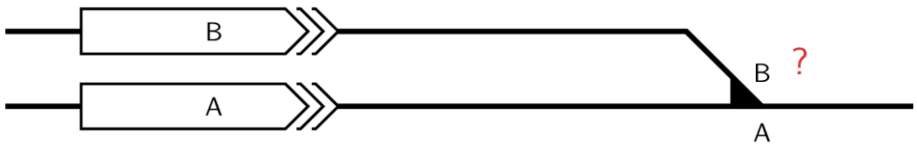

Figure 15: Conflict detection by competing requests

Beside solving individual conflicts, the control centre also has to perform more complex rescheduling tasks in case of serious delays that cannot simply be handled by changing the train sequence. That include re-routing of trains and changing the scheduled track use in station areas. For this, the results of the rescheduling have to be transmitted to the trains to update the onboard units to the altered timetable, enabling the trains to request the correct elements for the new paths.

3.2.7. Impact on the roadmap of Virtual Coupling

In conclusion, virtual coupling generates the following main research and development regarding key challenges concerning the control of the interlocking system:

- Developing the optimal interaction between train-centric train operation and trackside route setting management concerning fixed and dynamic routes, direction control, flank protection and level crossings.
- Establishing a new route release procedure for trains separated by relative braking distance.
- Examine the duty and authority of traffic control to prioritise trains, routes, direction control and updating onboard timetable data.

3.3. Communication structures

3.3.1. Communication requirements

Current railway control systems incorporating on train elements (e.g. ERTMS, CBTC) include data communication between train and infrastructure. However, currently these do not support the needs of virtual coupling, i.e., train-to-train communication with low latency.

Automotive developments with close synergy to railway virtual coupling are ongoing. For peer-to-peer communication these are focussed on the 'sidelink' implemented with ITS G5 or LTE-Direct. However, there is not the same need for peer-to-peer communication over the larger distances that are required for rail.

MOVINGRAIL Deliverable D3.1 on Virtual Coupling Communication Solutions Analysis investigated the communication requirements of virtual coupling and the state-of-the-art in communications technologies. It was found that the key requirements for the virtual coupling communication system are:

- Peer-to-peer capability between all trains and over large distances (> 1km)
- Low latency
- High availability.

The most suitable technology to satisfy these requirements was found to be

- Cellular (5G/3GPP) evolutions.

3.3.2. Communications architecture to support virtual coupling

The introduction of Virtual Coupling into railway operations will require the specification and implementation of an innovative communication system. In terms of the path to provision of a communications system to support the needs of virtual coupling a lot depends upon the starting point. The technology differences between the market sectors is mainly the baseline control system, and therefore its associated communication system.

MOVINGRAIL Deliverable D3.3 on Proposals for Virtual Coupling Communication Structures proposes a communication structure where the direct train communication is merged with longer distance network capability. The most suitable technology for this is from the evolving 3GPP standards, 5G. This also gives synergy for the European rail network with the intention to replace GSM-R with FRMCS, which is also favouring 5G. This equipment architecture for the virtual coupling communication system is shown in Figure 16 with its application for the European mainline network shown in Figure 17.

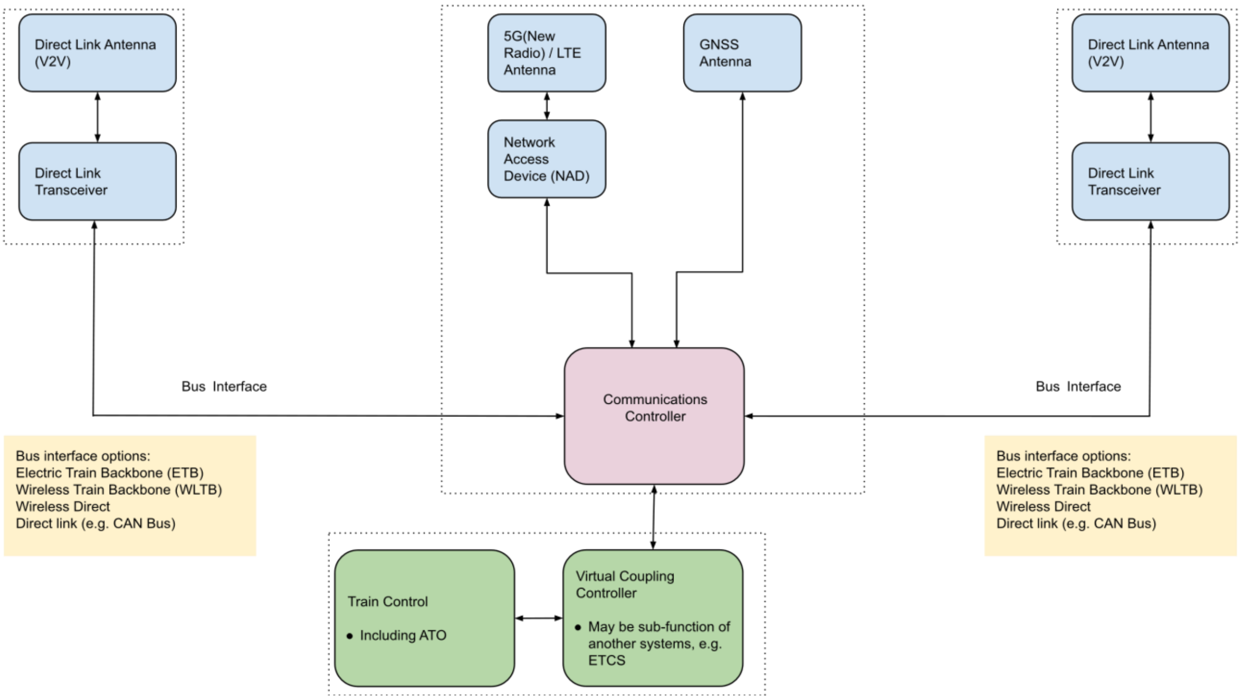

Figure 16: Virtual Coupling communication equipment architecture diagram

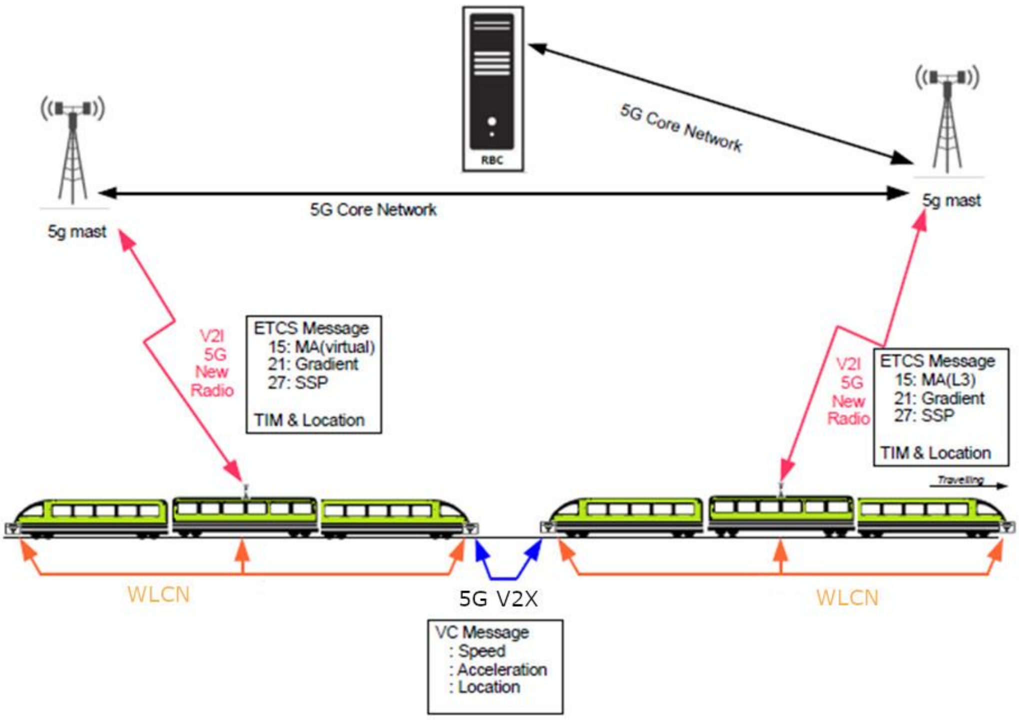

Figure 17: Virtual Coupling communication proposal for mainline railways

3.3.3. Considerations and challenges

The communication system must be capable of trust, including availability and security. The availability target will need to consider the impact of failure on operations, including fallback facilities. This should establish if redundancy is required. Safety responsibility is best addressed at the lowest layer, i.e. with the high-integrity control system.

The very fast pace of change in telecommunications compared to railway control systems poses a challenge. It is possible that current communication solutions may become obsolete before virtual coupling control systems are completed. To address obsolescence there is therefore a need to maximise equipment independence by producing specifications for virtual coupling communications which are as open and abstracted as possible.

For cost effectiveness and to avoid clashes between systems (both for space on trains and for available radio spectrum) maximum reuse and sharing of systems should be sought. To facilitate this, specifications for the virtual-coupling communication system should be produced that are as open and equipment independent as possible. Equipment can be selected that fulfils the architectural needs of a specific application, although again for cost effectiveness equipment should be as common as possible across the virtual coupling sectors and should draw equipment from the automotive market.

Since suitable communication platforms capable of supporting the needs of virtual coupling are available now, it is unlikely that communication equipment will be a restraint on virtual coupling when compared to the integration and safety challenges.

3.3.4. Impact on the roadmap of Virtual Coupling

In conclusion, virtual coupling generates the following main research and development regarding communication structures:

- Analysing acceptable communications latency in relation to distance and speed.
- Investigating the need for equipment redundancy in the context of operational availability.
- Confirming feasibility of implementations of virtual coupling communication structures.
- Developing and specifying communications protocols, including safety and security aspects, for use with virtual coupling.

3.4. Cooperative train protection of train convoys

A VCTS is defined as a set of virtually coupled trains that may follow each other at a distance closer than the absolute braking distance. During the entire lifetime of a VCTS the virtually coupled trains must be carefully monitored and coordinated to act as one train convoy to the outside world (i.e., the (moving) block signalling and interlocking) and to avoid collisions within the convoy. A VCTS onboard train protection system is therefore responsible for the safe and coordinated movement of the virtually coupled trains inside the convoy during the entire lifetime of the convoy, i.e., from the moment of a coupling request of a train until the decoupling of the last train from the convoy.

3.4.1. Main VCTS safety-critical functions

A VCTS train protection system has the following main functions:

- Protecting the trains inside a convoy against collisions,
- Coupling a new train to a train or already existing convoy,
- Coordinating virtual-coupled driving of trains in a convoy,
- Decoupling a train from the convoy.

X2RAIL-3 (2020) proposed to distribute these safety functions over a tactical VCTS train traffic management system and operational VCTS Controllers as follows.

- VCTS Train Management System (VCTS-TMS): a tactical onboard system that is installed on all VCTS trains. A master train uses this system to coordinate the convoy behaviour, while the other virtually-coupled trains use it for cross-checking to guarantee integrity of the tactical decisions. It coordinates the movements of virtual-coupled trains within the convoy, as well the coupling of new trains and the decoupling of trains. It receives coupling and decoupling orders (when, where, who) from a strategic (trackside) convoy management layer corresponding to the planned convoy compositions and ordering, and sends back the convoy ID and state. It collects relevant information from all trains in the convoy (integrity, braking and acceleration capabilities), derives the coordinated train characteristics (braking and acceleration curves), and provides high-level target states and relevant information to all trains in the convoy. The VCTS-TMS of the master train also provides the interface to the signalling system (e.g. train ID).
- VCTS Controller (VCTS-CTRL): an operational onboard system that supervises the safe movement of each train following the tactical commands from the master train, including the commands for coupling and decoupling. It uses relative distance, speed and acceleration with adjacent trains and the master, as well as the absolute state, to guarantee a safety margin between the virtually coupled trains.

These VCTS safety-critical functions are facilitated by two operational subsystems that are connected to the existing Train Control and Management System (TCMS): VCTS Sensors (VCTS-SENS) and VCTS Communication (VCTS-COM). The VCTS Sensors are installed on each train and are additional to the existing TCMS sensors and should guarantee high quality measurements under all conditions, including the absolute dynamic state (distance, speed, acceleration) and the relative dynamic state to adjacent and master trains. In particular, the relative dynamic states between trains at close distance (below 300 m) requires new sensors to increase the measurements accuracy. The VCTS Communication is active on all trains in the convoy and takes care of the communication of the current state of the trains to the VCTS-TMS of the master and other trains, performs handshakes during the coupling process, closes communication after decoupling, communicates relevant TCMS information updates like braking and acceleration curves of the train to the VCTS-TMS, and communicates VCTS-TMS parameters to the TCMS to update the local braking and acceleration curves of the consist to the coordinated requirements from the VCTS.

In the context of Virtual Coupling, ATP is considered as an already existing implemented train protection function based on absolute braking distances, which will be switched off on all trains except the leading train during virtually coupled operations. The existing ATP on board of the trains may interface (or not) with the VCTS system to exchange relevant supervision data (X2RAIL-3, 2020). Hence, the VCTS system replaces ATP for the safe train separation of virtual coupled trains up to relative braking distances using coordinated braking curves. The leading train uses ATP with absolute braking distance for the safe train separation of the convoy to other trains or train convoys. In this way the VCTS train protection system can be explained as a Cooperative ATP for virtually coupled trains running at relative braking distances.

In traditional railway signalling and control a clear distinction is made between vital safety-critical functions (ATP, interlocking, track-clear detection) on the one hand and non-vital control functions (ATO, route setting, train localization for other than safety-critical signalling purposes) on the other, where the two classes of functions have to work seamlessly together. The vital functions require a high Safety Integrity Level (SIL) and are thus more expensive to design and approve. In Virtual Coupling these two perspectives should also be distinguished with a clear demarcation of functions. Hence, the VCTS train protection system contains the vital safety functions that ensure cooperative train protection of virtually coupled trains. Instead, the non-vital cooperative train operation functions that ensure smooth and stable movements of the virtually coupled trains in a convoy are considered out of the scope of this train protection system and thus of the VCTS-TMS and VCTS-CTRL. They are considered in the context of automatic train operation.

3.4.2. Automatic train protection of a train convoy

A VCTS contains one master train that coordinates the behaviour of the entire convoy. All other trains follow the commands from the master and keep at least a relative braking distance from their predecessor (either the master or another train for longer convoys). Various communication topologies exist but here we assume that the leading train is the master, and all other trains in the convoy communicate bi-directionally both with the master and their predecessor. Note that if an intermediate train has the role of the master then the leading train has to provide ATP commands to the master regarding movement authorities with respect to traffic outside of the convoy. To keep the architecture as simple as possible, we assume that the leading train is the master of the convoy and therefore receives and responds to the movement authorities from the signalling system outside of the convoy directly.

The master train takes care of the ATP functions for the entire convoy, i.e., protects the convoy from collisions and derailments by supervising the most restrictive speed profile based on movement authorities obtained from e.g. the RBC for ETCS, and taking into account the coordinated braking curve dictated by the joint trains within the convoy. It therefore provides information about the convoy composition, length, position and speed to the RBC. The RBC provides movement authorities to the master train that is valid for the entire convoy. This also means that the interlocking must guarantee save passage for the entire convoy. This requires additional functionality of the interlocking to maintain route locking until the entire convoy has passed. Likewise for level crossings.

Depending on the cooperation mode of the VCTS (see next subsection) the master train can determine a cooperative braking curve, based on the braking characteristics of each train in the convoy, which essentially means that the performance of the braking curve worsens. In particular, this also means that the ATP braking curve of the leading train (i.e. the master train itself) has to be adjusted to that of the convoy, so that the emergency brake of the leading train can be absorbed by the VCTS. Each time a new train couples to the convoy the cooperative braking curve may have to be adjusted, which will change the dynamic speed profile and possibly violate the movement authority. So this requires a new procedure to update the dynamic speed profile in the protocol to accept a coupling request, including a procedure on how to handle when the actual train state would violate the new dynamic speed profile, such as postponing the coupling request. After coupling, the requests for new movement authorities must also take into account the longer absolute braking distance.

3.4.3. Cooperative modes and automatic train protection within the train convoy

The core of the VCTS train protection system is to guarantee a safe relative braking distance between successive virtually coupled trains within the convoy. For this each train in the VCTS cooperates to exchange the relevant data to implement a coordinated supervision of movements. Still, each train is responsible for its own train protection in coordination with the master train. As such each virtually coupled train computes the safe distance to its predecessor based on

- Its own specific braking characteristics,
- The characteristics of other virtually coupled trains,
- The dynamic absolute distance, speed and acceleration,
- The dynamic relative distance, speed and acceleration with the predecessor.

The relative braking distance from a following train to a predecessor is the difference of the braking distance $BD_f(v_f)$ of the following train with the braking distance $BD_p(v_p)$ of its predecessor plus a safety margin SM that must be kept at all speeds, i.e.,

$$RBD = \max\left(BD_f(v_f) - BD_p(v_p), 0\right) + SM.$$

The braking distance depends on train speed as well as the train-specific braking curve from that speed including latency/reaction time. If the following train has a longer (or same) braking distance then an extra safety distance $BD_f(v_f) - BD_p(v_p) \geq 0$ has to be taken into account. On the other hand, if the following train has a shorter braking distance then the relative distance must still always respect the safety margin SM. For stable following some extra buffer distance is needed to avoid immediate violation of the relative braking distance when either the speed of the following train increases or that of the predecessor decreases, e.g. due to varying gradients. In particular, the gradient profile must be taken into account in the computation of the braking curves of all trains in the convoy.

There are essentially three modes of VCTS behaviour which represent a trade-off between braking curve performance and inter-distance between the trains in the convoy:

1. **Uncooperative braking**: each train in the convoy computes its relative braking distance with respect to its own specific braking curve and the braking behaviour of its predecessor.
2. **Cooperative braking**: the master train computes a cooperative braking curve for all virtually coupled trains based on the characteristics of each train in the convoy.
3. **Cooperative braking and acceleration (platooning)**: the master train synchronizes the movement of all virtually coupled trains in the convoy including cooperative braking curves.

In the uncooperative braking mode the headways between trains will vary according to the relative braking characteristics of successive trains. In particular, a train with low braking capabilities will keep a longer safety distance after a train with fast braking capabilities to always keep a safe relative braking distance even when the predecessor brakes at its full capability. Conversely, a train with fast braking capabilities can adjust its braking behaviour to that of a predecessor with low braking capability and thus minimize the distance between the trains to the safety margin. This option means in particular that the leading train does not need to adjust its ATP braking curve and thus can use its full braking capability for ATP emergency braking. This mode is a straightforward application of the relative braking distance and enables closer running and merging to increase track capacity.

The cooperative braking mode harmonizes all braking curves to that of the worst-case braking train. In particular, also the ATP braking curve of the leading train is adjusted to the cooperative braking curve of the convoy. This mode implies that all trains can follow at the minimum safety margin (plus some buffer for stability) and thus at minimal convoy length. The effectiveness of cooperative braking depends on the heterogeneity of the trains in the convoy. In particular, coupling a train with slow braking and acceleration capabilities will slow down all the other trains due to harmonization to this lower performance. This mode enables optimal track capacity at bottlenecks such as junctions and point areas, traversed at a restricted speed, while maintaining flexibility of trains to run away from the convoy immediately after the bottleneck. In these cases, after the track speed increase each train may start accelerating one after another at a different time as soon as either its rear or front (depending on the restriction) has passed the restricted speed area. The distance to the following train will then grow until the following train accelerates to a higher speed after which it can close in on the predecessor again. Note that if the trains run at the track speed limit, the distance can only be shortened after the predecessor slows down again, possibly at a speed restriction or next station stop. Depending on the situation, it may occur that the distance between trains becomes so big that the leading train will (intentionally) decouple itself and the next train will take over the master role, which repeats itself for a convoy of more trains. The trains may then couple again into a new convoy at the next speed restriction or station stop.

The third mode of cooperative braking and acceleration aims at a fully synchronous behaviour of the trains in the convoy similar to a physically coupled train composition. In this case both the braking and acceleration characteristic of each virtual coupled train is harmonized to the worst-case braking and acceleration capabilities. Moreover, the acceleration and braking of all trains will be fully synchronized so that the convoy acts as one maintaining a minimal length (within some tolerance needed for stability). This mode is used for platooning with trains maintaining a distance as close as possible. In this case, a varying static speed profile will slow down the trains in a platoon even when composed of homogeneous trains. After an increase of the track speed limit, such as after a restricted station speed or point speed, all trains maintain the lower speed until the last train of the convoy is allowed to start accelerating. Hence, platooning with synchronized braking and acceleration will generally lead to increased running times. Still, synchronizing the braking and acceleration characteristics of the entire convoy is in line with physical coupling of train consists.

The VCTS train protection system also has to coordinate and supervise the approaching behaviour of a train that coupled to the rear of a convoy to reach a desired distance to its predecessor. In particular, the newly virtually coupled train will have to operate at a higher speed than its predecessor to close in from the absolute braking distance towards the relative braking distance. As the new train approaches its predecessor it has to slow down to the same speed of the predecessor before reaching the safety margin from the predecessor plus the possible extra safety distance in the case of uncooperative braking curves. If a slower braking train joins a cooperative braking VCTS then the cooperative braking curve has to be adjusted and the new one communicated to all trains in the convoy. Moreover, the ATP braking curve of the leading train will change to a lower performance, which will change the dynamic speed profile and possibly violate the movement authority. Hence, first a valid movement authority and dynamic speed profile has to be obtained by the master train before the new cooperative braking curve is communicated to all the other trains in the convoy and the new train can approach the safety margin.

Likewise the VCTS train protection system has to coordinate and supervise the decoupling of trains from the convoy. If the last train wants to decouple then it has to slow down until it is separated more than the absolute braking distance, or block distance in the case of fixed block signalling, in which case it can be decoupled and its ATP takes over the normal train protection again. In the case that a convoy splits in multiple convoys, the process is similar while in the case of a cooperative braking VCTS the cooperative braking curves will have to be adjusted in either convoy after the decoupling. In this case, the cooperative braking curve may improve resulting also in an improved ATP braking curve of the leading train.

Virtual Coupling also requires a more detailed safety analysis of specific types of railway incidents whose magnitude might be increased with respect to conventional signalling, plain moving block or even to physical coupling. An example is the immediate arrest (i.e. a dead stop) of the master train of a convoy due to e.g. a derailment or sudden collision with an embankment. In that case a physical coupling of trains would be expected to reduce the magnitude of the accident as opposed to virtually coupled trains that would collide one after another into their predecessor, unless additional safety margins separate the trains. Further research is hence needed in this direction also because the presence of unmitigated safety risks might compromise essential implementation steps such as regulatory approval and public acceptance.

3.4.4. Impact on the roadmap of Virtual Coupling

In conclusion, virtual coupling generates the following main research and development regarding automatic train protection:

- Defining various cooperative modes of VCTSs.
- Developing protocols and algorithms for determining cooperative braking curves and relative braking distances.
- Defining procedures for updating ATP braking characteristics for running trains.
- Defining the interfaces between safety-critical functions and train operation functions.
- Developing an appropriate safety analysis for virtually-coupled trains in a convoy.

3.5. Cooperative train operation of train convoys

The VCTS train protection system determines and supervises the cooperative braking curve of each train in the convoy to ensure that the relative braking distance to the predecessor is respected. However, the VCTS train protection system is not in charge of driving the trains within the convoy, which is done either manually by a driver or by ATO. In particular, the stability of the train movements within the convoy depends on the individual virtually coupled trains. When trains run in a platoon it will be hard for a driver to manually follow the behaviour of the preceding train, in particular considering gradients that will lead to asynchronous traction and braking commands for successive trains in a convoy. Also ATO algorithms have been developed for individual trains under safety envelopes for absolute braking distances, and they cannot be used for headway control of virtually coupled trains which requires a cooperative behaviour.

3.5.1. Platooning versus convoys

Train platooning requires cooperative automatic train operation in three phases:

- Joining the platoon after coupling to the convoy,
- Maintaining stable train movements within the platoon,
- Splitting from the platoon and decouple from the convoy.

Note that platooning was defined as one of the cooperative Virtual Coupling modes in the previous section, and therefore a platoon is not the same as a convoy or VCTS. A platoon is defined as follows.

- A **Platoon** is a set of trains that move cooperatively as close as possible using cooperative adaptive control to maximise track capacity. Joining or splitting a platoon can occur at stations or on-the-run.

As soon as a train moves towards a predecessor closer than the absolute braking distance they must already have been virtually coupled and considered as part of a train convoy and treated as such by the interlocking systems. Hence a train convoy has a signalling meaning of trains running with a train separation between absolute and relative braking distance that can only be safe when Virtual Coupling rules apply. Instead, a platoon has an operational control meaning of trains running synchronously. A platoon is also possible for Moving Block signalling where connected trains move cooperatively but keep an absolute braking distance. The platoon control functions do not necessarily have to be SIL 4, as long as the VCTS or ATP safety functions supervise safety for relative and absolute braking distances respectively. Of course, the cooperative control must be extremely reliable to avoid disturbances. Note that we defined different terminology for entering and exiting a convoy or a platoon to emphasize the distinctive feature of the signalling concept of Virtual Coupling and the cooperative adaptive control concepts such as platooning. Coupling and decoupling are related to Virtual Coupling and Convoys. For platooning, we use joining and splitting instead. Platoon joining and splitting occurs within a train convoy when it is applied to virtually coupled trains. Hence, we have split the safety-critical functions of convoy initiation, virtually coupled driving and convoy termination, from the cooperative adaptive control related functions of stable closer following in platoons, closer merging over converging tracks, and closer crossing.

Within a train convoy it makes sense that trains use some kind of cooperative control, in particular when more than two trains are involved, but there are more options besides platooning. In the literature of (road) Connected Automated Vehicles various types of cooperative control are defined depending on the information flow structure between successive vehicles and the leader, and the physical network configuration (like following vehicles/platooning, merging vehicle, and coordination at crossings) (MOVINGRAIL, 2020a). Likewise, future train-centric train operation may use Virtual Coupling for platooning (closer following) but also for other applications such as closer merging or closer crossing where cooperation using Vehicle-to-Vehicle communication can be exploited for effective close operational manoeuvres.

In summary, virtually coupled trains form a so-called train convoy or VCTS based on Vehicle-to-Vehicle communication and are viewed as one train by the interlocking systems. Virtual Coupling allows platooning where the trains in the convoy move cooperatively as close as possible following the leader to maximize track capacity. Formation of platoons can occur at stations or on-the-run. Likewise splitting can occur on-the run, which can be used to decouple a train from the convoy and then run again as a separate train at an absolute braking distance using (moving) block signalling so that e.g. switches can be operated safely and the train can move to a different station track or railway line at a junction.

3.5.2. Car and train following models

The master train will dictate the reference speed profile of the entire VCTS. The simplest way to do this is that it determines its own optimal train trajectory based on the timetable, guidelines, expertise, DAS or ATO algorithms, and then the other trains in the convoy simply follow their predecessor and thus implicitly the master train using the relative dynamic distance, speed and acceleration. This leads to train-following behaviour (Quaglietta et al, 2020) similar to car-following models (Brackstone and McDonald, 1999) as used in Adaptive Cruise Control. More advanced approaches use cooperative systems based on Vehicle-to-Vehicle communication, with either cooperative sensing to improve performance by increased awareness of other vehicles, or cooperative control to improve performance by collaboration between the vehicles to optimize a common goal (Wang, 2014b). These cooperative systems are used by Connected Automated Vehicles (Li et al., 2017; Wang et al., 2020).

In the literature of car-following models various spacing policies and algorithms have been proposed to control the gap to the predecessor, including constant distance gap, constant time gap, variable time gap, and safe distance. Note that gap refers to the distance from the front of the follower to the rear of the predecessor, while headway is traditionally defined between the fronts of two successive trains. The constant time gap model is widely used for Adaptive Cruise Control (ACC) in cars, but it cannot guarantee collision-avoidance at all conditions, like all mentioned algorithms besides the safe distance model. So in practice the ACC is switched off at safety-critical and dense traffic conditions (Wang, 2014a). With V2V communication the car-following models can be extended to use information from the preceding vehicle or further downstream vehicles (like the leader of a platoon) to improve the awareness of the situation ahead resulting in improved traffic stability. This is the area of Connected Automated Vehicles as used in platooning. These models make use of cooperative sensing but the nature of the controllers is still non-cooperative, in the sense that the controlled vehicle makes decisions independently and tries to reach its own desired situation. Neither prediction nor consensus is reached with other vehicles in the decision-making process (Wang, 2014b).

Model-Predictive Control (MPC) is an optimization-based approach that typically minimizes the deviation from the desired relative distance (gap), the deviation from the predecessor speed, and the absolute acceleration, using a prediction over a rolling horizon (Wang, 2014a). In MPC also more complex cost functions can be applied including a high penalty when the vehicle approaches the predecessor at small headways to provide an explicit safety mechanism that can avoid rear-end collision with the predecessor. Moreover, the MPC approach can use V2V communication to use information from both predecessors and successors (cooperative sensing) and compute cooperative controls on manoeuvring a platoon together under a common objective. In this case the acceleration of other trains can also be taken into account leading to a more anticipative control. The multi-anticipation and cooperation with followers improves smooth and stable vehicle movements in a platoon. In particular, downstream cooperative vehicles compromise their own situation to benefit the upstream vehicles, which is the nature of cooperation (Wang, 2014b).

In the railway literature, (cooperative) control of multiple trains has only recently been explored with the emergence of moving block signalling, as for fixed-block signalling the literature focused on the scheduling of conflict-free timetables (Goverde et al., 2016) and conflict detection and resolution to maintain conflict free train paths (Quaglietta et al, 2016). Quaglietta et al. (2020) developed a rule-based train following model for virtual coupled trains demonstrating the impact of varying gradients on the speed and distance deviations of two virtually coupled trains. Felez et al. (2019) developed a preliminary MPC approach for virtual coupled trains using a predecessor-following information structure minimizing a function of desired safe relative distance, speed of the predecessor and the jerk. Several papers developed train-following (headway control) models for a set of trains using predecessor-following information from vehicle-to-vehicle communication under moving block signalling (absolute braking distance) by optimizing a function of relative distance and (relative) speed (Dong et al., 2016; Gao et al., 2019, Xun et al., 2019). Li et al. (2016) developed a coordinated cruise control for a predecessor-following information structure where each train tracks a desired speed while keeping the relative distance of following trains in a stable range between a minimum and maximum headway. Bai et al. (2019) developed a cooperative cruise control using a multi-agent system with distributed control, in which the trains reach a cruising speed consensus and the relative distances between successive trains converge to the absolute service braking distance, while staying below the absolute emergency braking distance. Several publications consider an optimal control approach that optimizes the entire train trajectory (speed profile) of multiple trains under fixed-block or absolute block signalling using sequential trajectory optimization of the following trains (Goverde and Wang, 2016a; Albrecht et al., 2015, 2018), joint (cooperative) optimization of the multi-train trajectories together (Wang and Goverde, 2016b; Ye and Liu, 2016), or both (Wang et al., 2014). Yan et al. (2016) developed a distributed multi-agent cooperative model for online multi-train trajectory optimization for a group of trains under moving-block signalling using MPC, and minimizing a function of energy consumption, relative distance, and acceleration for all trains together, assuming each train can communicate with all others. The main objective of this model is to decrease the total energy consumption over a corridor rather than infrastructure occupation (headways).

3.5.3. Cooperative train operation of platoons

For virtual coupling in railway operations, the relative braking distance depends on speed, and hence the constant distance gap policy is not applicable, although a constant time gap policy provides a constant distance for a given (cruising) speed. Train following is more difficult than for road vehicles due to the higher masses and slow braking and acceleration of trains. In particular, train following at a constant gap (either in distance or time) between successive trains in a platoon is complicated by varying static speed profiles as discussed in the previous section, and it is complicated further by varying gradient profiles, and in particular by steep slopes where it will be impossible for successive trains to maintain the same speed as they successively enter and leave the slopes at different times. For cruising over moderately varying gradients (i.e., no steep downward or upward hills) it may be possible to maintain stable relative distances but the traction and braking commands will be accordingly asynchronous. Also the braking curves depend on the gradient profile and thus are asynchronous for successive trains. This effect must be taken into account in a predictive model of the relative braking distance.

Manual driving in a platoon is thus very challenging. The VCTS train protection system will provide the (cooperative) braking curves at all times but running close to another train within the absolute braking distance will not be comfortable to train drivers. A DAS may be used to provide speed advice but that does not change the discomfort of a train driver running close behind a predecessor. As a result, manual driving will result in bigger headways between trains in a platoon while the train movements in a platoon can still be expected to be unstable by the reaction time of the successive drivers. Platoon performance (headway control) can be optimized by automation of train operation. The literature of Connected Automated Vehicles showed that the V2V communication must be used for cooperative sensing and control to improve platoon stability and performance. Therefore, the existing ATO algorithms based on single-train behaviour must be extended to cooperative train operation of multiple virtually-coupled trains in a convoy.

A basic platoon trajectory optimization problem has to determine the train trajectories for the successive virtually-coupled trains from stop to stop while keeping a safe distance between the train trajectories based on the relative braking distances. This provides a reference trajectory for each of the trains but it is questionable whether this will provide a basis for a stable train following given uncertainties in parameters and external conditions (e.g. mass, adhesion, wind). Instead, such a multi-train trajectory optimization problem could be used to derive the tactical reference trajectory of the leading train, while the following trains will be tracking the leading train via their predecessor using predecessor-following information by either a train following (cooperative sensing) model or cooperative MPC. Such algorithms still have to be developed. The developed models based on moving-block signalling and automotive Connected Automated Vehicles could be used as a guide. A particular interesting open question is the impact on energy consumption of a platoon. The literature on single and multi-train trajectory optimization mostly considers energy consumption as the main objective besides punctuality, so that the running time supplement is used as effective as possible for energy savings. In particular, coasting regimes are applied in which case a train does not use any traction or braking so that the acceleration (or deceleration) is determined by the resistance forces only, and specifically by the gradient profile. Coasting in a convoy will lead to varying headways between the successive trains in the convoy with possibly corrective braking and/or acceleration to keep a safe distance. Hence, coasting may turn out to be inadmissible for stable movements in a platoon which may affect the energy efficiency of all the trains in a convoy.

Joining a platoon on-the-run under virtual coupling requires a special approach trajectory from the absolute braking distance after coupling to the convoy to a stable safety distance close to the relative braking distance. During the entire approach the speed exceeds that of the predecessor and has to converge to the speed of the predecessor at the optimal safety distance, while the relative braking distance may never be exceeded. This is a specific train trajectory optimization problem for which a dedicated algorithm has to be developed.

Splitting from a platoon seems easier as this means that the train has to slow down and so does not generate a risk of exceeding the relative braking curve. Nevertheless, also this process can be optimized to a controlled train trajectory from tracking a predecessor in a platoon within a convoy to decoupling from the convoy and running separately again according to an own train trajectory. In particular, energy can be saved by avoiding a too big decline in speed before picking up the own train trajectory to follow the predecessor train or convoy at an absolute braking distance or fixed-block. Moreover, splitting from a platoon typically occurs before a diverging point towards another railway line or platform track in a station. This is another cooperative train trajectory optimization problem that has to determine the optimal splitting time and the subsequent train trajectory until the stop or after the junction. This process is even more challenging when a platoon of multiple trains has to dissolve with successive trains heading towards different platform tracks. This also requires cooperation with the point or route control to synchronize the train movement with the point movements and route interlocking.

In summary, train trajectory generation and tracking of multiple virtually-connected trains in a convoy is a nontrivial issue and in particular requires a cooperative train control approach where the train trajectories of all trains in the convoy are jointly optimized. This is then typically a task for advanced ATO using cooperative train control rather than for a safety-critical system. Hence, a VCTS train protection system should be restricted to computing and supervising relative braking curves for each train in the convoy, which will be used as hard constraints to a cooperative ATO system that generates and tracks the train trajectories for the successive virtually-coupled trains. This cooperative train operation should be an essential component of virtual coupling, in particular for platoons, to obtain effective and stable train movements. The train trajectory tracking problem must be specifically aware of the possible changing relative braking distance depending on the gradient profile.

3.5.4. Impact on the roadmap of Virtual Coupling

In conclusion, virtual coupling generates the following main research and development regarding cooperative train operation:

- Developing a cooperative train operation method for stable and optimal platooning.
- Developing a cooperative approach trajectory algorithm to join a platoon.
- Developing a cooperative platoon splitting train trajectory algorithm.
- Developing a cooperative platoon dissolving algorithm with trains diverging to different platform tracks.
- Investigating energy-efficient train platooning.

3.6. Railway traffic planning and management

Virtual coupling will change railway traffic planning as the capacity allocation may now incorporate relative braking distances and therefore reduce path conflicts. In addition, platoons may have to be carefully planned including types and order of trains. Also railway traffic management will have to interface with cooperative train operation.

3.6.1. Capacity allocation and conflict detection

Virtual coupling enables trains to move as close together as the relative braking distance. This means that existing infrastructure capacity calculation models and train path conflict detection models need to be adjusted. These models are generally based on microscopic blocking time theory (Pachl and Hansen, 2014; Pachl, 2018), such as the well-known UIC timetable compression method (UIC, 2013). In particular, blocking time theory needs to be adapted to include headways related to relative braking distances between trains.

Blocking time theory models the time that a train claims (or blocks) a track section from the time the track section is setup for a train until it is released again. For fixed-block signalling a track section corresponds to a (partial) block section, while for moving-block signalling it corresponds to a continuous section on the track except for point sections that provide discontinuities corresponding to a given time to set and lock the point. These models have in common that overlapping blocking times indicate train path conflicts. For relative braking, a track will already be claimed by a train when its predecessor is still occupying it, which is not a conflict if the two trains are virtually coupled and run at a relative braking distance. Hence, virtual coupling allows overlapping blocking times of virtually coupled trains that needs to be incorporated in these models to correctly calculate the infrastructure occupation and conflicts. Still diverging movements at points require an absolute braking distance between trains to guarantee that the following train can still brake when needed if the point cannot be locked for some reason. Another issue is that virtually-coupled trains adapt their speed profile, and therefore their time-distance path, to that of the train ahead in a convoy. Hence, differently from moving block and fixed-block signalling where train trajectories are calculated independently, Virtual Coupling entails a joint computation of time-distance train paths within convoys before blocking times can be computed.

After extending the blocking time theory with relative braking and virtual coupling principles, all methods based on blocking time models can be applied also for virtual coupling, including the UIC infrastructure occupation calculation method (UIC, 2013), microscopic conflict-free timetabling methods (Goverde et al., 2016), and conflict detection (and resolution) methods for railway traffic management (Quaglietta et al., 2016).

3.6.2. Platoon planning

In the case of platooning where trains are virtually coupled and operate in a train convoy for longer stretches it might payoff to plan the platoon compositions in advance, including the train types and the order of the trains. In particular, platoons of homogeneous virtually coupled trains are easier to manage than trains with largely varying braking and acceleration capabilities. Also the order of coupling to a train convoy will determine how easy a train can be decoupled again. Hence, a platoon planning model may be developed and added to the planning or traffic management systems such that 'bundling' of homogeneous trains can be done effectively with platoons of virtually-coupled trains to increase capacity on corridors and bottleneck areas. Here, the arrival and departure times of the trains should be coordinated to be able to couple and decouple train convoys at the most convenient locations, including virtually coupling or decoupling in stations and on-the-run. In general, the decision which trains should form virtually-coupled platoons depends on multiple objectives, including capacity, punctuality, operational costs, running time, waiting time, and energy efficiency. The platoon decision may also affect the timetable and rolling stock allocation to align compatible trains for effective platooning.

Platoon planning may also be included in rolling stock circulation planning when train compositions are replaced by platoons of virtually coupled trains that can dynamically join or split either at stations or on-the-run. This allows a flexible adjustment of train compositions to passenger demand by adding or removing trains to/from the platoon where needed. In this case optimal platoon composition plans can be developed that satisfy passenger demand on a railway line with a minimal number of virtual-coupled trains including when and where trains join and leave the platoon.

These platoon planning models fit the strategic layer as proposed in X2RAIL-3 (2020), which defines the convoys, their composition and ordering, as well as when and where trains are coupling to and decoupling from a convoy. 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. It is connected to the traffic management system which on its turn is connected to the planning system that defines the train services (timetable or on-demand Mobility as a Service (MaaS) platform).

3.6.3. Integrated traffic management and cooperative train operation

Virtual coupling may be used on-the-fly like any other railway signalling system whenever needed as long as trains are equipped with virtual coupling. This can increase capacity at certain bottlenecks such as track areas with speed restrictions, where trains may follow closer than the absolute braking distance. Trains can then flexibly couple to and decouple from a train or train convoy such that they can follow safely at a relative braking distance and save infrastructure occupation.

Current developments in ATO focus on the interaction between traffic management systems (TMSs) and ATO trackside systems to define targets for the ATO onboard of the connected trains. This architecture fits perfect for platoon planning on the ATO trackside that then sends the coupling and decoupling locations to the cooperative ATO onboard relevant trains. When a train couples to a train or train convoy, the ATP will be switched off and the VCTS train protection takes over, and likewise, the ATO will be replaced by the cooperative train operation system.

A perfect alignment of traffic management and train operation is in particular required for merging train movements of trains that will join in a platoon. In particular, trains departing from different platform tracks that will join in a platoon towards the same destination. Since moving points require absolute braking distance between successive trains from different directions, it is essential that the departure times and route setting are carefully synchronized with the merging train movements over the point into the same track. The closer the following train can merge after the release of the point by the leading train the smoother the coupling process can be with the least running time loss. This requires cooperation between both the trains involved and the route setting. A similar situation holds for a merging manoeuvre of running trains over a railway junction. And likewise, diverging train movements after decoupling from a convoy needs perfect alignment with the route setting between the successive trains to minimize time loss and therefore enable divergent train movements as close as possible.

The merging and diverging processes may be further optimized by innovations in switch technology, and in particular, the development of passive switches, wherein the rails at the switching point remain in a stationary position while the railway vehicles possess mechanisms that determine the direction of travel at the switch. The primary purpose of such devices is to allow trains to travel in different directions at a switch without any time needed to move and lock the switch between the passage of the trains. Moreover, because the switch is now stationary an absolute braking distance is no longer needed, and so successive virtually coupled trains can have divergent movements over a switch at relative braking distance, while the diverging train gets decoupled from the convoy as soon as it has moved towards the other track. Such passive switch technology thus allows close merging and diverging at switches at a relative braking distance, which also requires the interlocking to set routes and grant movement authorities to the switch at the same time while relying on the VCTS train protection to maintain a sufficient relative braking distance between the virtually coupled trains. For trains merging into a convoy this then requires that the merging trains will already be virtually coupled before the switch and the merging movements must be carefully coordinated using cooperative train operation.

An existing switch technology that could also be exploited for closer merging are spring switches. Spring switches allow trailing point movements where the flanges on the wheels will force the switch to the proper position. This also allows merging at relative braking distance for virtually-coupled trains. Spring switches may be restricted to lower speeds and therefore could be specifically interesting for merging after standstill at different platform tracks. New technology may be developed for spring switches that can be used at high speeds for trailing movements from either trailing direction. This technology then allows close following over merging tracks which will greatly increase the potential of platooning for virtual coupled trains starting from different platform tracks. In this case the trains at different tracks will be virtually coupled before departure, where also the train order in the platoon is determined. Then the leading train departs, followed closely by the other virtually coupled trains in the order specified. The cooperative train operation optimizes the train trajectories of the successive trains so that effectively all trains accelerate one after another and join the platoon right after the switch at the optimal distance.

3.6.4. Impact on the roadmap of Virtual Coupling

In conclusion, virtual coupling generates the following main research and development regarding railway traffic planning and traffic management:

- Extending blocking time theory with relative braking distances and virtual coupling principles.
- Including the extended blocking time theory in conflict detection models for railway timetable planning and railway traffic management.
- Developing models for platoon planning.

- Developing integrated cooperative train operation and traffic management.
- Developing passive switch technology for merging and diverging at relative braking distance.

3.7. Conclusions

This chapter discussed the scope of Virtual Coupling and the existing knowledge gaps that need to be filled for the main operational and technical railway system components. In particular, the communication, safety, and control technology has been emphasized, including communication structures, interlocking and route setting and release, automatic train protection of convoys, cooperative train protection within train convoys, cooperative train operation within train convoys, platoon planning, and integrated railway traffic management.

All of these components are critical for an implementation roadmap, in the sense that each of them needs to be sorted out or it will halt the implementation as a whole. Moreover, a safety and performance analysis should be developed for the integrated system rather than for separate components. For instance, safety and performance of the entire system depends on the interactions between communication structures (train-to-train and train-to-trackside), the safety systems (e.g. interlocking, convoy route locking and route release, cooperative train protection within convoys), and automated train and traffic control systems (e.g. traffic management and cooperative train operation), which may differ for the different market segments.

Another main recommendation is that a clear distinction should be made between VCTS safety functions and cooperative automatic train operation functions. In particular, a convoy or VCTS is a vital safety system concept that allows virtual-coupled trains to follow each other up to relative braking distances, including the associated safety protocols and procedures. In contrast, a platoon is a non-vital multi-train control concept that enables (virtually-coupled) trains to move synchronously and stable together, including the associated cooperative control algorithms. Both use the vehicle-to-vehicle communication for cooperative sensing. The VCTS train protection system supervises the relative braking distances for each train in a convoy, while the cooperative train operation system guarantees stable operation in a platoon under the constraints of relative braking distances. The interactions between these two components are comparable to ATP and ATO under fixed-block and moving-block systems. Smooth performance of trains in a platoon is only possible when these two components work seamlessly together, but their distinctive vital versus non-vital functions are essential for an efficient implementation of Virtual Coupling.

4. Application Roadmap

4.1. Introduction

This chapter applies a technology roadmap for the implementation of VC. The roadmap is developed by associating the identified step-changes with market segment and time of implementation referring to MOVINGRAIL WP1 (operation), WP3 (technology) as well as Tasks 4.1 and 4.2 (business). Particularly, the SWOT analysis will be used from MOVINGRAIL D4.1 to show the benefits and enablers (i.e. strengths and opportunities) of the implementation of VC to each market segment through optimistic scenarios. The weaknesses and threats will be used instead to identify potential pessimistic scenarios for the VC roadmap (see Chapter 5). In MOVINGRAIL D4.2, railway operation simulation models were used in combination with expert opinions of key stakeholders to feed a Multi-Criteria Analysis (MCA) that unveiled the impacts of Virtual Coupling for each of the market segments in terms of quantitative criteria (i.e. capacity, costs, system stability, energy consumption and travel demand) and qualitative criteria (i.e. safety, public acceptance and regulatory approval). The MCA was developed for two resignalling alternatives:

- S1: Migration from conventional multi-aspect signalling systems to ETCS L3 Moving Block,
- S2: Migration from conventional multi-aspect signalling systems to Virtual Coupling (via ETCS L3 Moving Block).

Based on the outcomes of MOVINGRAIL D4.1 and D4.2, a gap analysis is performed to identify a roadmap for the railway business which can effectively lead towards the deployment of Virtual Coupling by year 2050 (European Commission, 2011). The gap analysis consists of determining steps that must be undertaken to improve a present state towards a desired state. More details on the roadmapping methodology approach in this deliverable can be found in Section 4.3.

This chapter describes a quantitative-qualitative comparative analysis between current and future states in the operational, technological and business domains that will identify differences and the step-changes that need to occur to migrate each of the domains towards Virtual Coupling. By crossing step-changes identified in these three domains, a roadmap is developed which details transitions that need to occur to progressively deploy VC. The roadmap also considers costs and investments that need to be setup for Research and Innovation (R&I) and implementation of technologies that require further development. Input of key stakeholders is used to allocate possible timelines to each of the operational, technological and business changes identified by the roadmap. In addition, a set of optimistic and pessimistic scenarios for each market segment is detailed in Chapter 5 for the development of associated roadmaps for each market segment in Chapter 6.

In the following sections, a literature review is provided on technology roadmapping, particularly on scenario-based roadmaps, followed by the approach used in this deliverable. Then a Swimlane roadmap is presented based on a stakeholder survey to assess priorities and time orders for a set of future steps and actions relative to the implementation of Virtual Coupling.

4.2. Literature review on technology roadmapping

4.2.1. Scenario planning

A scenario is defined as hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points (Kahn and Wiener, 1967). Troch et al. (2017)

define a scenario as an exploration of hypothetical future events, highlighting the possible discontinuities from the present and used as a tool for decision-making. Lobo et al. (2005) mentioned that scenario-building is important as a powerful tool to broaden perspectives and to explore the universe of possibilities for the future. They also stated that scenario building is an interesting bridge between citizens and decision makers, helping to identify present critical branch points for a sustainable future. Scenario building is used to help thinking about possible futures and their implications (European Commission, 2007). Lindgren and Bandhold (2003) define scenario planning as an effective strategic planning tool for medium- to long-term planning under uncertain conditions. It helps to sharpen up strategies, draw up plans for the unexpected and keep a lookout in the right direction and the right issues. Geum et al. (2014) state that scenario planning can be applied as an effective approach to deal with a complex and rapidly changing business environment. Bauwens (2015) showed that scenarios are developed in order to help people empathize in plausible futures.

Troch et al. (2017) explored scenarios for the development of a Belgian rail transport system based on a SWOT analysis. Results showed that the obtained scenarios allow the quantification and measurement of the impact of future developments and decisions towards the Belgian rail freight market. Quiceno et al. (2019) used scenarios to support strategic development for electricity companies in the Colombian electricity industry facing technological transformation. Results showed that the most advantageous and challenging scenario for electricity companies represented a continuous decrease of the renewables' cost and a favourable policy and regulation towards new technologies, so they have to downsize their traditional business and seek new opportunities. These examples illustrate that scenario planning is a useful tool to put forward strategies, seize opportunities and offset the threats presented by the uncertain changes in technologies and the business environment.

4.2.2. Technology roadmap

A roadmap is defined as a way to illustrate and communicate alignments of technology and product development with market requirements and the right timing guided by a common vision (Phaal, 2004). Phaal and Muller (2009) consider roadmapping and its many derivatives as a useful graphical tool to structure the development of a strategic plan within the broader picture of a sector. Ricard and Borch (2011) define the roadmap as a visual representation of layers of information related to developments of technologies in the explored context. Bauwens (2015) defines roadmapping as a useful graphical tool to structure the development of a strategic plan within the broader picture of a sector. The focus on condensing the complex information into a graphical framework is considered as a key-benefit of technology roadmaps, allowing for visualization of market pull and technology push and checking the consistency in alignments.

The aim of a technology roadmap is to provide a strategic framework for aligning and prioritizing market trends and drivers with technology developments and R&D. Bauwens (2015) considers that roadmapping is a powerful and flexible technique for supporting strategic planning. Roadmapping is therefore useful as a structural and strategically flexible tool when navigating in uncertainties.

Roadmaps are mostly represented in a layered structure of solution strategies together with a time dimension (Lee et al., 2015). Roadmaps can also be used for illustrating the sequence of actions in time (Phaal et al., 2004; Phaal et al., 2009; Robinson & Propp, 2008).The main layers identified in a roadmap are market/business, service/product, technology/science and resources (Yang and Yu, 2003; Phaal et al., 2009; Ricard et al., 2011; Phaal et al. 2012; Hussain et al., 2017).

In the past decade, dynamic roadmaps have been used to overcome the key challenge for technology managers and practitioners for implementing a robust roadmap and keeping it alive (Phaal et al., 2001). Bauwens (2015) adopted a dynamic roadmap where he uses a quantitative approach in a qualitative way, since it provides a step-by-step approach to map dynamic actions. He mentioned that the stakeholders involved in the research need guidance to turn their awareness of the system vulnerabilities and insights into actions, and therefore the need of a roadmap. Results show that dynamic roadmaps should be designed by involving strategic planners and that validation is important if the roadmap should be respected by strategic planners. Gerdsri and Kocaoglu (2007) used the Analytic Hierarchy Process (AHP) to build a strategic framework for technology roadmapping. They presented a new methodology called the Technology Development Envelope (TDE) to transform the roadmapping approach to the level in which it is dynamic, flexible and operationalizable. Quiceno et al. (2019) showed that the robust strategy focuses on transforming the current business with existing resources and the development of new capabilities. In addition, the process to construct the strategy requires systems' thinking, as the scenarios present a variety of different dynamics that have to be considered and compared.

4.2.3. Scenario-based roadmap

Scenarios must be used to design a robust roadmap (Bauwens, 2015). Moreover, using scenarios in an early stage of roadmapping ensures that risks and uncertainties are considered and that the roadmap is more robust (Wise et al., 2014; Ilevbare et al., 2014). Geum et al. (2014) proposed a three-step combined approach to support scenario planning consisting of scenario building, technology roadmapping, and system dynamics simulation. They considered three scenarios (i.e. optimistic, pessimistic and neutral) for a case study of carsharing services in Korea to demonstrate the applicability of the proposed approach. Lee et al. (2015) used a scenario-based roadmapping approach to help decision makers in assessing the impacts of changes on organizational plans. Cheng et al. (2016) used a scenario-based roadmapping (SBRM) method for strategic planning and decision-making to incorporate the scenario planning (macro level) and roadmapping (micro level) perspectives. Results showed that the proposed method allows companies to externalize their insights of practical future scenarios with positive and negative impacts at micro level for strategic planning and forecasting. It also help companies –specifically dealing with strategic planning and technology management– to visualize the future action plan according to the plausible future scenarios in an effective way.

4.3. Roadmapping methodology

The scenarios presented in this deliverable are a collection of plausible future events to assess their impacts over a long-term strategy. The scenario building is closely related to the outputs of the SWOT analysis developed in MOVINGRAIL D4.1 and to criteria results in MOVINGRAIL D4.2. The roadmap is used as a strategically flexible tool to visualize timelines and priorities of market trends, actions and steps towards the real deployment of Virtual Coupling. In this deliverable, we consider that optimistic and pessimistic scenarios should be aligned with the EU vision towards the deployment of Virtual Coupling by year 2050 (European Commission, 2011). We also build an action plan to achieve the benefits (strengths and opportunities) developed in MOVINGRAIL D4.1 to each market segment in optimistic and pessimistic scenarios.

A Swimlane roadmap was initially developed on the online platform Roadmunk to group time orders and priorities collected from a survey distributed to the MOVINGRAIL partners into different themes and categories. The survey results were revealed during an online workshop with the same partners and the roadmap was updated on-line during the workshop based on feedback and brainstorming discussions. Timeline roadmaps were then developed based on the Swimlane roadmap for each market segment by means of the project management software Primavera P6 Pro. The constructed roadmaps in Chapter 6 provide a step-by-step approach to map dynamic actions that vary in terms of duration based on the defined optimistic and pessimistic scenarios for each market segment in Chapter 5.

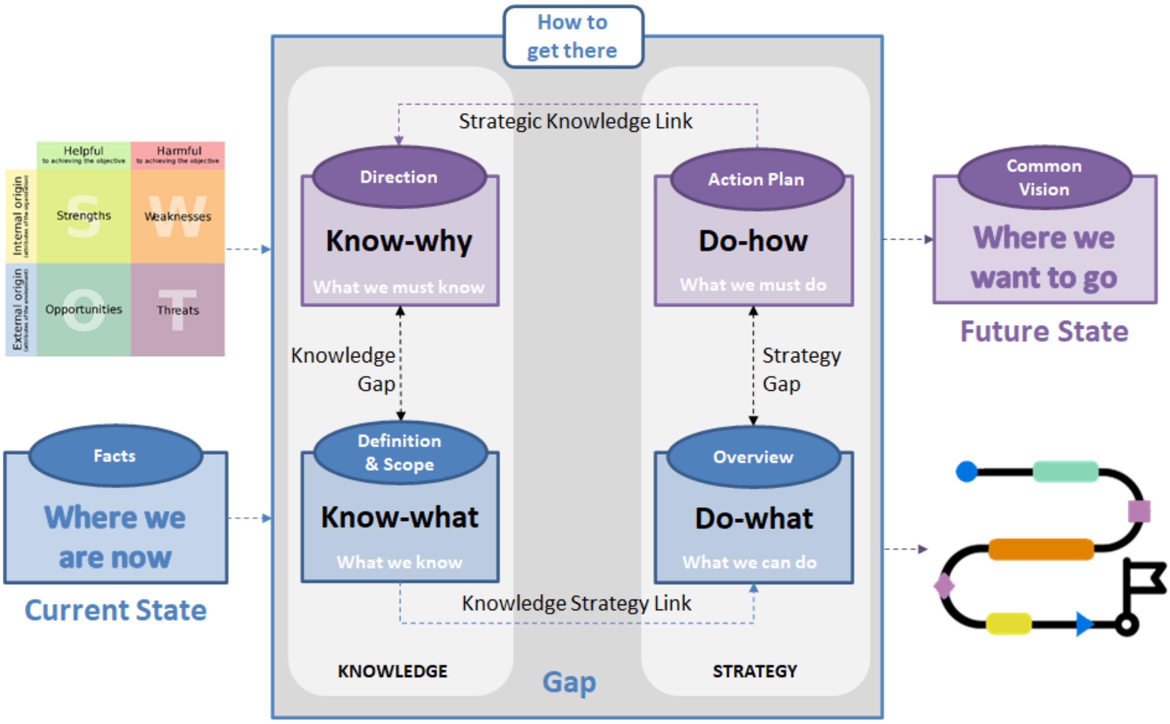

Figure 18: A SWOT-based framework for roadmap design

Figure 18 illustrates the framework developed to design a roadmap based on a SWOT analysis. The process focuses on developing a gap analysis to migrate from the current state to a desired future state. The first step to design a roadmap is to define objectives and a common vision (i.e. where we want to go/be). This corresponds to the EU vision of having VC deployed by year 2050, and thus reducing CO_2 emissions by 60% and increasing railway demand by 30% for passengers and 50% for freight by year 2050. The second step consists of understanding the current situation (i.e. where we are now) that considers fixed-block signalling. The third step in-between is the gap analysis with the necessary steps and actions (i.e. how to get there). This step is achieved by four interacting modules related to knowledge and strategy. The initial principle is based on Tiwana (2002) where the main goal is to identify precisely what knowledge the organization and its people possesses currently and what knowledge they would require in the future in order to meet their objectives and goals. The gap analysis fits into the strategic management process when reviewing how well the current strategy is working. However, proceeding on with the current strategy gives rise to a gap that needs to be covered to reach the goal of the European Commission. As a result, a knowledge gap arises between what we know from the current state (i.e. the state-of-the-art, definition, scope, etc.) and what we must know to cope with the future changes and decide which direction/scenario to follow. A strategic gap arises between what must be done (in an optimistic scenario to reach the common vision) and what we could actually do given the facts and limitations of the current circumstances. The action plan provides a strategic link to the future knowledge that interacts with the current knowledge state. Brainstorming among these components results in the identification of steps in the operational, technological and business domains to serve a roadmap.

Chapter 3 was devoted to the knowledge gap for Virtual Coupling. It considered what we know and what we must know about the main operational and technical railway system components, and thus also provided the knowledge-strategy link towards what we can do to make Virtual Coupling happen. To close the loop the strategy gap must still be explored to understand what we must do which also includes the business domain. Finally, the action plan will provide the strategy-knowledge link and define the direction of the knowledge development in the roadmap for the introduction of Virtual Coupling.

This process is supported by understanding the strengths, weaknesses, opportunities and threats (SWOT) of a certain technology or vision. The SWOT is useful for strategic planning as it provides a clearer overview on what we can do in a current situation by taking into account the knowledge in the current state. The "Do-what" module can be affected by threats encountering a certain technology as they can engender business risks that hamper the effective development of an application roadmap. The SWOT results are used to develop the strategies and generate ideas on how to close the gaps. To develop a good strategy, we need to build on the strengths, address or remedy the weaknesses, grasp the opportunities, and avoid or minimise the threats. This has been achieved through the development of scenarios for each market segment (Chapter 5) where the SWOT results are extracted from MOVINGRAIL (2019). The size of the gaps (i.e. how big/important the problem is) is assessed by means of priorities and time orders for a set of steps and actions in the operational, technological and business domains, as illustrated in the Swimlane roadmap of the next section (Section 4.4). The evaluation of the strategies in the roadmap allows us to see if they will be able to close the gap (i.e. they are sufficient to reach the EU vision) by developing scenario-based roadmaps (Chapter 6).

4.4. Stakeholder survey and Swimlane roadmap for Virtual Coupling

A survey was distributed to the MOVINGRAIL partners to assess priorities and time order for a set of steps defined in a brainstorming session, and to collect further steps/actions relative to the implementation of Virtual Coupling. Both priorities and time order were based on a score from 1 to 20. Respondents were asked to consider the following rules when answering the survey:

- *The **highest priority** is represented by number 1 while the **lowest priority** is assigned a value of 20.*
- *For **time order**, rank the steps by starting with number 1.*

Note: (1) The same number can be used more than once; (2) You do not need to use all numbers; (3) Please consider the steps in all the categories/questions before assigning the priority and time order for each step.

Based on the survey results, a Swimlane roadmap was built during an online workshop with the MOVINGRAIL partners on the 6th of May 2020. The results were grouped into six themes (Feasibility study; Research and Innovation; Requirements; Specifications, Design, develop and build; and Deploy) and three categories (i.e. operation, business and technology). Based on the priorities and time orders extracted from the survey results, the step changes or activities were sorted chronologically per group (i.e. theme/category box) while assessing priority based on the following colours: red – very high priority; orange – high priority; yellow – medium priority; green – low priority; blue – very low priority; grey – no priority. The items in the 'Feasibility study' theme were not assessed in terms of priority since these steps are related to previous or ongoing tasks of the MOVINGRAIL project. However, those steps are crucial to bridge the gap between the current and future states and are listed below:

- Definition of VC, scope and boundaries — Operation
- Identification of operational scenarios — Operation
- Market analysis and use cases — Business (Section 1.2)
- Cost-effectiveness analysis, including capacity analysis — Business (Section 1.3)
- Technology roadmap to develop VC — Business
- Business risk analysis — Business
- Analysis of communication solutions for Virtual Coupling — Technology
- Proposals for Virtual Coupling communication structures — Technology

The outcome of the survey is displayed in Table 1 and the Swimlane roadmap is illustrated in Figure 19.

The survey results are detailed as follows. The major steps that represent the highest priorities are all within the R&I theme and are related to the longitudinal motion control systems in convoys, operational procedures as well as the integrated traffic management and train control. These steps were assessed as first in time order and are considered as input to the upcoming events and activities. The high priority steps are related to the concept of operations, the system requirement specifications, the initial Reliability, Availability, Maintainability and Safety (RAMS) analysis, and the initial Risk Assessment of Virtual Coupling according to the Common Safety Method (CSM-RA). In addition, specifications related to system architectures for Virtual Coupling (i.e. integrated communication and control architecture intra & inter convoys) were considered of high priority and require as input two specifications of medium priority related to the operational procedures in interlocking (IXL) areas and the operational procedures for coupling, coupled running and decoupling. All the other specifications were assessed as medium priority and emphasize the communication protocols (including safety and security) as well as the communication models for Train-to-Train (T2T), also known as Vehicle-to-Vehicle (V2V), and RBC to Train (I2T), also known as Infrastructure-to-Vehicle (I2V). System architectures were considered as input to the last two mentioned medium-priority steps. Standardization (e.g. within ERTMS) requires input from operational and engineering rules within the 'Requirements' theme which was also assessed as medium priority. In the 'Design, Develop and Build' theme, all the steps were considered of medium priority except the final RAMS analysis, safety case, and safety approvals that were allocated to low priorities. Regulatory approvals were also represented by a green colour (i.e. low priority). This is most probably because respondents assessed the steps looking at the current knowledge and strategy (see Figure 18). This means that although very low priorities were provided to the deployment of ETCS L3 MB and VC, this is just for the time being, as there are other priorities that require dedication and attention to be able to successfully reach the lower-priority steps that are indeed crucial for the real implementation of VC.

Table 1: Survey results for the development of a roadmap towards Virtual Coupling

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

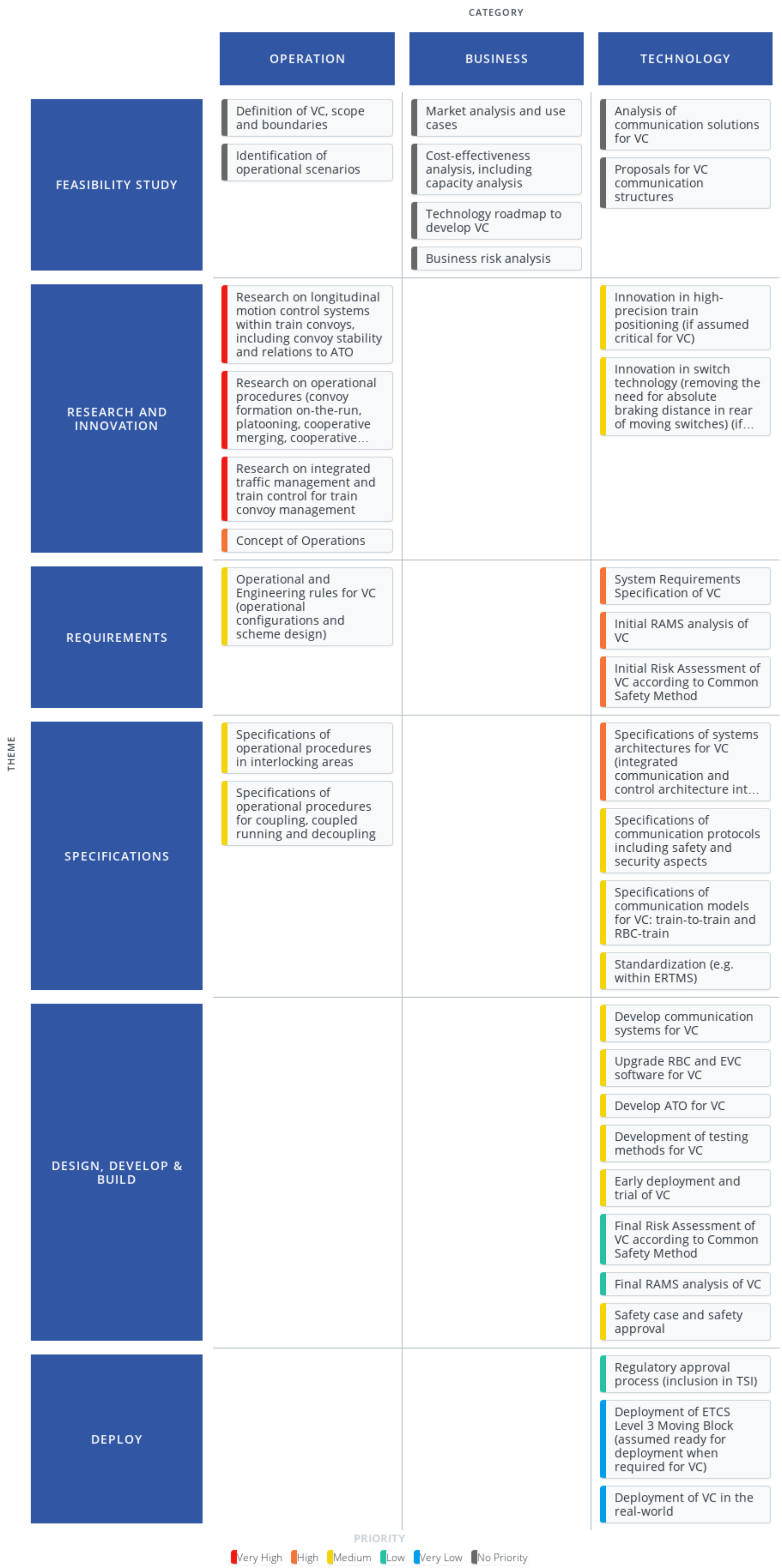

Figure 19: Swimlane roadmap for the implementation of Virtual Coupling

5. Scenarios for Virtual Coupling implementation

5.1. Introduction

This chapter develops scenarios that are used to describe various expected or assumed future situations to each of the market segments (MS) defined in the Shift2Rail MAAP (2015), namely high-speed, mainline, regional, urban and freight. The use cases for each market segment are:

1. High-speed: the Italian corridor Rome-Bologna.
2. Mainline: the UK route between London Waterloo and Southampton on the South West Main Line (SWML).
3. Regional: the UK stretch between Leicester and Peterborough on the Birmingham-Peterborough line.
4. Urban: the UK route London Lancaster-London Liverpool Street on the London Central Line;
5. Freight: the Rotterdam-Hamburg corridor between the Netherlands and Germany.

A scenario takes into account alternative characteristics based on certain assumptions and conditions. Those scenarios convert weaknesses of the SWOT analysis for each market segment into strengths and match strengths with opportunities. On the other hand, the remediation of weaknesses helps in converting a threat into an opportunity. Two scenarios have been defined for each market segment: optimistic and pessimistic. Scenarios vary in terms of duration based on specific features defined for each market segment. The goal is to fulfil the European Commission's strategic target set in the White Paper on Transport towards the deployment of a more competitive, capacity-effective and sustainable railway by 2050 (European Commission, 2011). In this study we assume that the achievement of the EC's targets entails a necessary deployment of the Virtual Coupling concept within 2050. Five criteria are defined for each scenario, namely: travel demand, CO_2 emissions, CAPEX, OPEX and regulatory approval (i.e. policies and rules). The baseline values are derived from MOVINGRAIL D4.2 for each market segment.

Default percentages are assumed in the optimistic scenarios based on the European Commission vision in the White Paper on Transport (2011) and the Shift2Rail MAAP (2015). The European Environment Agency (EEA) forecasted a big increase in the number of passengers that must be accommodated by the railways in the next 30 years. This corresponds to a 30% increase in passenger transport demand in 2050 compared to year 2000 (see Figure 20). The railway demand is estimated to increase by 50% for freight in 2050 compared to 2010 (European Commission, 2011). In addition, the European Commission has a strategic vision to railways to cut down the greenhouse gas emissions by 60% within year 2050 compared to year 1990, and envisages a massive modal shift of passengers and freight from road, air and water transport to railways (European Commission, 2011). The Shift2Rail MAAP (2019) states that European railways would have to deliver increased productivity to fulfil the demand growth across all modes in freight and passenger transport by 80% and 50% respectively by 2050.

The pessimistic scenarios are based on 'pessimistic' trends of the defined criteria. The pessimistic scenario is the opposite of the optimistic scenario. In general, the values are considered to increase or decrease by 50% with respect to the optimistic scenario, depending on whether the defined criterion is beneficial or non-beneficial, see MOVINGRAIL D4.2. The railway demand for passenger trains is considered to increase by just 15% and for freight trains by only 25% (50% less compared to the optimistic scenario). Similarly for CO_2 emissions, we assume a percentage decrease of Greenhouse Gas (GHG) emissions by 30% instead of 60%. The reasons and challenges that trigger the specific estimated values for the various scenarios arise from previous works related to the SWOT analysis for each market segment (MOVINGRAIL, 2019).

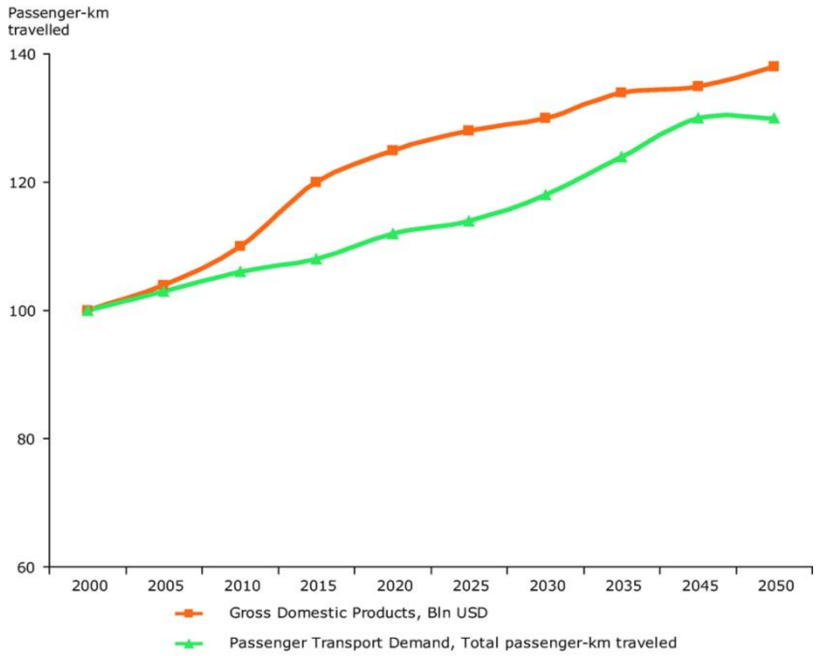

Figure 20: Trends in passenger transport demand and GDP in Pan-European region (EEA, 2012)

5.2. Generic scenarios for all market segments

Generic scenarios are applicable to all market segments and defined as follows.

Generic optimistic scenario: The railway demand is considered to significantly increase based on the EU vision and the CO_2 emissions are decreased by 60% to all market segments. An optimistic percentage of 40% decrease is assumed for CAPEX and OPEX with respect to the baseline percentage (see MOVINGRAIL D4.2). The incentives between IMs and RUs are well aligned and support the deregulation of the railway market with opening to smaller transport operators. The railway market enhances cooperative and positively competitive consortia of railway undertakings. Consequently, mobility is improved and railway services are easier to access by the customers who can choose route alternatives from different operators. This would support standardization and interoperability by providing a better choice for customers to improve quality and variety while enjoying all services in the transport market. In addition, a simple booking platform can be beneficial to customers who can book their railway trips with transparency in ticket prices (as is the case for airline). In this scenario, digitalisation creates new models and service providers where the railway industry would embrace liberalisation and establish new ways for setting efficient prices and improving data sharing and trust of information in the market by developing new regulation mechanisms. The share of data among different railway undertakings would provide a more comprehensive understanding of mobility systems and people's needs where rail would become part of an entire mobility chain. With such a cooperation, regulatory approval is fast and policies are aligned with the five scenarios defined in the White Paper on the future of Europe (European Commission, 2017).

Generic pessimistic scenario: The railway demand and CO_2 emissions are considered to decrease in value by 50% with respect to the optimistic scenario since it is expected that road transport will also become more sustainable due to technological evolutions (e.g. electric vehicles; battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)). The cooperative train control complexity is full of uncertainties that might arise from heterogeneous rolling stock or braking rates in one convoy. This scenario considers misalignment between the incentives of IMs and RUs and does not easily support the deregulation of the railway market with opening to smaller transport operators. The 'pessimistic' percentages of CAPEX and OPEX consider a 50% decrease in cost with respect to the percentage in the optimistic scenario (0.5 x 0.4 =20%). Mobility challenges arise from both institutional and regulatory perspectives; railway undertakings would have to migrate from their traditional monopolistic approach when it comes to data sharing and it is crucial to understand how regulators will make use of the data and the security measurements that need to be undertaken. Therefore, the railway market is uncooperative in this scenario and regulatory approval is considered critical (i.e. requires a long time).

5.3. Scenarios for each market segment

5.3.1. Scenarios for high-speed

Optimistic scenario: With the current modal share in railways of 84% on the line between Rome and Bologna (MOVINGRAIL, 2020), a 30% travel demand increase introduced by VC would provide further benefits due to the significant headway reduction, thanks to the relevant difference between absolute and relative braking distances at high speeds. The initial demand results for the high-speed case are already optimistic because there is a train running from Rome to Bologna every 15 minutes and the travel time is just 2 hours compared to bus (5 hours). The price is also similar to traveling by car which would take a much longer travel time (4h20m). Since coupling and decoupling can be performed on-the-run due to long interstation distances, this market segment would get a remarkable flexibility. The high-speed market is boosted by an improved high-speed train supply on the European and national high-speed networks resulting in a mode change from air to rail. New switch technology enables faster and fail-safe point locking. The interlocking functionality must also be extended accordingly to allow faster route setting for merging train movements of virtually coupled trains with cooperative train control. This technology would allow shorter headways for merging trains at junctions as well as departing trains from different platform tracks towards the same open track. Consequently, more flexibility is provided which would potentially increase the number of railway customers. In this optimistic scenario, the problem of substantial stress of overhead catenary due to high speed EMUs running closer is solved by either modifying the structure of the catenary system or improving the dynamic behaviour of the pantograph (Kießling, 2001; Lee, 2008; Pombo and Ambrosio, 2012; Sanchez et al., 2013; Liu, 2015). This would therefore help in optimizing the energy consumption on high-speed lines. Based on MOVINGRAIL D4.2, the total CO_2 emissions from all motorized transport modes (plane, bus, car) are 72.80 kg per passenger for the trip from Rome to Bologna, and are estimated to decrease by 41.1% on average in the case of VC. The reasoning behind this percentage is based on the computed modal shifts from other transport modes, i.e. car, bus, plane, to railways (assuming that the increase in ticket costs is restrained). Hence the decrease in CO_2 emissions by 41.1% represents the average decrease of CO_2 emissions from car, bus and plane. The initial CO_2 emission values were extracted from publicly available online sources such as EcoPassenger (2020), The Green Freight Handbook (Mathers et al., 2014) and the UK government (2019). In this optimistic scenario, we consider that the CO_2 emissions are further decreased by 60% (European Commission, 2011), resulting in 29.12 kg per passenger. CAPEX costs provide only a marginal increase to migrate from ETCS L3 to VC (11.5%), while OPEX costs are considered to increase by 35% compared to the baseline signalling system, i.e. ETCS L2 in this case. It should be noted that the OPEX between ETCS L3 and VC are almost equal for the two signalling alternatives (see MOVINGRAIL D4.2). In this scenario, we assume that costs are further reduced by 40%, i.e. only 6.9% CAPEX increase for the migration from ETCS L3 to VC, and 21% OPEX increase for the implementation of VC starting from ETCS L2. Given the fact that high-speed train lines can be cross-border between different countries, the notion of cooperative agreement between infrastructure managers (IMs) and railway undertakings (RUs) is crucial for this market segment and satisfied in this scenario. Therefore the roadmap steps are considered in line with the estimated durations and no issues are encountered with standardization and interoperability. Particularly, this market supports the cooperation on border management, asylum policies and counter-terrorism matters which are considered systematic in the White Paper on the future of Europe (European Commission, 2017). With all the above satisfied, policies and engineering rules would rapidly promote VC.

Pessimistic scenario: The pessimistic scenario is the opposite of the optimistic scenario. The railway demand for high-speed trains is considered to increase by just 15% (50% less compared to the optimistic scenario) since it is expected that road transport would also become more sustainable due to technological evolutions (see Section 5.2). In addition, the air transport mode is getting more sustainable and energy efficient. Particularly, the world's largest electric aircraft made its first successful flight in May 2020, landing safely in Moses Lake, Washington, about 180 miles southeast of Seattle (Reuters, 2020). In addition, on the 22nd June 2020, the largest electric plane in Europe flew for the first time over the UK (ECEEE, 2020). Safety risks and the problem of substantial stress of overhead catenary due to high-speed EMUs running closer to each other take time to be solved. The CO_2 emissions decrease by only 30% in this scenario resulting in 50.96 kg from Rome to Bologna. The costs are decreased by 20% instead of 40%, resulting in 8.3% increase in CAPEX and 28% increase in OPEX. This scenario considers misalignment between the incentives of IMs and RUs especially cross-border between different countries and does not support the deregulation of the railway market with opening to smaller transport operators. The regulatory approval process takes time due to the mentioned reasons and the description provided for the generic pessimistic scenario in Section 5.2.

5.3.2. Scenarios for mainline

Optimistic scenario: Considering the infrastructure stretch between Waterloo and Southampton (UK), the travel demand analysis in MOVINGRAIL D4.2 indicated a modal share in railways of 58%. An increase of 30% in demand results in 75% of total modal share for train users from Waterloo to Southampton. VC would provide additional capacity increases, thanks to the homogenisation of travel behaviour of the different train categories when platooning over open tracks. In addition, coupling and decoupling can be feasible on-the-run due to sufficiently long interstation distances. The introduction of swarming trains (composed of a single powered car unit) for the passenger trains –mixed with freight trains– could bring the mainline railways towards a completely different level of operations where travellers' satisfaction could be maximised by means of a personalised on-demand travel experience. Based on MOVINGRAIL D4.2, the CO_2 emissions from car and coach in the baseline situation are on average 17 kg per O-D trip per passenger. A decrease of 60% in CO_2 emissions results in just 6.77 kg of emissions. This market segment can attract more customers especially if the potential increase in ticket fees is restrained (see survey results in MOVINGRAIL D4.1 and MOVINGRAIL D4.2. CAPEX provide a marginal increase to migrate from ETCS L3 to VC (10.7%) while OPEX costs are considered almost equal for the two signalling alternatives (MOVINGRAIL D4.2). In this optimistic scenario, the CAPEX are further decreased by 40% resulting in just a 4.7% increase of VC investment costs compared to ETCS L3. OPEX for VC with respect to the multi-aspect signalling system are decreased from 27% to 16.2%. The cooperative train control complexity is managed by taking into account all the different uncertainties that might arise from heterogeneous rolling stocks in one convoy. Since main lines have heterogeneous traffic, the cooperation between IMs and RUs is an important step-change towards the speed-up of regulatory approval for the effective implementation of VC. In addition, the EU considers in Scenario 5 'speaking with one voice on all foreign policy issues' where 'decision-making is faster and enforcement is stronger across the board'. The Shift2Rail MAAP mentions that there is a need of developing and implementing wider and more sophisticated applications for mainline operation. Given the above, the mainline market segment would indeed profit from migrating to advanced systems for automatic traffic management and cooperative train operation to optimise management of trains with different characteristics.

Pessimistic scenario: The railway demand for mainline trains is considered to decrease by 15% less than the optimistic scenario, resulting in a total demand of 67% of train users between Waterloo and Southampton, since it is expected that road transport will also become more sustainable due to technological evolutions (see Section 5.2). The CO_2 emissions are decreased to 11.85 kg (instead of 6.77 kg) and total costs are decreased by just 20% with respect to multi-aspect signalling. The CAPEX are therefore increased by 5.7% and the OPEX by 22% (instead of 4.7% and 16.2% respectively for the optimistic case). Given the high uncertainty and complexity in managing heterogeneous rolling stocks in one convoy and the crucial planning of collaboration between IMs and RUs, more time is needed for regulatory approval.

5.3.3. Scenarios for regional

Optimistic scenario: Based on MOVINGRAIL D4.2, less than 60% of the respondents from the stated travel preferences survey would travel by train in the current situation on the 84 km track section between Leicester and Peterborough. The 30% increase in demand results in 77% of total train users by year 2050. The survey results showed that regional lines have a low demand and that the implementation of VC would enhance modal shifts from other modes of transport to railways. One of the main strengths for regional railways defined in D4.1 was the potential reduction of the amount of level crossing closures due to the grouping of trains into a single convoy. Therefore, traffic management for highly-frequent train services or platoons could be used in a dynamic cooperation between road/rail transport modes to optimize the required level crossing time to road users as well as the number of potential closures to allow the passage of a train (convoy). As the current regional service frequencies are considered unsatisfactory by most of the interviewees (see survey results in D4.1 and D4.2), this market segment could provide a substantial increase of customers, even if the ticket fees are increased by a certain percentage to support the higher service frequencies. The CO_2 emissions are in total 8.74 kg per passenger in the baseline case and would decrease by 60% (i.e. 3.50 kg per passenger) if VC is introduced by year 2050. CAPEX provide only a marginal increase to migrate from ETCS L3 to VC (10.7%) while OPEX costs are considered almost equal for the two signalling alternatives (MOVINGRAIL D4.2). In this case, CAPEX are further decreased by 40% (increase by just 6.4% with respect to ETCS L3) while OPEX are increased by 6.4% instead of 10.7%. In terms of safety, level-crossing protection devices are installed to avoid that road users try to cross between vehicles in a platoon. If all the above are satisfied, the partial redesign of policies, processes and engineering rules would be rapidly endorsed across the wide rail industry in this optimistic scenario.

Pessimistic scenario: Road transport increases its dominant position in the market affecting the already existing low demand for regional train services. The increase in train ticket fees is not well perceived by railway customers and could result in modal shifts from railways to road-related transport modes. Therefore it is assumed that there is just a 15% increase in demand instead of the forecasted 30% by the European Commission (2011). In this pessimistic scenario where technological advantages are held back due to the lack of cooperative dynamic solutions to manage level crossings, other inland modes of transport are pushed by the public and enhanced by private investments. In addition, road transport could result in a drop in CO_2 emission by more than 40% compared to a decrease by 30% for rail transport (i.e. 6.12 kg), given the technological evolutions that foster the development of green road solutions rapidly. Total costs are increased by an additional 8.5% with respect to the optimistic scenario. This is equivalent to 7.7% increase in CAPEX and 30% in OPEX instead of the optimistic 6.4% and 22.8% respectively. Time delays are expected specifically to the developed steps in the 'Requirements' and 'Specifications' themes of the Swimlane roadmap, which indeed affect all the steps in the 'Design, Develop and Build' theme (see Section 4.4) and consequently the regulatory approval (Section 5.2).

5.3.4. Scenarios for urban

Optimistic scenario: The Shift2Rail MAAP mentions that autonomous train operation exists in almost 40% of the metro systems worldwide. From Lancaster Gate to Liverpool Street (7 km), the current modal share in urban railways/metro is 68%. A forecasted railway share increase by 30% would hence result in 88% total travel demand by year 2050. The CO_2 emissions from car and bus would decrease by 60% resulting in just 0.59 kg per passenger on this urban line. As this market segment is considered to have a simple track layout compared to other markets, the advantage of homogeneous rolling stock characteristics provides more efficient and easy to implement platooning. Indeed, due to the satisfaction of most railway customers with the service headways already provided by this market (see survey results in MOVINGRAIL D4.1 and MOVINGRAIL D4.2), only a marginal capacity improvement can be expected. It must be noted that most of urban platform lengths are already fully used by long trains in urban/metro systems and dwell times are very short. Moreover, trains with different directions are uncommon due to the simple separated linear networks (with passengers transferring between lines, rather than trains). Therefore, the improvement for this market segment might only be in terms of a faster reoccupation time of platform tracks. However, for urban transit networks swarming trains help to alleviate congestion in crowded urban areas and could be a natural consequence of the vision of Mobility as a Service (MaaS) which envisages a fully customised dial-a-ride type of service aiming to maximise the flexibility of public transport modes. The CAPEX and OPEX costs show only a small marginal increase compared to the deployment of ETCS L3 MB (MOVINGRAIL D4.2). In this optimistic scenario, CAPEX increase by only 4.1% compared to the investment costs needed for ETCS L3, as this market segment would require the least amount of rolling stock to be installed with VC onboard systems, V2V communication, and cooperative ATO. The OPEX are almost indifferent since for this market segment, there is a 1% reduction in OPEX instead of an increase, as is the case for the other market segment. Several measures could potentially contribute to a modal shift in urban areas, such as road vehicle access restrictions, car parking costs, integration of public transport ticketing, and improved on-time and on-demand information for rail transport. Concerns about congestion and pollution in cities also mean that local residents would be more open to using more sustainable transport modes including metro systems. This would therefore accelerate the regulatory approval and consequently an early deployment of VC.

Pessimistic scenario: Transport demand does not meet the 30% forecast by the European Commission and no specific measures are taken to stimulate or develop on-demand train services. Consequently, no significant shift from road to rail transport is achieved and road transport increases its dominant position in the market. This is assumed to result in an increase of metro demand by only 15% (i.e. 78% of total travel demand for metro users between Lancaster Gate and Liverpool St.). The scenario stems from the reflection that the delay and cancellations of crucial investments are holding back standardization. This results in a low level of flexibility and attractiveness for urban railway users. In this pessimistic scenario where technological advantages are held back due to the insufficient compensation of the required investments for VC deployment by a sufficient customer increase, urban railways lose their advantageous position in terms of sustainability compared to road transport. Pushed by the public acceptance opinion and helped by private investments, this scenario considers that road transport is becoming cleaner/green more rapidly, resulting in a drop in emission values by more than 40% compared to a decrease of 30% for rail transport. The CAPEX and OPEX do not show significant changes for this market segment; the difference in total costs increase between both optimistic and pessimistic scenarios is just 0.7%. However, the market cooperation between different railway undertakings is expected to decrease within this scenario. Therefore, longer durations are needed to achieve the regulatory approval and deployment of VC in real life.

5.3.5. Scenarios for freight

Optimistic scenario: Based on MOVINGRAIL D4.1, only 19% of the goods would be transported by freight trains over the 503 km from Hamburg to Rotterdam. Survey results showed that 46.6% of the respondents would shift from road transport (i.e. truck) to freight rail transport given the additional benefits introduced by VC. This percentage is almost in line with the 2011 Transport White Paper stating that 30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050 (European Commission, 2011). With a 50% increase in the modal shift to railways, the demand for freight trains would reach 29% of the total freight demand across all modes. On-demand freight train services are favoured by this market segment given the fact that multi-commodity freight with different types of goods going to different destinations could be transported by means of smaller single fully automated freight self-propelled units (25-30 m long) which can virtually couple to a main convoy at merging junctions (so to increase capacity at bottlenecks) and decouple at diverging junctions to reach their specific destinations. This benefit would impose further CAPEX. Technological developments and investments in R&I are expected to increase the environmental sustainability of freight rail transport, while improved standardization and interoperability can make it more flexible and therefore an attractive alternative to inland and international transport in the future. Although it might be expected that road transport will also become more sustainable thanks to technological evolutions indicated by a further decrease in emissions, rail transport is given a greater advantage within this explored scenario (60% reduction in CO_2 emissions, i.e. 212.45 kg instead of 531.12 for the 503 km). Troch et al. (2017) consider that the decrease for all modes of hinterland transport strengthens the opportunities for intermodal transport to become a key factor for rail freight development in the future. The costs are increased in total by 8.6% instead of 14.4% (i.e. 4.4% for CAPEX and 4.2% for OPEX). In order to increase efficiency and as such attractiveness within the rail sector, market competition is expected to increase, resulting in an increase in the deregulation of the railway market which opens up to smaller transport operators and potentials for cooperative consortia of freight train operating companies leading to higher Benefit/Cost ratios. The imposed road taxes on highway networks are explored to be increased by 20% in this optimistic scenario. As such, a continued internalization of external costs impacts the attractiveness of rail freight transport as a considerable option for shippers and speeds up regulatory approval for the deployment of VC.

Pessimistic scenario: Transport demand grows slower than expected and no specific measures are taken to stimulate or develop rail freight transport. Consequently, low shift from road transport over the 503 km from Hamburg to Rotterdam is achieved and road transport increases its dominant position in the market. This is assumed to result in an increase of freight rail demand by only 25% instead of 50% (i.e. 24% total demand by year 2050). This scenario stems from the reflection that the delay and cancellations of crucial investments are holding back standardization. This results in a continuation of the currently weak interoperability and international O-D relations, and as such a low level of flexibility and attractiveness of rail freight transport. In this pessimistic scenario where technological advantages are held back due to legislative rules in terms of weight and length of platooning (number of freight trains per convoy), rail transport is also losing its advantageous position in terms of sustainability compared to road transport. Pushed by the public acceptance opinion and helped by private investments, road freight transport is becoming swiftly green, resulting in a drop in emission values by more than 40% in this scenario compared to a decrease of 30% for rail transport (i.e. 371.78 kg instead of 212.45 kg in the optimistic case). In this scenario, OPEX and CAPEX are increased by almost 5% each. The total increase in costs with respect to the optimistic scenario is 2.3%, i.e. 10.9% instead of 8.6%. Cooperative consortia of railway undertakings is expected to last for long, thus affecting the 'Design, Develop and Build' theme in the Swimlane roadmap and consequently the 'Deploy' theme (see Section 4.4).

5.4. Summary of Scenarios for each market segment

The described percentages in Section 5.2 are summarized in Table 2 for the optimistic scenarios and in Table 3 for the pessimistic scenarios. The values for the defined scenarios in Section 5.3 are summarized for each market segment in Table 4, Table 5 and Table 6 for baseline, optimistic and pessimistic scenarios, respectively.

Table 2: Percentage estimates for optimistic scenarios

Criteria	Optimistic Scenarios				
	High-Speed	Mainline	Regional	Urban	Freight
Demand	30%				50%
CO_2 emissions	-60%				
CAPEX	-40%				
OPEX	-40%				
Regulatory approval	Described qualitatively				

Table 3: Percentage estimates for pessimistic scenarios

Criteria	Pessimistic Scenarios				
	High-Speed	Mainline	Regional	Urban	Freight
Demand	15%				25%
CO_2 emissions	-30%				
CAPEX	-20%				
OPEX	-20%				
Regulatory approval	Described qualitatively				

Table 4: Values for baseline scenarios for each market segment

Criteria	Baseline Scenarios				
	High-Speed	Mainline	Regional	Urban	Freight
Demand (%)	84%	58%	59%	68%	19%
CO_2 emissions (Kg)	72.80	16.93	8.74	1.46	531.12
CAPEX (%)	11.5%	7.9%	10.7%	6.9%	7.4%
OPEX (%)	35%	27%	38%	-1%	7%
Regulatory approval	Described qualitatively				

Table 5: Values for optimistic scenarios for each market segment

Criteria	Optimistic Scenarios				
	High-Speed	Mainline	Regional	Urban	Freight
Demand (%)	109%	75%	77%	88%	29%
CO_2 emissions (Kg)	29.12	6.77	3.50	0.59	212.45
CAPEX (%)	6.9%	4.7%	6.4%	4.1%	4.4%
OPEX (%)	21.0%	16.2%	22.8%	-0.6%	4.2%
Regulatory approval	Described qualitatively				

Table 6: Values for pessimistic scenarios for each market segment

Criteria	Pessimistic Scenarios				
	High-Speed	Mainline	Regional	Urban	Freight
Demand (%)	97%	67%	68%	78%	24%
CO_2 emissions (Kg)	50.96	11.85	6.12	1.03	371.78
CAPEX (%)	8.3%	5.7%	7.7%	5.0%	5.3%
OPEX (%)	28.0%	21.6%	30.4%	-0.8%	5.6%
Regulatory approval	Described qualitatively				

6. Scenario-based roadmaps for each market segment

In this chapter, timeline roadmaps are illustrated to each of the five market segments in optimistic and pessimistic scenarios. If the five criteria defined in Chapter 5 are optimistic, e.g. demand will be increased by 30% for passengers and by 50% for freight by year 2050, the deployment of Virtual Coupling would indeed be accelerated. Similarly, if CO_2 emissions will be significantly decreased by 60% and costs will be decreased, policies and regulations would foster the deployment of Virtual Coupling. Based on an online workshop held with stakeholders across Europe and experiences within MOVINGRAIL, indicative durations to each of the steps defined in Section 4.4 were estimated for optimistic and pessimistic scenarios. Since the durations regarding the actual deployment of VC depend on the corridor length and in order to provide generalised roadmaps that are not just applicable to the case studies defined in MOVINGRAIL D4.2, the timelines were estimated in a way to equip a route of average length (200 km) for the high-speed, mainline, regional and freight market segments. For the urban line a corridor of 20 km was considered instead.

Activities can start simultaneously or consecutively. Dependencies among the different steps are related to the time order derived from the stakeholder survey and the Swimlane roadmap (Section 4.4) where one item can be considered an input to a following step, resulting in a cascading sequence of timelines. The generation of roadmaps has been executed on a project management software, named Primavera P6 Pro, where working hours have been considered on average 40 hours per week or 172 hours per month.

The duration of steps for each market segment in optimistic and pessimistic scenarios is shown in Table 7. The gradual colours of the estimated values denote that the reddish cells are the most critical, i.e. require the longest duration as explained above. Figure 21 shows the summary of the estimated optimistic and pessimistic time until deployment of Virtual Coupling for the five markets. The detailed scenario-based roadmaps for each market segment are illustrated in Figure 22 to Figure 31.

The results show that the deployment of Virtual Coupling can be fulfilled to all market segments in optimistic and pessimistic scenarios, except for the mainline pessimistic scenario where VC would be deployed by 2054 instead of year 2050. This is because mainline railways have high uncertainty and complexity in longitudinal cooperative motion control and managing heterogeneous rolling stock that have different braking rates in one convoy. Consequently, there is a need of further time extension for R&I in integrated traffic management and train control between freight and passenger trains that operate on the same lines. In addition, regulatory approval might engender further delay since there is a need of crucial cooperation and agreement between IMs and RUs due to the heterogeneous traffic conditions. The fastest deployment is estimated for the urban railways which is the least complex.

The time estimates of all step changes must be viewed as rough expert opinions based on experience with past technology whereas governmental policy may change the speed of developments. Therefore the total estimated time until deployment must be taken as indicative. More important are the lessons from the orders and critical paths illustrated in the roadmaps of Figure 22 to Figure 31. These may give guidance to put emphasis on certain step changes. In particular, the roadmaps show that Research & Innovation must be done in the beginning and they take time. So it is important to start these R&I topics in parallel as soon as possible. These and other business risks are discussed in detail in MOVINGRAIL Deliverable D4.4.

Table 7: Duration Estimation of optimistic and pessimistic scenarios for each market segment

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

Priority scale

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

Legend

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

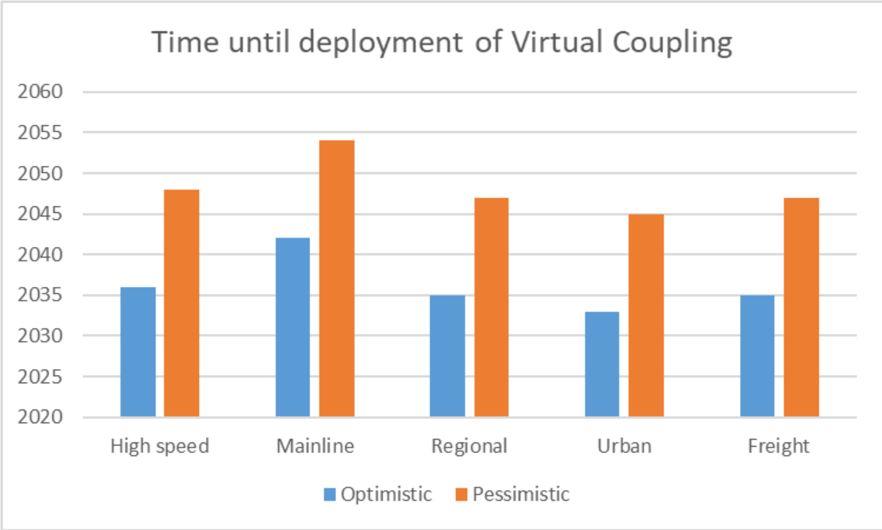

Figure 21: Estimated times until deployment of Virtual Coupling

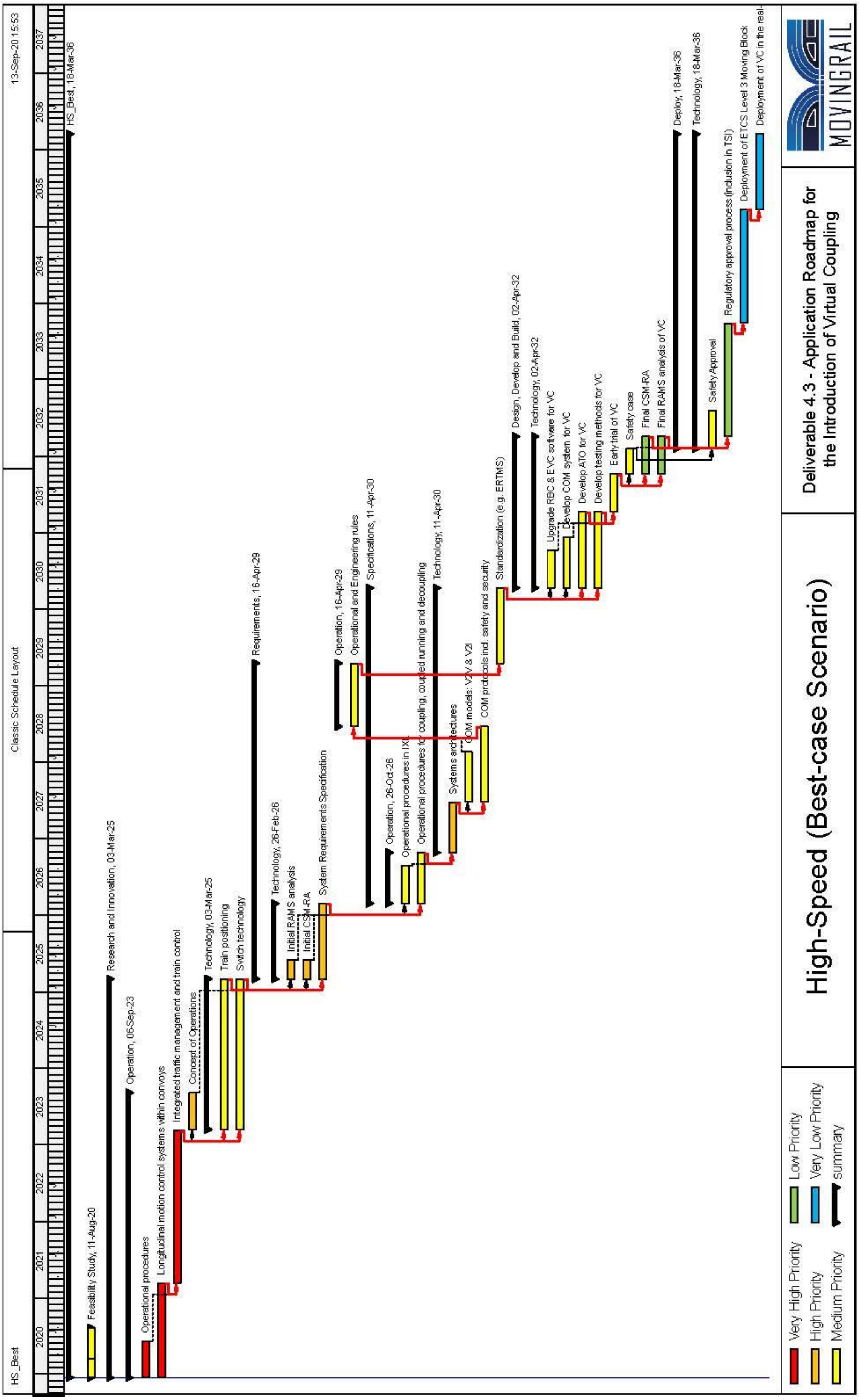

Figure 22: High Speed – Optimistic scenario (16/12/2019 – 18/03/2036)

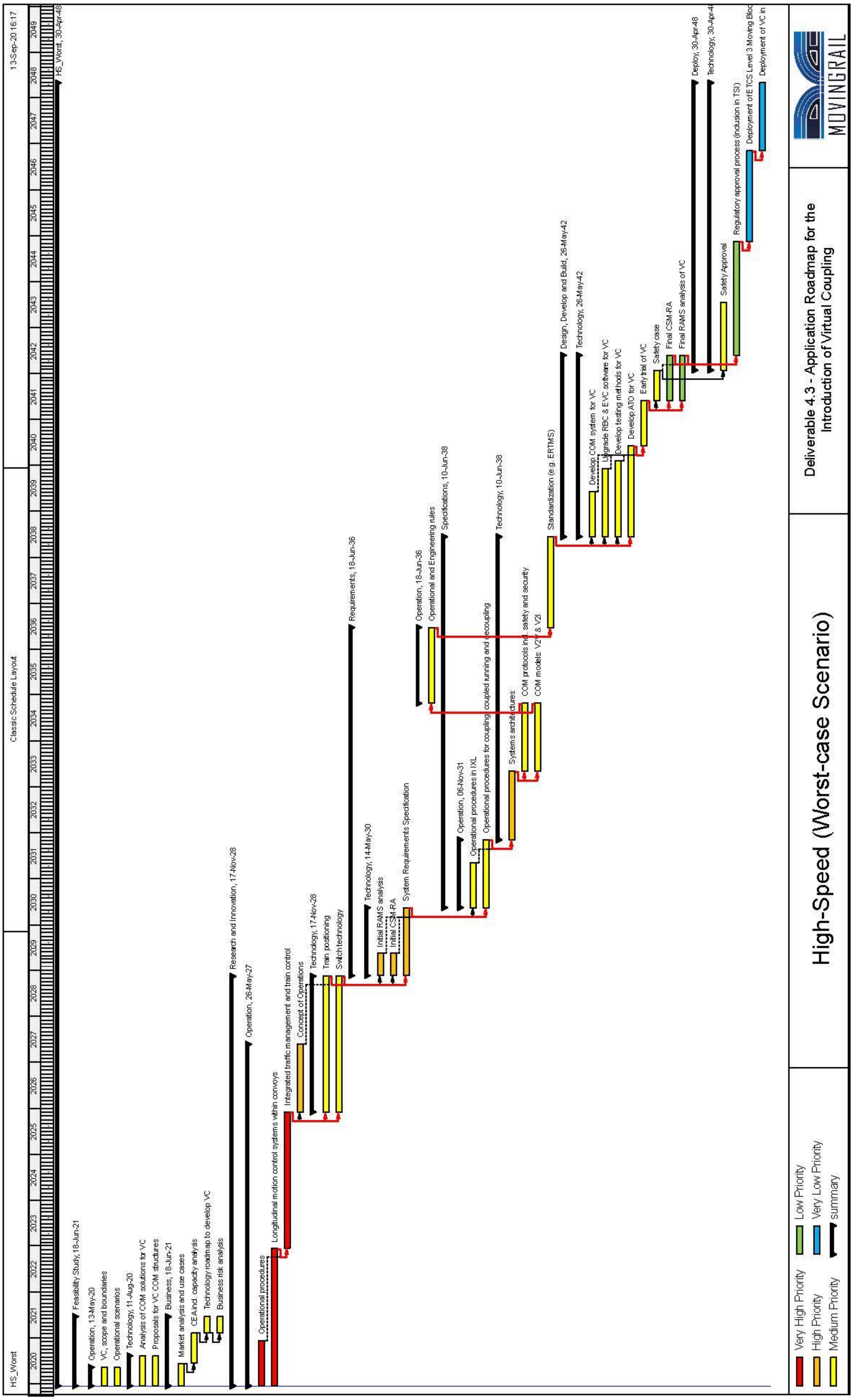

Figure 23: High Speed – Pessimistic scenario (16/12/2019 – 30/04/2048)

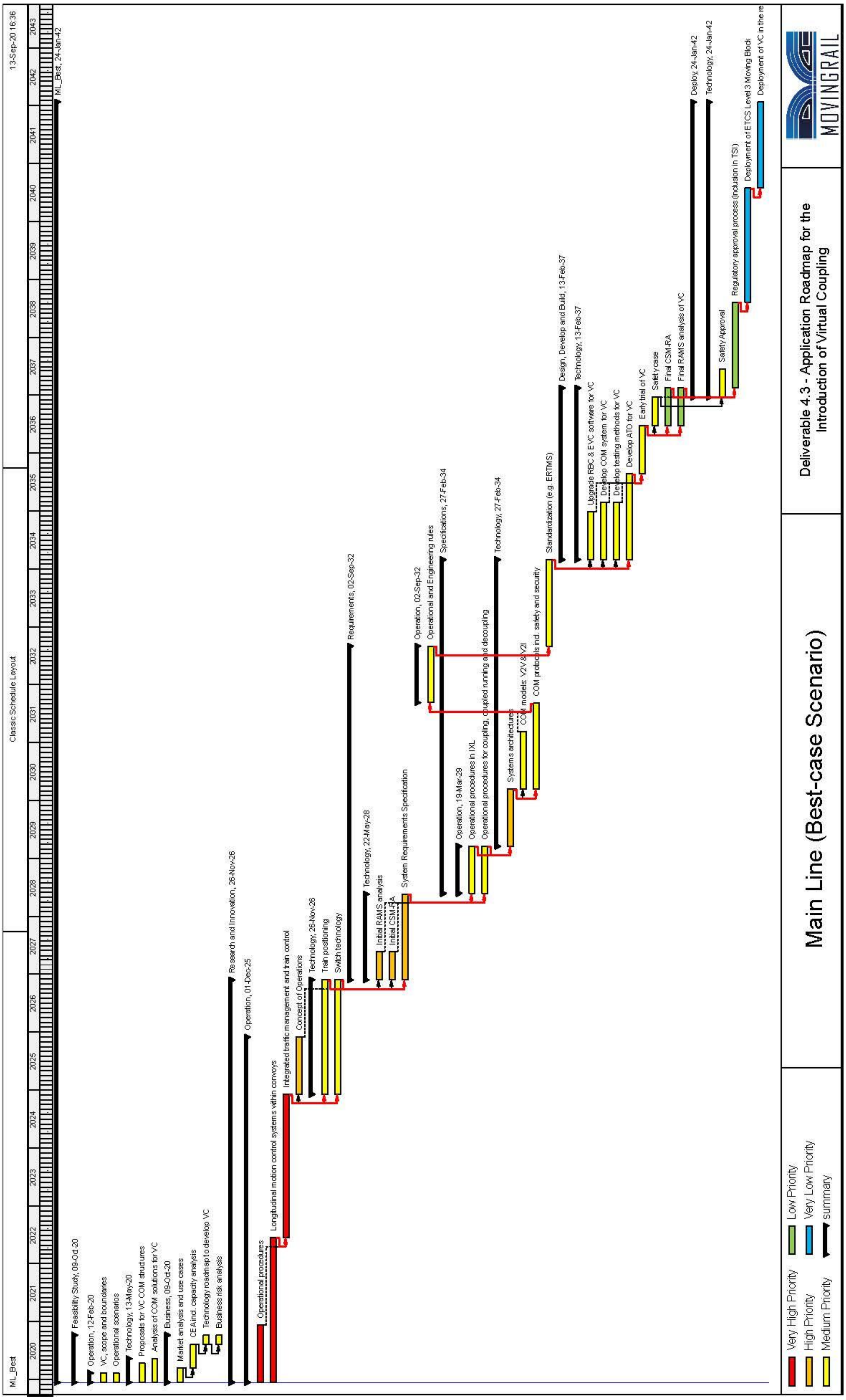

Figure 24: Main Line – Optimistic scenario (16/12/2019 – 24/01/2042)

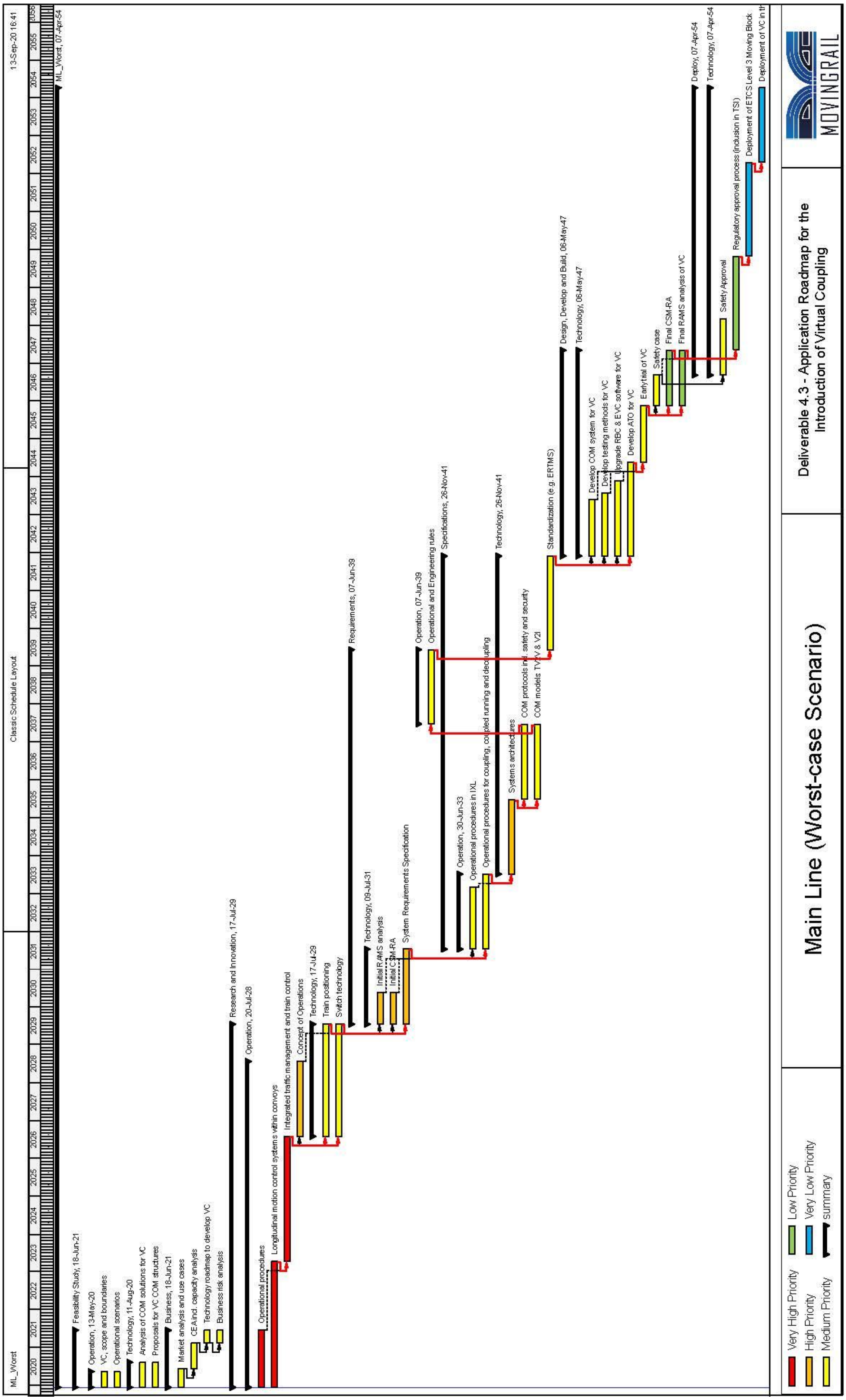

Figure 25: Main Line – Pessimistic scenario (16/12/2019 – 07/04/2054)

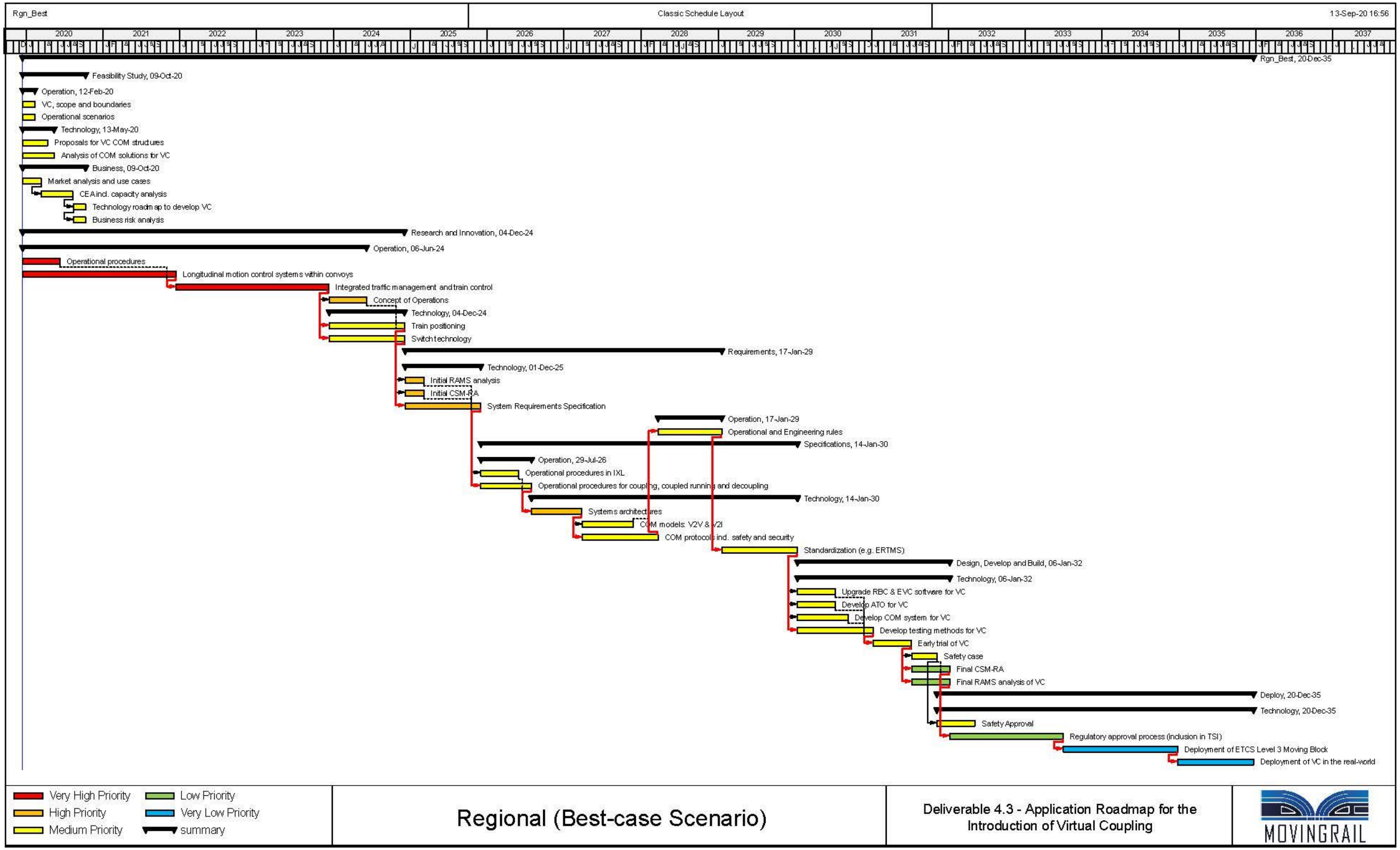

Figure 26: Regional – Optimistic scenario (16/12/2019 – 20/12/2035)

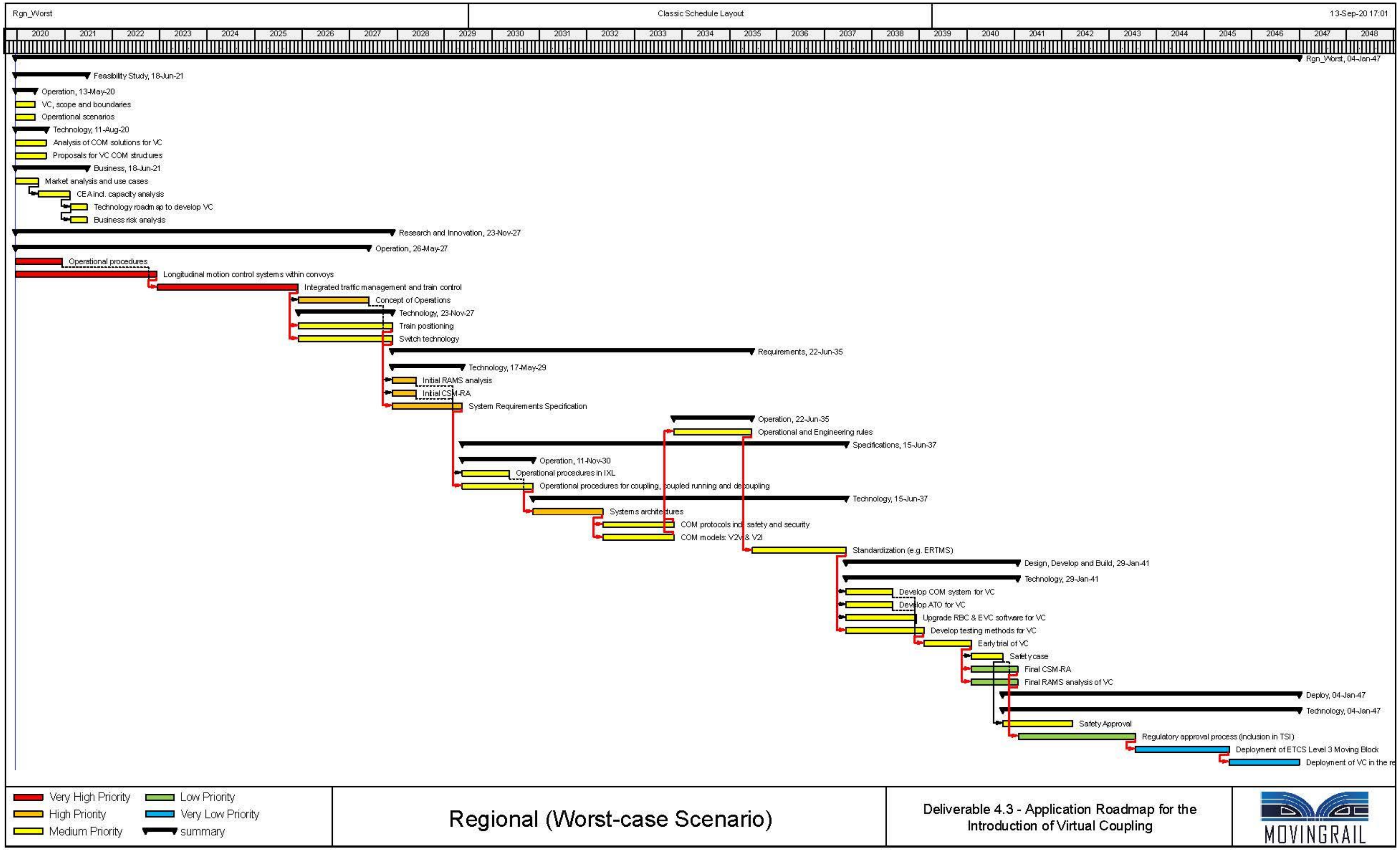

Figure 27: Regional – Pessimistic scenario (16/12/2019 – 04/01/2047)

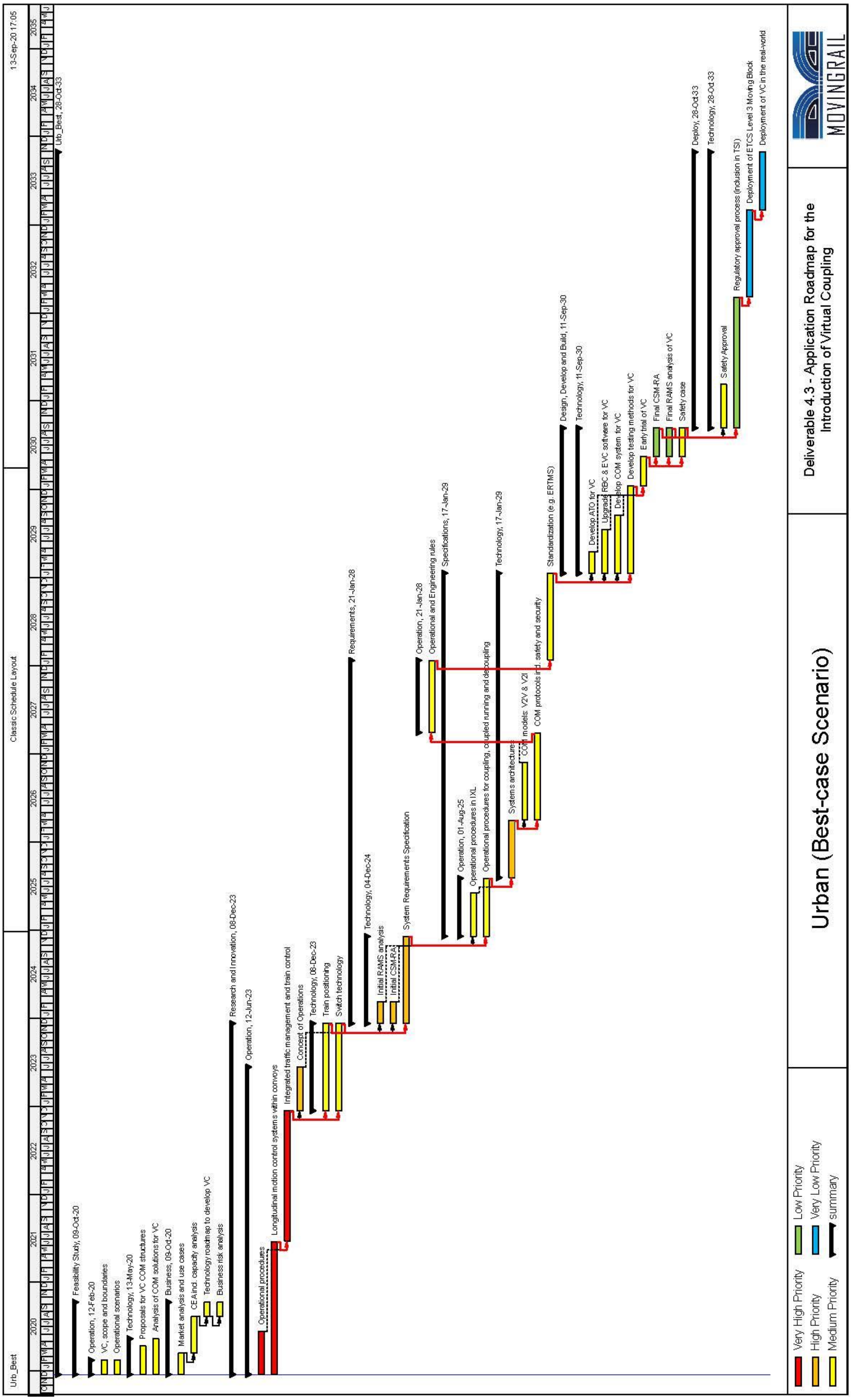

Figure 28: Urban – Optimistic scenario (16/12/2019 – 28/10/2033)

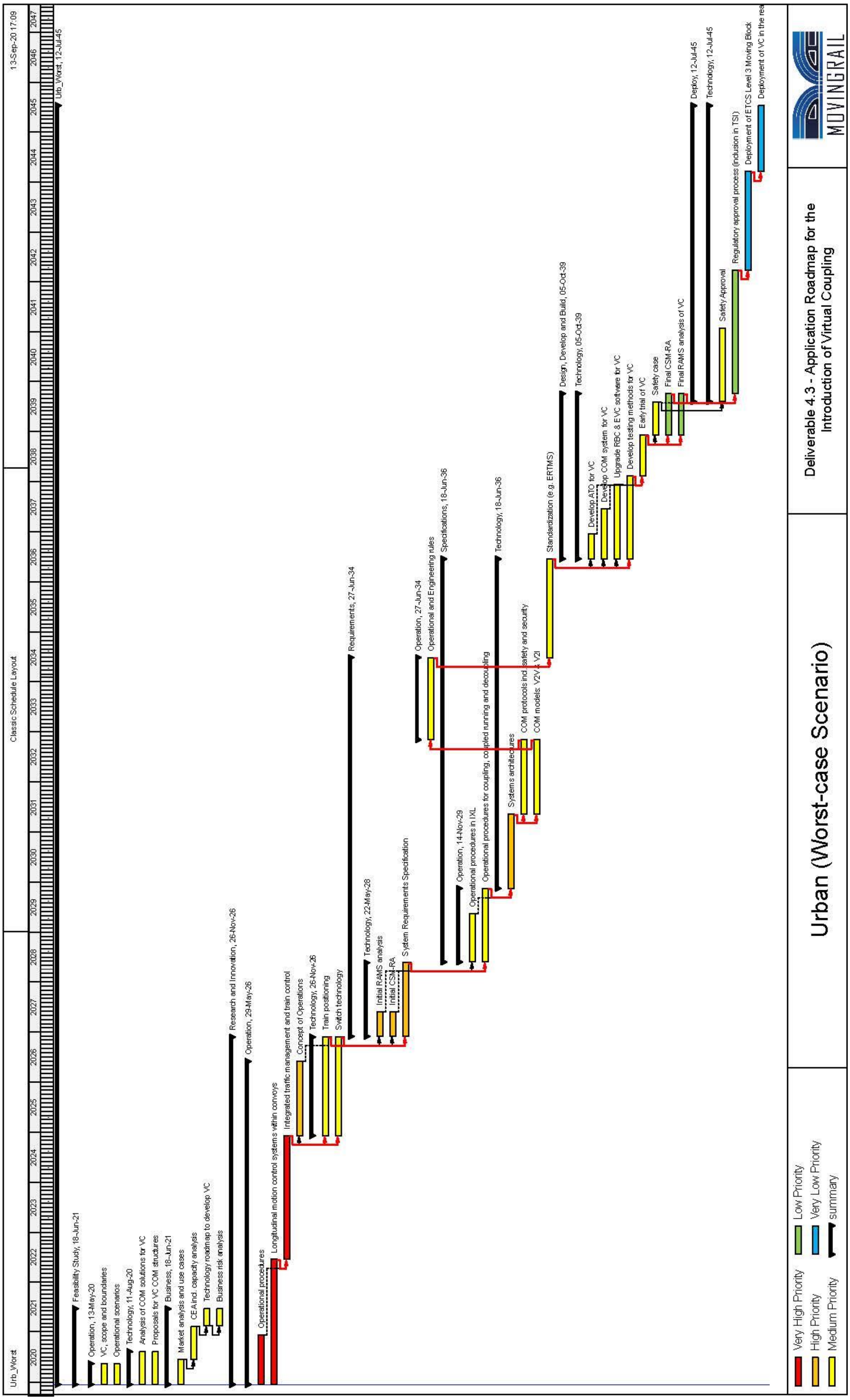

Figure 29: Urban – Pessimistic scenario (16/12/2019 – 12/07/2045)

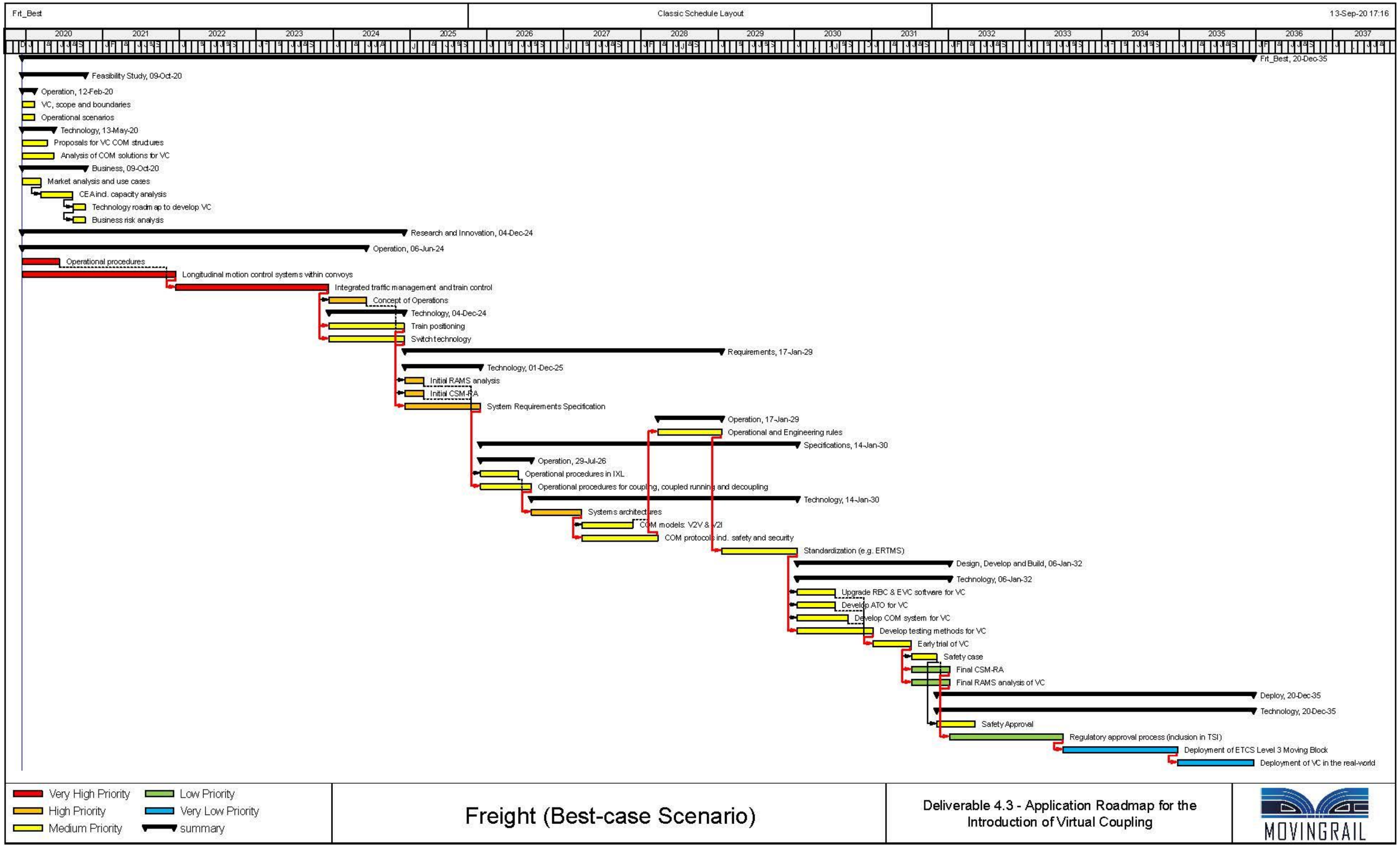

Figure 30: Freight – Optimistic scenario (16/12/2019 – 20/12/2035)

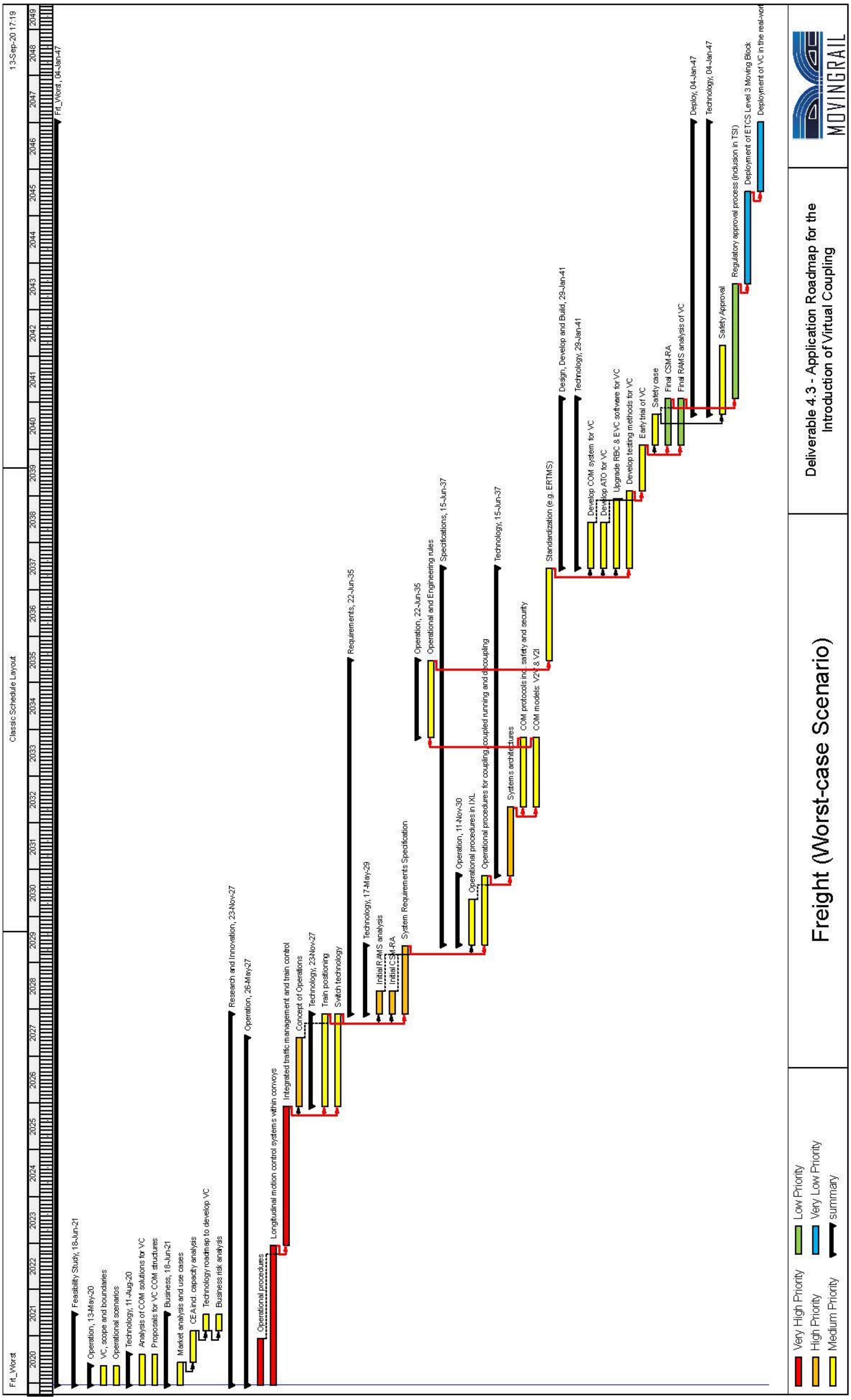

Figure 31: Freight – Pessimistic scenario (16/12/2019 – 04/01/2047)

7. Conclusions

This deliverable aimed at capturing operational, technological and business differences between traditional and future train-centric signalling systems, as well as identifying potential optimistic and pessimistic roadmaps for each market segment to foster the migration of railway operations to next-generation signalling.

The main technological and operational challenges for the introduction of virtual coupling were discussed in required step changes to the essential system components: interlocking, communication structures, automatic and cooperative train protection, automatic and cooperative train operation, railway traffic planning, and railway traffic management. This led to a list of necessary R&D topics to be carried out as critical components in a roadmap before Virtual Coupling can be implemented. In particular, the interlocking and cooperative automatic train operation system components are essential ingredients for virtual coupling that have not been considered in detail within Shift2Rail and the railway industry in general yet. Still, the interactions of these components with the other Virtual Coupling components are essential before an overall system safety analysis and system performance analysis can be executed.

A main point made was the required distinction between VCTS train protection functions and cooperative automatic train operation functions, similar to ATP and ATO but then for virtual-coupled trains. In particular, a convoy or VCTS is a vital safety system concept that allows virtual-coupled trains to follow each other up to relative braking distances and routes being set and locked for the entire convoy, while a platoon is a non-vital multi-train control concept that enables (virtually-coupled) trains to move synchronously and stable together. The cooperative train operation system guarantees stable operation in a platoon, while the VCTS train protection system supervises the relative braking distances. A smooth interaction between both systems is essential for optimal performance of virtually-coupled trains running in platoons within convoys. Nevertheless, the cooperative train operation control should be separated from the safety systems otherwise the requirement and safety case will become highly complex and expensive. Hence, one challenge is still to align and interface the functions and responsibilities between the safety-critical VCTS functions and the cooperative train operation functions to allow efficient developments of VC components by the industry.

The roadmap was developed in several steps, starting with a survey to collect priorities and time orders for each activity or step and group them into different themes and categories by using a Swimlane roadmap. Optimistic and pessimistic scenarios were developed for each market segment defined in the Shift2Rail Multi-Annual Action Plan using the SWOT results from MOVINGRAIL D4.1. The developed scenarios supported the criteria results for the cost-effective implementation of VC in Deliverable 4.2 and were based on a quantitative/qualitative gap analysis between current and envisaged future target states. In this study we assumed that the implementation of the Virtual Coupling concept by 2050 is deemed necessary to meet future railway needs enabling the achievement of EC White paper targets for a competitive, capacity-effective and sustainable transport. Optimistic scenarios are related to estimates by the European Commission for demand and CO_2 emissions, and on assumptions emerging from results in Deliverable 4.2 for costs (CAPEX and OPEX) and regulatory approval. Pessimistic scenarios considered a reduced growth of the railway demand and an increase in CO_2 emissions and costs. Regulatory approval and mobility were considered as crucial factors for defining scenarios and timelines. For all market segments, the need for an initial investment might not be well received by infrastructure managers and local governments. Both optimistic and pessimistic scenarios fulfilled the target of deploying Virtual Coupling by 2050, except for the pessimistic scenario of mainline railways where VC could only be implemented by 2054. This is mainly due to the time needed to manage train control complexity for heterogeneous traffic composed of freight, regional and IC trains operating on the same line. This market segment would also involve high coordination between railway undertakings and infrastructure managers to enable virtual coupling of trains belonging to different train operators (where train information exchange is essential) as well as to provide a better choice of travel alternatives, crowd management and mobility promotion in general.

The defined scenario-based roadmaps provide support to identify potential risks and criticalities that could arise when migrating towards VC operations. Results from this study thus can be used as a tool for stakeholders to steer and plan investment decisions, technological development, definition of rules and regulations as well as the system overall system migration process.

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