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Roadmap development for the deployment of virtual coupling in railway signalling

Joelle Aoun *, Egidio Quaglietta, Rob M.P. Goverde

Department of Transport and Planning, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands

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A B S T R A C T

Developments in the railway industry are continuously evolving and long-term transition strategies can enable an efficient implementation of signalling technologies that provide a significant increase in network capacity and operation efficiency. Virtual Coupling (VC) advances moving block signalling by further reducing train separation to less than an absolute braking distance using train-to-train communication and cooperative train control within a Virtually-Coupled Train Set (VCTS). This paper proposes a method to develop scenario-based roadmaps based on a SWOT and hybrid Delphi-AHP multi-criteria analysis. Step-changes are identified and initially assessed in a Swimlane based on priorities and time order collected from stakeholders through a survey and further developed in a workshop. Optimistic and pessimistic scenarios are assessed regarding various factors and timelines. Step-changes are initially defined in a Swimlane and then enriched with optimistic and pessimistic scenarios to ultimately derive scenario-based roadmaps. Durations for each of the step-changes are developed into scenario-based roadmaps that can be used as an efficient tool for stakeholders to identify and solve potential criticalities/risks to the deployment of VC as well as to setup investment and development plans. The approach is applied to deliver implementation roadmaps of VC for different market segments with particular focus on mainline railways.

1. Introduction

The implementation of new railway technologies necessitates well-developed strategies that move forward the current state of railways. Virtual Coupling (VC) is an advanced railway signalling technology that requires the need of developing actions and step-changes towards its real deployment. Several gaps arise from the implementation of this technology mainly relating to communication, safety and cooperative train control. Therefore, there is a need to understand the different railway system components that will be affected by VC, and identify the step-changes that allow the migration from the current state to the desired state by means of a roadmap.

The business and societal benefits of VC mainly come from the significant reduction of headways between trains, which consequently increases the railway capacity and allows higher train frequencies and shorter arrival and departure intervals. Additionally, with VC a train can virtually couple and decouple on the run, as opposed to fixed train formations, allowing an increased service flexibility which can attract a relevant share of customers from other modes of transport to railways. This in turn increases the profit of railway undertakings (RUs) and infrastructure managers (IMs) as their turnover would raise while operational costs would potentially reduce or remain the same. The latter is because when migrating from fixed-block signalling to VC, the increased track maintenance due to higher traffic volumes would be compensated by the removal of trackside equipment (e.g. signals, track-clear detection) and the installation of faster more reliable switch technologies. The revenues of RUs would increase as more tickets are sold with a marginal increase in the fees for delivering a more frequent service. Additionally, IMs will gain higher productivity of the railway network due to the larger availability of train paths to be sold.

The MOVINGRAIL European project assessed operational procedures and advanced testing methods for the European Rail Traffic Management System Level 3 (ERTMS) Moving Block signalling, as well as communication technologies and market potential of VC. Moving block signalling (Theeg and Vlasenko, 2009), or the European Train Control System Level 3 (ERTMS/ETCS L3), substitutes vital track-side equipment with onboard devices to monitor train integrity (i.e. all cars are safely held together), next to train positioning, and continuous speed

* Corresponding author.
E-mail addresses: J.Aoun@tudelft.nl (J. Aoun), E.Quaglietta@tudelft.nl (E. Quaglietta), R.M.P.Goverde@tudelft.nl (R.M.P. Goverde).

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and braking supervision. In this way, train separation is reduced from a given number of fixed-block sections to an absolute braking distance (i.e. the safe distance needed to brake to a standstill). The concept of VC advances moving block operations by reducing the train separation to less than an absolute braking distance. When forming a Virtually-Coupled Train Set (VCTS) or convoy, the distance between consecutive trains can be reduced to a relative braking distance (i.e. the safe distance of a train behind the rear of the predecessor taking into account the braking characteristics of the train ahead) using Vehicle-to-Vehicle (V2V) communication and cooperative train control while ensuring a safety margin. This concept is analogous to the automotive industry where the V2V communication can support a significant capacity increase via cooperative adaptive cruise control (CACC) while enabling the preservation of much shorter, though still safe, gaps (Diakaki et al., 2015). In railways, the V2V communication is particularly beneficial when trains move synchronously together in a platoon, and consequently a safety margin would be sufficient between the trains in a VCTS (Quaglietta et al., 2022).

VC is still under development by the railway industry due to safety-related issues as well as the need of developing specific technologies such as the V2V communication and a cooperative automatic train operation system. The railway industry hence urges to understand the set of tasks and technological developments which ought to occur before VC could be deployed.

In MOVINGRAIL (2019) and Aoun et al. (2020), market needs and preliminary VC operational scenarios were assessed based on the outcomes of a 'Strengths, Weaknesses, Opportunities and Threats' (SWOT) analysis. A multi-criteria analysis (MCA) for ETCS L3 moving block and VC consisted of using a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach to weight eight different criteria, i.e., infrastructure capacity, system stability, lifecycle costs, energy consumption, travel demand, safety, public acceptance and regulatory approval. The outcomes of the SWOT and MCA analyses have been used as input to the current study to build roadmaps. The goal of using both a SWOT and MCA is to identify the criteria and critical step-changes for developing VC.

There are several types and visual representations for a roadmap. Roadmaps can have various levels of granularity, from components to complex systems, to sectors or fields of science (Phaal and Muller, 2009). The architecture of a roadmap must be configured to suit the focus and scope of the investigated technology towards its implementation. Roadmaps have a wide spectrum of applications including science/research, industry, technology, product, project, etc. (Kostoff and Schaller, 2001). Since our main focus in this paper is on the development of a technology roadmap, we provide more details on the types of technology roadmaps in Section 2.1. We use a Swimlane visualization functionality as a supportive tool to show how to bridge gaps though a list of step-changes that can be assessed in terms of priorities and time order for the deployment of VC. The Swimlane was developed on the Roadmunk software and is defined as "a theme-oriented visualization of roadmap items that works best for 'no dates' roadmaps or more agile roadmaps that can be pivoted on themes, sprints, or epics" (Roadmunk, 2022). The Swimlane was shared in a workshop with railway stakeholders for easily identifying step-changes, together with their priorities and time order in a theme-domain oriented visualization. In addition, as this tool is flexible and allows plotting items on a dynamic grid, modifications were made online during the workshop by dragging and dropping items and changing the properties they belong to based on the stakeholders' feedback.

The aim of this paper is to provide a methodology for developing roadmaps for the introduction of VC considering uncertainties represented by scenarios for five different railway market segments. We focus on five factors relevant to the European Commission goals and the deployment of VC, namely demand, CO_2 emissions, CAPEX, OPEX and regulatory approval.

The main contributions of this paper are as follows:

(i) Identifying the main railway system components that will be affected by VC;
(ii) Developing a gap analysis and step-changes between current and future states of the operational, technological, and business domains for the introduction of VC;
(iii) Proposing a generic roadmapping framework based on various approaches to derive scenario-based roadmaps;
(iv) Applying the proposed framework to generate VC deployment roadmaps for different market segments that support stakeholders in the practice of technological forecasting and planning.

Section 2 presents a literature review on roadmapping with particular interest in technology roadmap, scenario planning and scenario-based roadmap. Section 3 explains the methodology proposed in this paper. Section 4 focuses on fundamentals of VC operations and introduces necessary changes and gaps to current operational rules and technologies. Section 6 presents the results of the Swimlane for the phased deployment of VC, as well as the scenarios and the corresponding scenario-based roadmaps, with particular focus on the mainline case study (described in Section 5). Section 6.3 provides a discussion on the results. Finally, conclusions and future work are provided in Section 8.

2. Literature review

This section presents a literature review on technology roadmap, scenario planning and scenario-based roadmap. It provides the reader with a better understanding of the concepts that are used in this paper as well as the adopted approach in the upcoming section. The methods described below are used as a basis for developing a new framework for roadmap design.

2.1. Technology roadmap

A roadmap has been explained in several ways where for instance Phaal et al. (2004) define it as "a means to communicate intent and associated plan". Ricard and Borch (2011) define a roadmap as a visual representation of layers of information related to developments of technologies in the explored context. A recent publication states that a roadmap is "a structured visual chronology of strategic intent" (Kerr and Phaal, 2022). The same authors mentioned that a roadmap is a critical artefact for onward communication within an organization and across various stakeholders. DeGregorio (2000) mentioned that roadmaps provide a "compact method" of visually summarizing and communicating information.

A distinction shall be made between roadmap and roadmapping. Particularly, Kerr and Phaal (2022) define roadmapping as "the application of a temporal-spatial structured strategic lens". In their research, roadmapping is represented by a governing framework which allows for a generic structure to be applied across temporal-spatial canvas. The roadmapping methodology has an integrative functionality which is useful for explaining the role of the other methods involved in this research and how they relate, including scenario planning and the SWOT analysis. Roadmaps represent the future, a vision that is achieved through possible routes. A roadmap is used to illustrate and communicate alignments of technology and product development with market requirements and the right timing guided by a common vision (Phaal et al., 2004). The aim of a technology roadmap is to provide a strategic framework for aligning and prioritizing market trends and drivers with technology developments and Research and Development (R&D). 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. Duin et al. (2016) state 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 and Propp, 2008). The main layers identified in a roadmap are market/business, service/product, technology/science and resources (Yang and Yu, 2005; Hussain et al., 2017). Duin et al. (2016) consider 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.

We refer to the eight categories of a technology roadmap in Phaal et al. (2001), where our scope fits into the third, sixth and eighth categories: strategic planning, programme planning, and integration planning, respectively. From the strategic planning perspective, our study includes a strategic dimension in terms of supporting the evaluation of different opportunities or threats derived from the SWOT, typically at the business level. The roadmap focuses on the development of the EU vision in terms of business, operation and technology domains. Gaps are also identified by comparing step-changes that are explored to bridge the identified gaps and migrate railways from the current state to the desired future state. In terms of programme planning, Phaal et al. (2001) state that this type of roadmap focuses on the implementation of strategies, and relates more directly to project planning like R&D programmes. Our roadmap includes an entire theme dedicated to Research and Innovation (R&I). Furthermore, our roadmap focuses on the management of the development for next-generation railway signalling systems between technology development and programme phases and milestones. Finally, from the integration planning perspective, we focus on the integration and evolution of the technology, since VC builds on moving block railway signalling and follows several of its business and operational standards, based on a certain 'technology flow'. It must be noted that the development of the VC technology also requires integrating various technologies (i.e., software, communication system) besides the ones that are developed for moving block signalling.

As a means of communication, Kerr et al. (2012) mention that a roadmap visualization conveys information, connects stakeholders and mobilizes action. Roadmap visualizations can have different forms such as tables, bars, graphs, Gantt charts, bubble charts, multilayer block diagrams, tree diagrams, flow-based schematics or metaphor-based illustrations (Phaal et al., 2001; Kerr and Phaal, 2015). A technology roadmap provides a graphical means for exploring and communicating relationships between markets, products and technologies over time (McCarthy et al., 2001; Lee and Park, 2005). A condensed visual format of a roadmap provides a 'one-page' high-level view of the system by incorporating various key perspectives for developing consensus, aligning step-changes or actions, and identifying risks. This kind of roadmap is thought as a general-purpose 'strategic lens', through which a complex system can be viewed. The aim of this lens is "to structure and represent multiple interrelated perspectives on the evolution of the system, providing a framework to support understanding and dialogue" (Phaal and Muller, 2009). In this paper, we consider the bars representation for each layer to simplify and unify the required outputs to migrate railway signalling business, operation and technology domains, and consequently deploy VC.

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). Das (1987) states that strategic planning is "dynamic by nature". Duin et al. (2016) adopted a dynamic roadmap where they use a quantitative approach in a qualitative way, since it provides a step-by-step approach to map dynamic actions. They 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 for 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. Phaal et al. (2005) mention that a roadmap is dynamic due to the inclusion of the time dimension. 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 must be considered and compared.

2.2. Scenario planning

In the past decades, scenario planning has gained increased attention in both academia and practice as an effective method to examine future uncertainties (Schwartz, 1991). Murray (1965) defines a plan as "a conscious attempt, made in advance, to identify a desirable end, and to specify how this end is to be achieved". The concept of planning is broadly articulated by Dauten (1958) as the "determination of what is to be done". A scenario is defined as a (hypothetical) sequence of events constructed for the purpose of focusing attention on causal processes and decision points (Kahn and Wiener, 1967). The work of the mentioned authors relates to the sequence of events. 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. Thus their approach concerns future states. Both approaches of Kahn and Wiener (1967) and Troch et al. (2017) can be related to the timeline presented in the roadmaps, and provide insights to define plausible future states and pathways to bridge the current state to the future one. 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. Duin et al. (2016) showed that scenarios are developed to help people empathize in plausible futures.

Several methods have been integrated with scenario planning. A multi-objective system architecting and design integrates single aspects into a complete system that fits the customers' context and needs (Phaal and Muller, 2009). Hickman et al. (2012) indicate that there is an emerging set of methodologies, including scenario analysis, which can be combined with more conventional approaches such as the MCA, to offer much promise for the evaluation and implementation of sustainable transport futures. As an example, they define a framework that combines scenarios with a multi-actor discussion and a simulation tool (INTRA-SIM), to assemble and appraise future potential scenarios. Troch et al. (2017) explored scenarios for the development of a Belgian rail transport system based on a SWOT analysis. The 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. A SWOT analysis is at the core of all strategic planning processes, explicitly or implicitly. Wiehrich (1982) provided a structured method for relating the SWOT factors/components, leading to a balanced set of strategic options, and considered time explicitly. He also refers to the TOWS matrix which serves as a conceptual framework for future research about the combination of external factors (Threats and

Opportunities) and those internal to the enterprise (Weaknesses and Strengths), and the strategies based on these variables. Soria-Lara and Banister (2018) integrated the MCA with transport scenario analysis to assist policy-makers in deciding how the implementation of transport policy schemes can be made more central to the scenario building process.

2.3. Scenario-based roadmap

Scenarios must be used to design a robust roadmap. 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; Duin et al., 2016; Hansen et al., 2016). A roadmapping process should accommodate those uncertainties associated with forecasts by means of scenario planning or other methods such as a sensitivity analysis. Courtney et al. (1997) define a framework to determine the level of uncertainty surrounding strategic decisions and to tailor strategy to that uncertainty. 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. The main strength of this paper is that it provides a systematic combination of technology roadmap and system dynamics to support scenario planning. However, their study did not include the development of technology roadmaps for each scenario. Cheng et al. (2016) used a scenario-based roadmapping method (SBRM) 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 helps 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. Lee et al. (2015) used a scenario-based roadmapping approach to help decision makers in assessing the impacts of changes on organizational plans. They propose an approach to make scenario-based technology roadmapping more robust by assessing the impacts of future changes on organizational plans. However, their approach does not include the analysis of internal factors of organizational plans. In addition, they do not integrate different methods and processes for building scenarios.

2.4. Proposed approach

Results in Aoun et al. (2021) showed that VC entails regulatory approval barriers since a number of strategies depends upon the assumption that the system as designed will work towards a very high level of reliability and safety, and that there will be no wrong side failures during the full scale testing phase. The regulatory approval issues reported by the stakeholders included safety incidents that have the potential to set back approval, as well as the requirements for headways and the maximum train length of a convoy. In addition, a set of engineering and operational rules should be defined and approved as VC will also change procedures in planning, management and control of railway traffic (MOVINGRAIL, 2018). There is also a need for a clear system definition and specifications, and a valid testing system through simulation and pilot/prototypes. Another important issue that needs to be solved concerns the description of operations and the sponsorship of specifications/standards throughout EU Processes. Those issues are symbiotically related to safety and public acceptance, e.g. safety challenges due to technical complexity and approval within the European Railway Agency (ERA). In addition, regulators are unlikely to take risks upon themselves by approving technologies that the public has concerns about.

The roadmapping process can be expert-based, computer-based or hybrid (Kostoff and Schaller, 2001). Our study builds on a hybrid roadmapping process since on one hand the results draw on the knowledge and experience of the participants and railway experts to subjectively identify the relationships and dependencies among the step-changes as well as the identification of timelines. On the other hand, objectivity arises from the involvement of a hybrid Delphi-AHP MCA since this approach identifies the most relevant assessment criteria and ensures consistency in the pairwise comparison matrix for criteria weighting, which is required for the calibration of the AHP technique. In addition, scenarios are quantified based on EU targets and real-data on quantitative factors, namely demand, CO_2 emissions, CAPEX and OPEX. In addition, a SWOT can provide an objective evaluation of the strengths, weaknesses, opportunities and threats of VC based on the functionalities of the system.

The discussed methods in Sections 2.1, 2.2 and 2.3 support the development of a generic methodological framework to design a roadmap. 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. Based on the existing literature, the SWOT has been used for scenario planning whereas the AHP was adopted for technology roadmapping. In this paper, we use two approaches, namely a SWOT and a Delphi-AHP MCA, together with expert judgement, in a single framework to define scenario-based roadmaps. The SWOT supports in the development of appropriate processes for strategic planning while the Delphi-AHP approach helps in identifying key factors and their quantitative importance towards the implementation of a certain product or technology. Delphi consists of combining points of view and opinions from a group of individuals by means of iterative questionnaires with controlled feedback. The AHP is a multi-criteria decision-making method that consists of weighting criteria by means of a pairwise comparison judgement matrix (Saaty, 1980). It is a compensatory scoring method which eliminates incomparability between variants and builds on a utility function of aggregated criteria. This approach has been considered as the most appropriate MCDM technique for solving complex cases (Lee and Kim, 2000). AHP has been widely applied for solving several decision-making problems such as socio-economics (Kumru and Kumru, 2014), manufacturing systems (Yang et al., 2009), roadway maintenance (Li et al., 2018), technology evaluation (Lai and Tsai, 2009) and various transportation fields (Barić and Starčević, 2015; Aoun et al., 2021).

Existing literature for developing roadmaps does not entirely involve decision makers in expressing their preferences for the type of strategies/step-changes that need to be evaluated in terms of priority, time order, durations and criticality with respect to other step-changes. They also do not consider always future scenarios by looking at different factors and durations for variant case studies. In addition, our study involves stakeholders and experts since the beginning of the design of the strategies to evaluate because we used their input for developing the SWOT and MCA which were in turn used as input to develop the scenario-based roadmaps. Therefore, our approach can support future thinking and the development of strategic values as it involves different stakeholders in various ways. It also develops consensus among decision makers on a set of research and technological needs. In particular, we look first at system components and their functions to identify gaps between current and future states, and generate the related step-changes to close those gaps by looking at the 'SWOT' of the investigated technology. In addition, case studies and criteria weights, which derive from a hybrid Delphi-AHP through stakeholders' judgement, help to determine how important the identified step-changes are by assigning their priorities. Those priorities were also set based on surveys and a workshop with sector experts. For the first time in literature, we apply the proposed framework for the deployment of VC to different market segments with particular focus on mainline railways. It must be noted that a roadmap can always be subject to changes given prevailing conditions and circumstances. It is therefore important to critically review the roadmap by analysing various dynamic options of moving forward and reaching a certain goal with respect to a certain context and situation. The term ‘dynamic’ is therefore used in our paper to reflect the fact that roadmaps do explicitly include the time dimension and are useful for mapping system change based on specific defined scenarios for different case studies. The scenarios help in keeping pace with the step-changes, exploring alternative paths, bringing attention to timely options, and dealing with the unexpected. Indeed, the preferred route corresponds to optimistic scenarios. However, as uncertainties in the business, operation and technology domains are unavoidable, outlining a ‘Plan-B’ option, hereafter referred as pessimistic scenario, would provide more depth of thinking behind the question ‘what if?’. For instance, the rate of change to which the VC system is subjected or the pace of technology advancements in wireless communication or the structural change in the railway market can cause several amendments in the built roadmaps, and consequently impact the five factors considered in Section 6.2.

3. Roadmapping methodology

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 VC. The most general and flexible approach to develop roadmaps is a visual time-based, multi-layered chart that enables several functions and perspectives to be aligned. An example can be found in Phaal and Muller (2009) based on typical perspectives for industrial applications, and three key questions that must be answered for any coherent strategy: where do we want to go, where are we now, and how to get there.

The outputs of the SWOT analysis (MOVINGRAIL, 2019; Aoun et al., 2020) and the hybrid Delphi-AHP multi-criteria analysis (MOVINGRAIL, 2020a; Aoun et al., 2021) are applied in this paper to close technological, operational and business gaps, as well as to assign priorities for the resulting step-changes. An action plan is built to address the benefits (strengths and opportunities) and drawbacks (weaknesses and threats) to each market segment (i.e. high-speed, mainline, regional, urban and freight) in optimistic and pessimistic scenarios. Several factors are considered in the identification of scenarios where values are defined optimistically or pessimistically based on policy goals, real data and certain assumptions.

Phaal and Muller (2009) state that a practical way to impart a progressive story arc is to use a series of “stepping stones that lead from the current situation to the desired future state”. The proposed roadmapping methodology in this paper applies a gap analysis in the operational, technological and business domains that identifies differences between current and future states and the step-changes that need to occur to migrate each of the domains towards VC. Based on the step-changes identified in these three domains, a roadmap is then developed which details transitions that need to occur to progressively deploy VC.

Fig. 1 illustrates the framework developed to design roadmaps based on a SWOT, a hybrid Delphi-AHP multi-criteria analysis, and expert judgement. The gap analysis consists of determining the step-changes to be taken to migrate from a 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). In this paper, this corresponds to the EU vision in addressing demand and consequently increasing railway

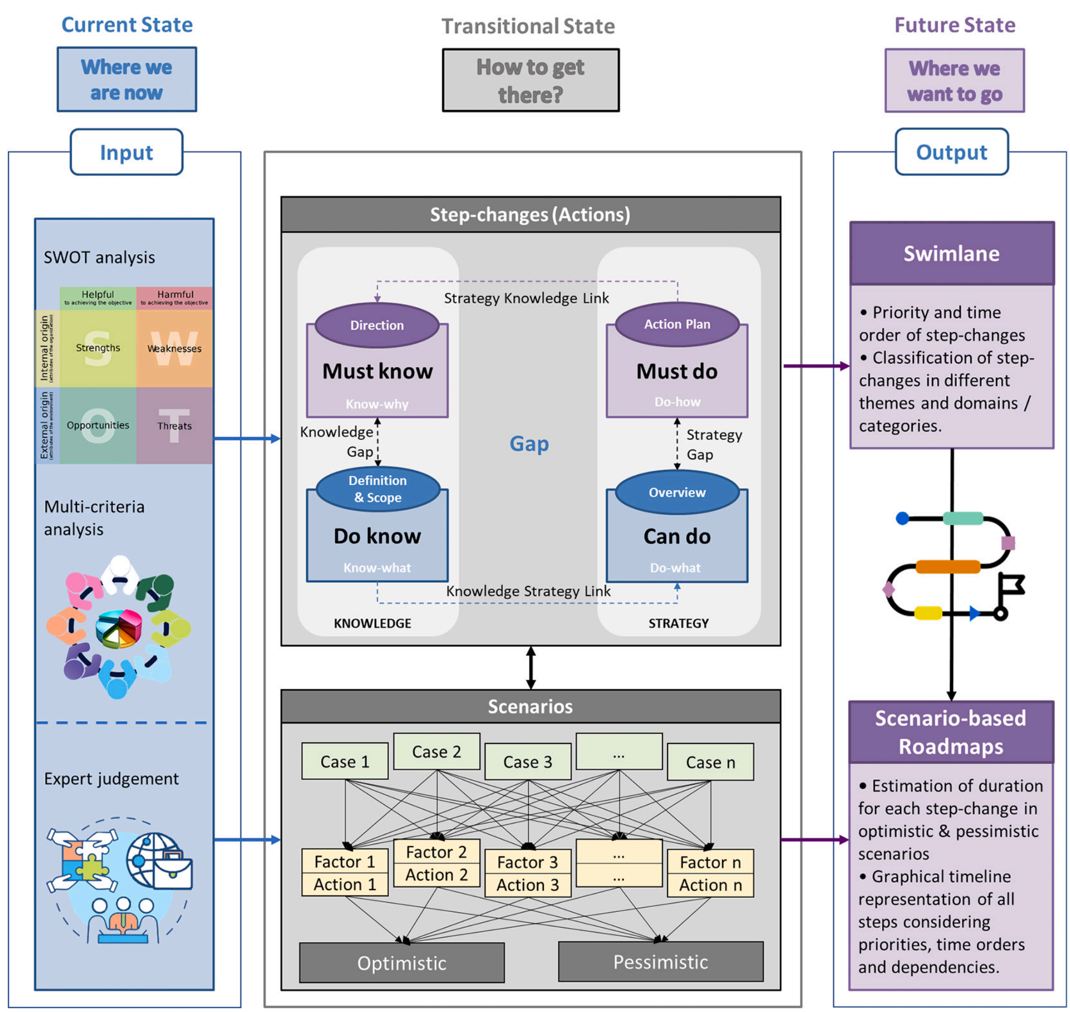

Fig. 1. Roadmapping framework.

capacity, reducing CO_2 emissions and decreasing lifecycle costs. The second step consists of understanding the current situation (i.e. where we are now) where in our study fixed-block signalling is mainly adopted. The third step in-between is the gap analysis that fits into the strategic management process when reviewing how well a current strategy is working with the necessary steps and actions (i.e. how to get there). Proceeding on with the current strategy gives rise to a gap that needs to be covered to reach the desired goal. 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.

The definition of step-changes is achieved by four interacting elements related to knowledge and strategy. The initial principle is based on Zack (1999) and Tiwana (2002) who aimed at precisely identifying what knowledge the organization and its people possesses currently and what knowledge they would require in the future in order to manage their needs and meet their goals. According to the last two mentioned references, the knowledge strategy link describes the overall approach an organization intends to take to align its knowledge resources and capabilities to the intellectual requirements of its strategy. This relates to the link between what we know in terms of definition and scope and the overview of what can be done. The Strategy knowledge link is based on the organization's identification of the knowledge required to execute the intended strategy, and compare that to its actual knowledge, thus revealing the gaps between knowledge and strategy. This link relates to what we must do by following a certain action plan and the direction towards why we must expand the current knowledge. Fig. 1 shows how the gaps can be bridged by means of certain step-changes, referred also as 'actions', which are then analysed in different scenarios for various cases (in our study rail market segments). The knowledge strategy link is based on the knowledge gaps discussed in Section 4 which motivate the railway business market to apply specific step-changes (Do-what). The strategy knowledge link stems from the fact that we get to know which research is required to increase the knowledge based on the action plan. After developing the scenarios, we get to know what is the most critical market segment for which a particular attention would be given from regulatory bodies and suppliers of signalling technologies.

The relations between the four elements in the 'Step-changes' box of Fig. 1 are based on three components: the core (middle text in each box), the aim (the upper text in the oval) and an identifier (the bottom text in each box). The connections between those elements are explained as follows:

1) We define the 'Do know' because we aim at understanding the definition and scope of the strategy that we want to build. To do that, we need to investigate what we know in the current state to be able to build what we can do (knowledge strategy link).
2) We define the 'Must know' because we aim at a certain direction by looking at what must be known. To do that, we need to understand why there is a need for new knowledge. This is an identifier to determine the 'Must know' based on what we do know.
3) We define the 'Can do' because we aim at having an overview of the current strategy to be able to build a futuristic one. To do that, we need to understand what can be done in the current state.
4) We define the 'Must do' because we aim at building an action plan that leads to the desired direction (strategy knowledge link). To do that, we need to look at how we can do what we can do.

A strategy gap is the gap between what we must do in the future state and what we can do in the current state. It arises between the current performance and the desired performance towards a common vision and well-defined objectives. The strategy for achieving them stems from what must be done 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.

This process is supported by understanding the 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 "Can do" element can be affected by threats encountering a certain technology as they can engender business risks that hamper the effective development of an application roadmap. Drucker (1994) mentions that "the central challenge facing management" is "what to do". The SWOT results are therefore used to develop the strategies and generate ideas on how to close the gaps by identifying step-changes in the operational, technological and business domains to ultimately serve a roadmap. 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.

The development of scenarios for each market segment (Section 6.2) includes baseline values which are initially derived from MOVINGRAIL (2020a) that consists of implementing a hybrid Delphi-AHP MCA for ETCS L3 and VC. Other baseline values derive from data collected through surveys and publicly available governmental sources. The size of the gaps (i.e. how big/important the problem is) is assessed by means of priorities and time order for a set of steps and actions in the operational, technological and business domains, as illustrated in the Swimlane (Fig. 2). In this paper, the Swimlane is used as a domain/theme-oriented visualization of roadmap items on dynamic grids where fields can be moved, ordered and prioritized based on stakeholders' feedback. The identification of gaps that stem from the SWOT are addressed by means of the Swimlane through a list of step-changes that are categorized based on defined domains and themes.

Outcomes from the SWOT analysis, the MCA and expert judgement were used as input to define the step-changes in the roadmap. The scenarios presented in this paper are a collection of plausible future events to assess their impacts over a long-term strategy. The different defined scenarios are interrelated since on one hand, the scenario-based roadmaps vary in terms of optimistic and pessimistic timelines for different market segments. On the other hand, optimistic and pessimistic scenarios represented in terms of five factors (i.e. demand, CO_2 emissions, CAPEX, OPEX and regulatory approval) are crucial within the developed scenario-based roadmaps since they represent the desired vision (i.e. the why) or the market pulls set by the European Commission. Those five pulling factors are hence the targets VC aims at. Therefore, the optimistic and pessimistic scenarios in the developed scenario-based roadmaps vary for each market segment (case) in terms of (*i*) durations for each step-change (action) based on expert judgement, and (*ii*) prediction uncertainties represented by five factors related to the VC market pulls that are estimated based on the European Commission targets, policy goals and data collected from the MCA developed in MOVINGRAIL (2020b) and Aoun et al. (2021).

Section 4 is devoted to the knowledge and strategy gaps for VC. It considers what we know and what we must know about the main operational and technical railway system components, and thus also provides the knowledge-strategy link towards what we can do to make VC happen. To close the loop, the strategy gap must be explored to understand what we must do by providing the strategy-knowledge link and defining the direction of the knowledge development in the roadmap for the introduction of VC.

Optimistic and pessimistic percentages are defined for each factor (Section 6.2) to understand the impacts of the estimated timelines (defined in consultation with stakeholders) on market pulls. In particular, the higher the positive impact of the factors (e.g. more demand, less costs), the faster is the development of the technology. Reciprocally, the longer the estimated duration of the step-changes defined for each market segment (pessimistic case), the lower would be the overall positive impact on the societal, environmental and economic factors. The evaluation of the strategies in the roadmap allows us to see if they will be able to bridge the gap (e.g. they are sufficient to reach the EU vision) by developing scenario-based roadmaps (Section 6.2). Timeline roadmaps are therefore developed for each market segment based on the Swimlane

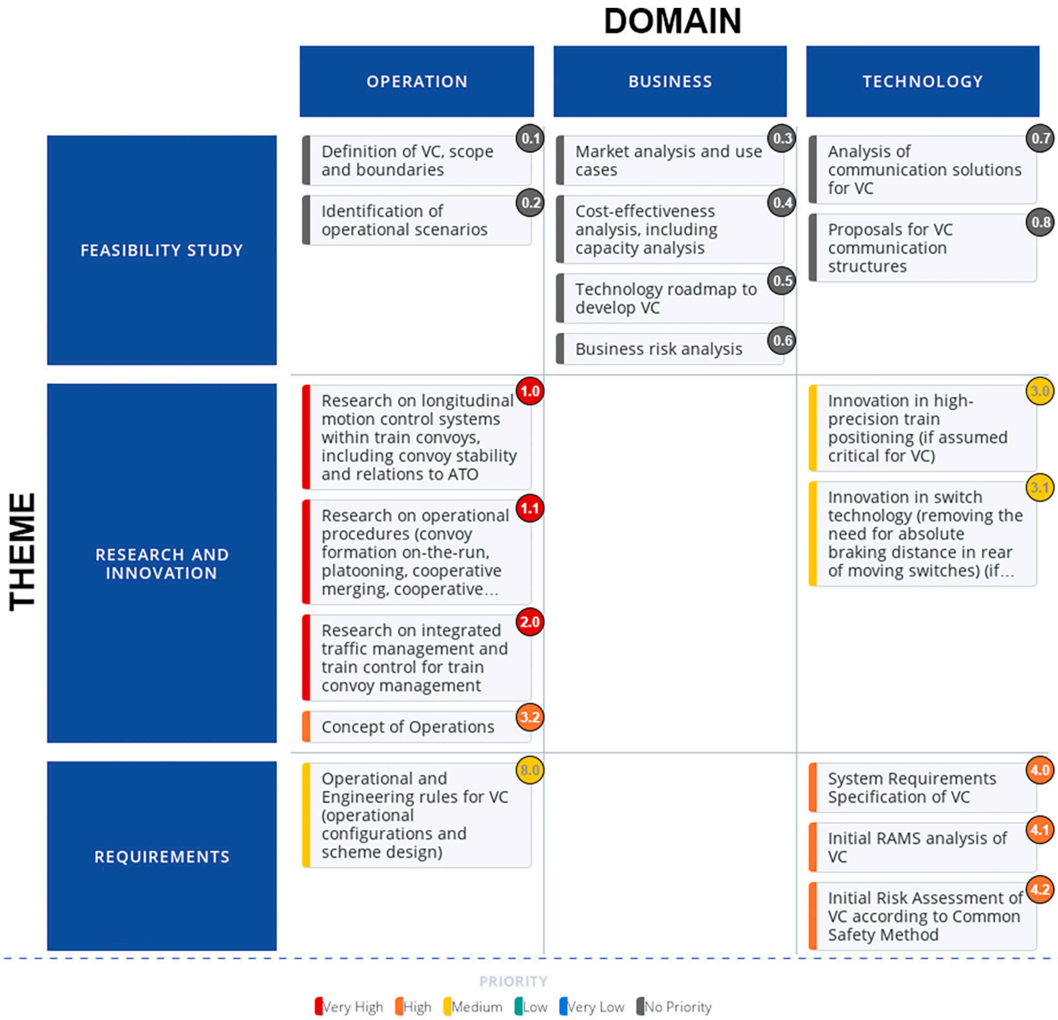

Fig. 2. Part of the Swimlane for the implementation of Virtual Coupling.

by means of the project management software Primavera P6 Pro. The built roadmaps provide a step-by-step approach to map dynamic actions based on the defined optimistic and pessimistic scenarios for different market segments.

4. Virtual Coupling scope and gaps

This section discusses the scope of VC and the knowledge gaps that need to be filled for the main operational and technical railway system components. In particular, the communication, safety, interlocking and control technology are emphasized, including communication structures, platoon planning, and integrated railway traffic management.

All of these components are critical for the real deployment of VC, in the sense that each of them needs to be sorted out or it will halt the implementation as a whole. In interlockings, when a train (usually the leading train -henceforth addressed as “leader”- in a convoy) gets exclusive right to control and occupy the points, the request is declined for all other trains until relevant elements have been released by the last train of the convoy. The control time for points is the time to request the points, to get them assigned and to move them. Moving points is only possible in the gaps between train convoys, and assigning points to the leader requires action from a traffic control centre. The main function of this control centre is to regulate the train (convoy) sequences and timings to avoid conflicting train paths. 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 Automatic Train Protection (ATP) and Automatic Train Operation (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. Communication (COM) structures require peer-to-peer capability between all trains and over large distances (>1 km), low latency and high availability. In addition, specifications for VC COM should be as open and abstracted as possible to maximize equipment independence. Cellular 5G/evolving 3GPP standards are also needed to address current COM solutions obsolescence, cost-effectiveness and avoid clashes between the other system components. One of the main challenges of the cooperative train protection of train convoys is to have carefully monitored and coordinated virtually coupled trains in a VCTS and avoid collisions within the convoy. 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 depend 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 operation and traffic control systems (e.g. traffic management and cooperative train operation), which may differ for the different market segments. Capacity performances of VC and potential gains over state-of-practice signalling systems have been addressed on a portion of the South West Main Line (UK) by Quaglietta et al. (2020). VC will change railway traffic planning as the capacity allocation may incorporate relative braking distances and therefore reduce train headways. In addition, platoons may have to be carefully planned including the type and order of trains. More details about the various railway system components and their challenges can be found in MOVINGRAIL (2020b). The main gaps identified for each of those components are summarized in Table 1.

As mentioned in Section 3, the strategy gap is the gap between what we must do in the future state and what we can do in the current state. It must be noted that so far, nothing has be done for developing VC but only actions have been taken to implement moving block which components are considered a pre-requisite for VC. The several strategy gaps for developing VC are mainly highlighted in the identified step-changes (see Section 6) based on the knowledge gaps identified in Table 1. These gaps are specifically about the step-changes identified by the experts, which might vary in terms of technological developments for different market segments. From the technological point of view, the strategy misses at the moment concrete deployment/test installations for VC as its deployment cannot be made if regulatory bodies do not approve this technology and authorize testing or a real-scale proof-of-concept.

Table 1
Gaps for the implementation of Virtual Coupling.

Component	Gaps
Interlocking	• 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 a relative braking distance. • Examining the duty and authority of traffic control to prioritise trains, routes, direction control and updating onboard timetable data.
COM 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 for use with Virtual Coupling, including safety and security aspects.
Cooperative train protection of train convoys	• 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.
Cooperative train operation of train convoys	• 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.
Railway traffic planning and management	• Extending the 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.

5. Case study

VC is considered to be deployed over several rail market segments such as high-speed, mainline, regional, urban and freight. In this paper, we present the optimistic and pessimistic scenarios for different market segments with a particular focus on the mainline market as the different components (Section 4) for this market are the most critical compared to the other segments. Particularly, mainlines have heterogeneous traffic that requires advanced systems for automatic traffic management and cooperative train operation to optimise the management of trains with different characteristics. This needs to be addressed by considering all the uncertainties that might arise from heterogeneous rolling stocks in one convoy. In addition, mainline railways are characterised by a higher complexity of junction station layouts due to branches from other rail networks of other categories (e.g. regional, freight or even high-speed) which connect to it, with a consequent elevated complexity of train manoeuvres at junctions/stations. This level of complexity and traffic heterogeneity requires longer development and deployment processes before VC could be deployed on mainline railways. The scenarios for the other market segments can be found in MOVINGRAIL (2020b).

The mainline case study considers the South West Main Line in the United Kingdom (UK) where a train runs from Waterloo to Southampton (127 km) every 30 min for 1 h20′ compared to a headway of 60 min for a 2 h20′ trip by coach (regional bus) with €28.45 and €9.00 ticket fees, respectively. A trip for the defined Origin-Destination (OD) pair by car takes 2 h10′ and costs €14.40. In MOVINGRAIL (2020a), the travel demand analysis indicated that based on a survey conducted with 229 respondents in year 2019–2020, the modal share in railways for this particular case study is 58 %.

The total transport CO_2 emissions for the considered case study are 16.928 kg per passenger, i.e., 13.904 kg for traveling by car and 3.024 kg for traveling by coach/regional bus. The initial emissions values were extracted from publicly available online sources such as EcoPassenger (2020), CostToTravel (2020) and the UK government (2019). In MOVINGRAIL (2020a), modal shifts were computed based on stated preference surveys to collect potential customer attractiveness for the introduction of VC. Modal shifts from motorized transport modes to railways were used to compute CO_2 emissions assuming that there is no increase in ticket costs. By further expanding this analysis, results showed that VC can reduce CO_2 emissions by 46.7 % on average. Based on the report by the UK Government on “2019 UK Greenhouse Gas Emissions, Final Figures” (UK GOV, 2021), transport was the largest emitting sector in the UK in 2019 and is responsible for over a quarter of all greenhouse gas emissions in the UK (27 %). Due to increased road traffic that has largely offset improvements in vehicle fuel efficiency, transport emissions were estimated to have been around 5 % lower in 2019 than in 1990.

CAPEX provides a marginal increase to migrate from ETCS L3 to VC (10.7 %) while OPEX is considered almost equal for the two signalling alternatives. The OPEX for VC with respect to the multi-aspect signalling system is 27.4 % (MOVINGRAIL D4.2).

In the case study, the knowledge strategy link is set by the outcomes of the feasibility study and represents the link between what we know from developments and technologies currently implemented in railway signalling (in our case studies, this refers to ETCS L2 for high-speed and multi-aspect signalling for the other market segments) and how we can bridge the knowledge gaps in Table 1 to bring the railway market to VC through a set of step-changes which build a strategy. On the other hand, the strategy-knowledge link mainly provides input to the ‘Direction’ (see Fig. 1) that the knowledge will be extended. Given the time to implement a certain strategy, we get to know what are the most critical rail segments and the knowledge required by stakeholders such as regulatory bodies and signalling system suppliers to overcome strategy-related challenges.

6. Results

This section presents results of the roadmapping analysis. The process consists of developing the technology roadmap (Section 6.1), then defining generic and market-specific scenarios with a specific focus on the mainline market segment (Section 6.2). Optimistic and pessimistic scenarios are defined based on the required durations for the different step-changes and on prediction uncertainties represented by five factors related to the VC market pulls. A Swimlane is defined by assessing priorities and times orders of step-changes towards the deployment of VC. Finally scenario-based roadmaps are developed based on the outcomes of Sections 6.1 and 6.2.

6.1. Stakeholder survey and swimlane for Virtual Coupling

A key initial step when designing a roadmap architecture is to understand the strategic context in terms of focus, scope and aims (Phaal and Muller, 2009) as shown in the 'Do know' element in Fig. 1. In addition, it is crucial to define goals, explore strategic options or scenarios, and implement step-changes as described in Section 3. These are developed by a process team -which represents a small group of people- that liaises with other key stakeholders.

The priorities of the step-changes were defined based on MCA criteria weights and the expert judgement A survey was distributed to the MOVINGRAIL partners to assess priorities and time order for a set of steps defined in a workshop with the MOVINGRAIL project partners and members of the advisory board, and to collect further steps/actions relative to the implementation of VC. Both priorities and time order were based on a score from 1 to 20. The highest priority is represented by number 1 while the lowest priority is assigned a value of 20. For time order the steps were ranked by starting with number 1.

From the MCA perspective, the priorities for the different step-changes were developed based on previous results from a hybrid Delphi-AHP MCA (MOVINGRAIL, 2020b; Aoun et al., 2021). For instance, we found that the safety criterion had a weight of 45 % when compared to the weights of seven other criteria. Therefore, the step-change 'Research on longitudinal motion control systems within train convoys, including convoy stability and relations to ATO' (see Fig. 2) has a very high priority because it should guarantee a safe distance between the trains before being able to move to the next step-change. In addition, the ATO should interact with the onboard safety system to promptly respond to the indication of position, speed and acceleration communicated by a predecessor to its follower within a convoy. Similarly, the regulatory approval criterion had a weight of 33 % which is assigned a high priority when compared to the weights of the other seven criteria. This is reflected in the step-changes related to the concept of operations and requirements as regulatory bodies would be able to approve the VC technology and authorize testing or real-scale proof-of-concept only after the requirements, the concept of operations and the systems architectures are supported by them. We found in our study that the input provided by the stakeholders in the survey and workshop was aligned with the priorities assigned to the step-changes based on the MCA results.

The aim of the Swimlane is to show how to bridge the gaps discussed in Section 4 though a list of step-changes towards the real deployment of VC. A Swimlane was developed to group time order and priorities collected from the survey into different themes and domains. The survey results were revealed and further expanded during an online workshop (given the Covid-19 circumstance) scheduled on the 6th of May 2020 with 22 participants representing project partners and railway experts in both academia and industry. The criteria adopted for the selection of the stakeholders included the type of professional background/company and the level of expertise, i.e. limited, practitioner, expert. The development of roadmaps requires the involvement of stakeholders, often with very different perspectives. Kostoff et al. (2004) mention that identifying appropriate participants to be involved, particularly in workshops, is a key consideration during the planning phase. We mainly focused on the five most important types of stakeholders in the railway field including: 9 representatives from academic institutions, 5 from infrastructure managers, 3 from railway signalling/manufacturing companies, 3 from passenger/freight train operating companies and 2 from governmental agencies. The workshop process which we adopted was based on the Delphi method where the roadmap was created in multiple iterations. First, the process team determined the scope of the roadmap and shared a list of initial step-changes with the stakeholders. The stakeholders were asked to come up with further step-changes and to share feedback on the provided step-changes. Scenarios, facts and brainstorming helped in identifying different roadmapping opportunities, and we updated the roadmap during the workshop based on the received feedback and brainstorming discussions. The survey's participants all attended the workshop which had the aim of reaching consensus about the chronological sequence and priorities of each action step in the roadmap towards VC. The iterations between the survey and workshop ensured feedback between the why, what and how perspectives. Survey results highlighted that respondents who defined themselves as experts provided a more consistent opinion across all the questions formulated in the survey. After both the survey and the workshop, the collected information was synthesized and consolidated in a set of visualizations which are packaged in this paper in a strategic roadmap relating to the why, what, how and when, as illustrated in Fig. 5.

The results were grouped into six themes (Feasibility study; Research and Innovation; Requirements; Specifications, Design, develop and build; and Deploy) and three domains (i.e., Operation, Business and Technology). Based on the priorities and time order extracted from the survey results, the step-changes were sorted chronologically per group (i.e., theme/domain 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 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
• Cost-effectiveness analysis, including capacity analysis	Business
• 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

Fig. 2 shows part of the Swimlane. All the step-changes, themes, domains, priorities and time order among the steps are illustrated in Section 6.2. The results showed that 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 actions. 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 VC according to the Common Safety Method (CSM-RA). In addition, specifications related to system architectures for VC (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 V2V, and RBC/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, and the final CSM-RA that were allocated to low priorities. Regulatory approvals were also represented by a green colour (low priority). This is most probably because respondents assessed the steps looking at the current knowledge and strategy (see Fig. 1). This means that although very low priorities

Table 2
Duration estimation of optimistic and pessimistic scenarios for each market segment.

	Short title of step	Time order & priority	Optimistic Scenario (months)					Pessimistic Scenario (months)				
			HS	ML	RGN	URB	FRT	HS	ML	RGN	URB	FRT
Feasibility Study	VC, scope and boundaries	0.1	2					5				
	Operational scenarios	0.2	2					5				
	Market analysis & use cases	0.3	3					6				
	CEA including capacity analysis	0.4	5					8				
	Technology roadmap	0.5	2					4				
	Business risk analysis	0.6	2					4				
	COM solutions	0.7	5					8				
	VC COM structures	0.8	4					8				
Research & Innovation	Longitudinal motion ctrl systems in convoys	1.0	24	30	24	18	24	36	40	36	30	36
	Operational procedures	1.1	6	12	6	6	6	12	18	12	12	12
	Integrated traffic mgt & train ctrl	2.0	24	30	24	18	24	36	40	36	30	36
	Train positioning	3.0	24	24	12	12	12	36	36	24	24	24
	Switch technology	3.1	24	24	12	12	12	36	36	24	24	24
	Concept of Operations	3.2	6	12	6	6	6	18	24	18	18	18
Requirements	System Requirements Specs	4.0	12	18	12	12	12	18	24	18	18	18
	Initial RAMS analysis	4.1	3	6	3	3	3	6	10	6	6	6
	Initial CSM-RA	4.2	3	6	3	3	3	6	10	6	6	6
	Operational & Engineering rules	8.0	10	12	10	10	10	20	24	20	20	20
Specifications	Operational procedures in IXL	5.0	6	10	6	6	6	12	20	12	12	12
	Operational procedures for coupling, coupled & decoupling	5.1	8	10	8	8	8	18	24	18	18	18
	Systems architectures	6.0	8	12	8	8	8	18	24	18	18	18
	COM protocols including safety and security	7.0	12	18	12	12	12	18	24	18	18	18
	COM models: V2V & V2I	7.1	8	12	8	8	8	18	24	18	18	18
	Standardization (e.g. ERTMS)	9.0	12	18	12	12	12	24	30	24	24	24
Design, Develop & Build	Develop COM system	10.0	8	12	8	8	8	12	18	12	12	12
	Upgrade RBC & EVC software	10.1	6	10	6	6	6	18	24	18	18	18
	Develop ATO	10.2	12	18	6	3	6	24	30	12	6	12
	Develop testing methods	10.3	12	12	12	12	12	20	20	20	20	20
	Early deployment & trial	11.0	6	10	6	4	6	12	18	12	10	12
	Final CSM-RA	12.0	6	8	6	4	6	12	18	12	10	12
	Final RAMS analysis	12.1	6	8	6	4	6	12	18	12	10	12
	Safety case	12.2	4	6	4	4	4	8	10	8	8	8
Deploy	Safety approval	13.0	6					18				
	Regulatory approval process (inclusion in TSI)	13.1	18					30				
	Deployment of ETCS Level 3 MB	14.0	18	24	18	12	18	24	30	24	24	24
	Deployment of VC	15.0	12	18	12	8	12	18	24	18	16	18

Legend

Priority scale		Market segment		Duration
(red)	Very high	HS	High-Speed	short → long
(orange)	High	ML	Mainline	
(yellow)	Medium	RGN	Regional	
(green)	Low	URB	Urban	
(blue)	Very low	FRT	Freight	

were provided to the deployment of ETCS L3 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.

6.2. Scenarios for Virtual Coupling implementation

This section develops scenarios that are used to describe various expected or assumed future situations to different market segments. A scenario considers alternative characteristics based on certain assumptions and conditions. The aim of the scenarios is to evaluate the most prominent factors/criteria for the deployment of VC by considering their pros or cons, and to build scenario-based roadmaps based on estimated durations (see Table 2). We analyse five measures or factors that affect the real (business) deployment of a certain technology or transportation project, i.e., demand, CO_2 emissions, CAPEX, OPEX and regulatory approval.

Two scenarios have been defined for each market segment: optimistic and pessimistic. The scenarios were grouped into two categories: generic and market specific. In this section we describe the generic scenarios and the ones related to the mainline market. Details on the scenarios defined for other market segments can be found in MOVINGRAIL (2020b). 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 VC concept within 2050. The baseline values of the defined factors are derived from Aoun et al. (2021) and from publicly available governmental sources.

Default percentages for demand and CO_2 emissions in the optimistic scenarios are 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 the year 2000 (European Environment Agency, 2012). 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). Optimistic costs consider a 40 % less value with respect to the baseline percentage. The regulatory approval criterion is described qualitatively in generic scenarios for all market segments. We also represent this quantitatively in Fig. 3 based on the criterion index of 0.320 computed in Aoun et al. (2021) by adding a 40 % increase in the case of the optimistic scenario.

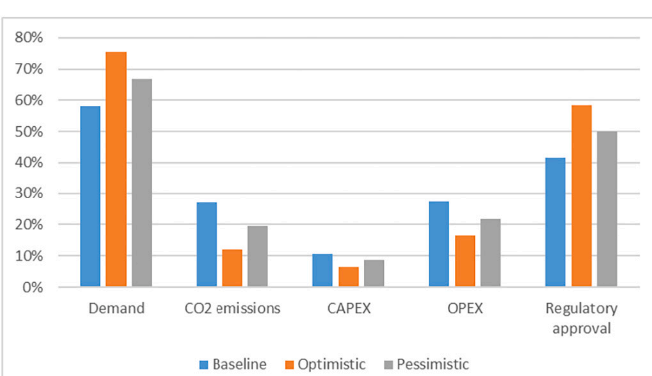

Fig. 3. Scenarios for the mainline market segment.

The pessimistic scenarios are based on 'pessimistic' trends of the defined criteria. In this case, the values are considered to increase or decrease from by 50 % compared to the optimistic scenario, depending on whether the defined criterion is beneficial (e.g. demand) or non-beneficial (e.g. costs). The railway demand for passenger trains is considered to increase by just 15 % and for freight trains by only 25 %. Similarly for CO_2 emissions, we assume a percentage decrease in CO_2 emissions by 30 % instead of 60 %, and for regulatory approval, the increase is by 20 % instead of 40 %.

6.2.1. 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 and the CO_2 emissions to notably decrease for all market segments. An optimistic percentage of a 40 % decrease is assumed for CAPEX and OPEX with respect to baseline percentages extracted from the cost analysis in MOVINGRAIL (2020a). The incentives between IMs and RUs are well aligned and support the deregulation of the railway market by 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 airlines). 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 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 is considered to increase by only 15 % instead of 30 %, and CO_2 emissions are considered to decrease in value by 50 % with respect to the optimistic scenario. This is because 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 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 compared to the percentage in the optimistic scenario ($0.5 \times 0.4 = 20$ %). 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 longer time compared to the optimistic scenario).

6.2.2. Scenarios for the mainline market segment

In an optimistic scenario, an increase of 30 % in the demand results in 75 % of the total modal share for train users from Waterloo to Southampton that was initially 58 % (see Section 5). The homogenisation of travel behaviour of the different train categories when platooning over open tracks facilitates coupling and decoupling on-the-run due to sufficiently long interstation distances, which provides additional capacity benefits. Travellers' satisfaction can be maximised by means of a personalised on-demand travel experience if swarming trains (composed of a single powered car unit) are introduced for the passenger trains (mixed with freight trains). In the case of the pessimistic scenario, the railway demand for mainline railways 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.

Since the European Commission has a strategic vision for railways to cut down the greenhouse gas emissions by 60 % within year 2050 compared to year 1990 and based on Section 5, we consider in this paper that the optimistic transport-related CO_2 emissions are reduced by 55 % from year 2019 to 2050 (from 27 % to 12.2 %). In the case of the pessimistic scenario, the reduction is equivalent to 27.5 % (50 % of 55 %) resulting in 19.6 % emissions by the year 2050.

In the optimistic scenario, the CAPEX increase of 10.7 % in VC investment costs compared to ETCS L3 is further decreased by 40 % resulting in just a 6.4 % increase. OPEX for VC with respect to the multi-aspect signalling system is decreased from 27.4 % to 16.4 %. In the pessimistic case, CAPEX is increased by 8.6 % and OPEX by 22 %.

As mainlines 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. The Shift2Rail MAAP mentions that there is a need for 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. On the contrary, a pessimistic scenario considers that 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 would be needed for regulatory approval.

A summary of the results is illustrated in Fig. 3.

6.3. Scenario-based roadmaps for each market segment

The main reasons for developing the scenario-based roadmaps relate to the goals of the VC deployment which can satisfy the EU vision. The main objective of VC is to increase line capacity by reducing headways, as well as to increase operational flexibility by insuring interoperability between all railway vehicles. VC also aims at improving the use of the existing station platforms by adopting several platform tracks. Costs are reduced with the implementation of VC since this technology relies on onboard equipment and electronic systems instead of lineside signals and/or the need to build new tracks or applying major infrastructural changes. Another reason that reduces costs is the reduced operational expenditure (OPEX) due to automatic operations (Aoun et al., 2021).

In this section, roadmaps are illustrated for optimistic and pessimistic cases by estimating timelines for the step-changes defined in Table 2. If the five factors defined in Section 6.2 are optimistic, e.g., demand will be increased by 30 % for passengers and by 50 % for freight by year 2050, the deployment of VC 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 VC. On the other hand, short timelines mean that the environment would rapidly become less pollutant and that the need for high investment costs and payments for staff would be reduced. Reciprocally, the longer the estimated duration of the step-changes defined for each market segment (pessimistic case), the lower would be the overall positive impact on the societal, environmental and economic factors. Based on the results in Sections 6.1 and 6.2, indicative durations to each of the steps 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 (2020a), the timelines were estimated based on an online workshop held with stakeholders across Europe and professional experiences by sector experts.

Actions can start simultaneously or consecutively. Dependencies among the different steps are related to the time order derived from the stakeholder survey and the Swimlane (Fig. 2) where one item can be considered as an input to the following step, resulting in a cascading sequence of timelines. The generation of roadmaps has been executed with the project management software Primavera P6 Pro.

The results show that the deployment of VC 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 2050 (see Fig. 4). This is because for mainline railways there is a 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 for further time extension for R&I in integrated traffic management and train control for both freight and passenger trains that operate on the same lines. In addition, regulatory approval might engender further delay since there is a need for crucial cooperation and agreement between IMs and RUs due to the heterogeneous traffic conditions. The duration of steps for each market segment in optimistic and pessimistic scenarios is shown in Table 2. The gradual colours of the estimated values denote that the reddish cells are the most critical, i.e., require the longest duration. The resulting scenario-based roadmap for the pessimistic scenario of the mainline market segment is illustrated in Fig. 5. Note that this figure is just an example of one scenario for one market segment. However, the roadmap builds on two scenarios for each market segment towards the deployment of a visionary concept that is not yet implemented in real-life, i.e. VC. The scenario-based roadmaps for the deployment of VC to each of the defined market segments in both optimistic and pessimistic scenarios can be found in MOVINGRAIL (2020b).

The roadmap in Fig. 5 represents a high-level, strategic plan that aims to communicate the VC project goals and vision. Particularly, each step-change represents a goal. In our research, we do not make a detailed and linear schedule of tasks, but we rather look at the bigger picture since each of the step-changes shown in Fig. 5 requires further investigation and has several uncertainties in terms of the adopted methodology or technology. This figure also shows the high-level domains, themes and dependencies between the step-changes, in addition to the priorities associated to each step-change.

In the illustrated roadmap, we follow the two key dimensions of a roadmap structure, namely timeframes (i.e. when) and layers/sublayers, as discussed in Phaal and Muller (2009). The aspects of why, what and how are attributed to the layers of the structured roadmap. First, we show the current situation, mainly related to the step-changes

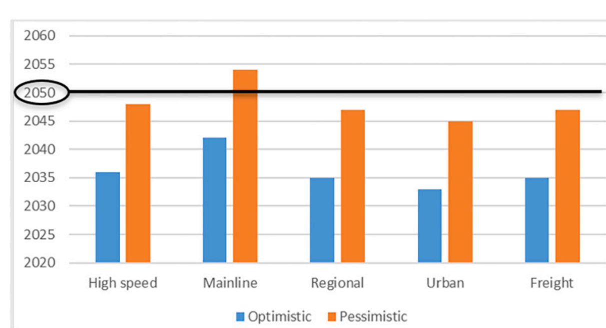

Fig. 4. Time until deployment of Virtual Coupling for each market segment in optimistic and pessimistic scenarios.

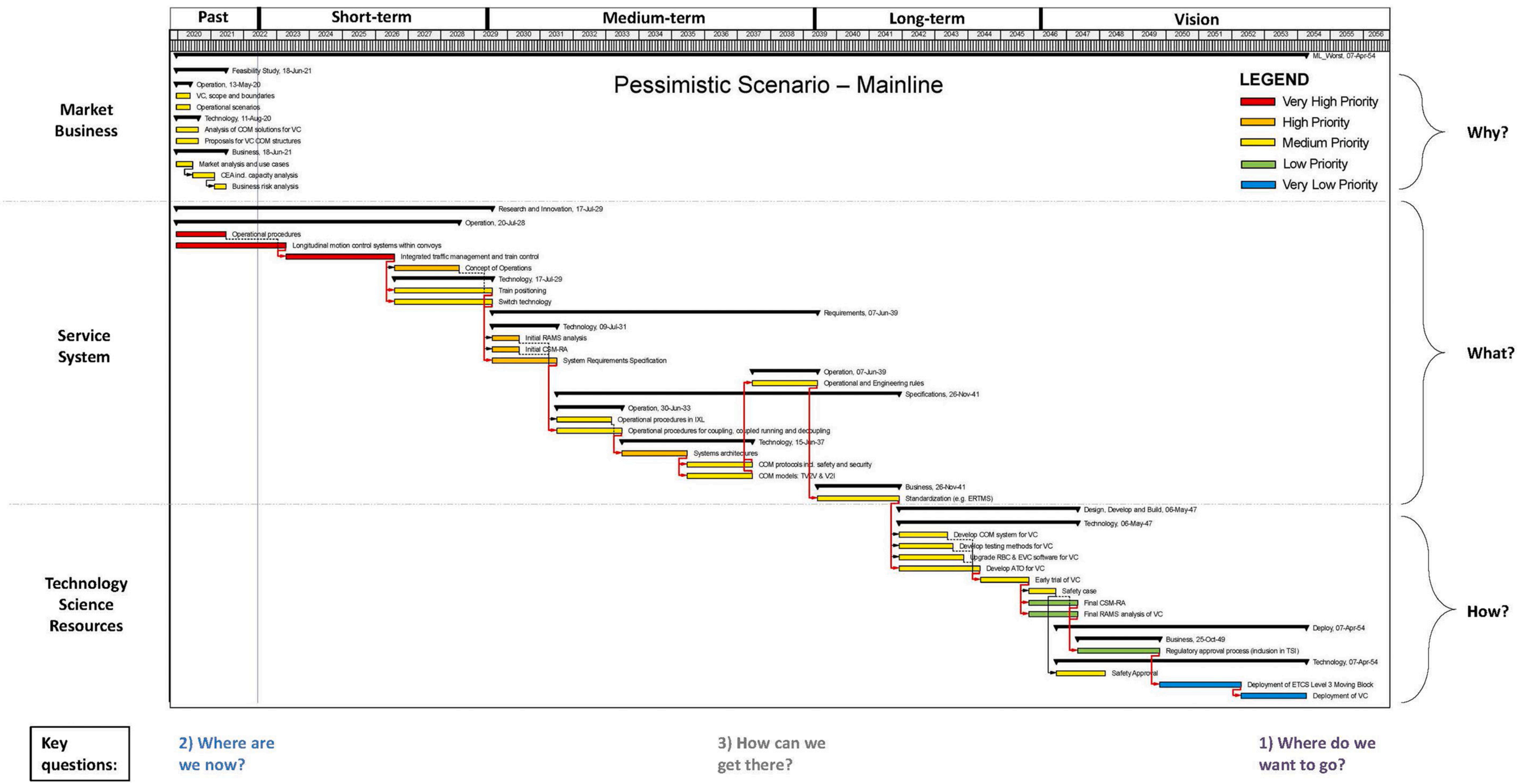

Fig. 5. Mainline – pessimistic scenario (16/12/2019–07/04/2054).

under the theme 'Feasibility Study'. We then progressively illustrate the step-changes in the short-, medium- and long-terms towards the vision of deploying VC. A long-term strategy enables key uncertainties and scenarios to be articulated, and shifts in the operation, business and technology domains, to capture and assess long-term issues that affect current decisions and plans, like R&I. The strategic lens provided by this roadmap magnifies and focuses on the issues and areas of the VC system which are of most importance. Those are assessed by means of priorities, time order, dependencies and durations. As mentioned previously, the main objective 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), represented in our study by the deployment of VC. The middle layer (what) constitutes the evolution of the technology, we represent this by sub-layers or intermediate layers to highlight key enablers and barriers/gaps which must be overcome through step-changes that lead towards the deployment of VC, and consequently benefit both customers and stakeholders. Therefore, the *what* in Fig. 5 corresponds to the strategical step-changes (see Fig. 1) to migrate from current state to future state. Those step-changes can be related to functions (e.g. RAMS analysis), features (e.g. ATO), performance (e.g. operational procedures in interlocking) and knowledge (e.g. operational procedures). Finally, the bottom layer *how* deals with the resources required to develop the VC system. Based on Phaal and Muller (2009), those resources can be related to knowledge (e.g. technology, skills, competences) or other resources (e.g. finance, alliances/partnerships, facilities). In our study, the *how* corresponds to the resources and the regulatory bodies responsible for the validation of the safety and engineering rules of VC, consequently leading to its deployment.

The Swimlane developed in Section 6.1 helps in understanding how each theme will evolve for each layer and sub-layer, and how the layers relate to each other. Fig. 5 portrays pushing and pulling perspectives as it supports the identification and discussion of the general requirements and capabilities offered or needed, respectively. The market pull leads from the *why* to the *what*. In the case of VC, it corresponds to the business and market needs for increasing capacity due to the significant increase in population and rail demand growth. Another main pull is given by the strategic EU vision for a competitive and sustainable transport envisaging a significant increase in current railway capacity, as well as a decrease in CO_2 emissions and lifecycle costs. The market pulls represented in optimistic and pessimistic scenarios (Fig. 1) are based on the percentages obtained in Section 6.2. The technology push is the relation between the *how* and *what*. Technology pushes in the case of VC are given by advances in telecommunications, informatics and rail signalling technologies whose increasing efficiency and capabilities are pushing railway operations towards a higher level of digitalization and automation of traffic management and train control. The latest developments relate to high-accuracy satellite-based vehicle positioning, high-speed/high-capacity signalling systems like ERTMS/ETCS, high-frequency long-range radio communication systems, and algorithms for Automatic Train Operation. These developments are pushing the upgrading of railway operations towards a digital future where train separation could be reduced (hence capacity increased) as automation will potentially improve driving reaction times, hence reliability and safety of current trains.

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 dependencies, orders and critical paths illustrated in the roadmaps. These may give guidance to put emphasis on certain step-changes. In particular, the roadmaps showed that R&I must be done in the beginning and was assessed as a lengthy process. It is therefore important to start these R&I topics in parallel as soon as possible. The business risks that entail those step-changes are discussed in detail in MOVINGRAIL (2020c).

7. Discussion

The research conducted in this paper proposes a novel roadmapping approach by developing a framework that supports various tools, scenarios and data flow. We applied the proposed framework for the first time to generate roadmaps for the VC deployment to different railway market segments to support stakeholders in the practice of technological forecasting and planning. The practical perspective is also highlighted in the critical aspects shown by the roadmaps which need to be considered both on the technological and regulatory sides to support regulators and policy makers in satisfying the market needs.

The policies and strategies that can be supported by the developed roadmaps include changes in engineering rules and operational principles for operating railways. Based on the feasibility study performed on VC in the MOVINGRAIL project, a set of enhanced engineering and operational rules have been drafted to support the IMs and regulatory bodies in writing VC and MB related rules (MOVINGRAIL, 2018). The responsible for approving these principles is the European Railway Agency (ERA) together with IMs and RUs. The roadmaps also provide the necessary elements that would need to be incorporated to reach approvals from the railway industry when it comes to technological developments and regulations. The ERA specifies which kind of certification process needs to be set to make the future technologies compliant to the current safety standards. In addition, rail system suppliers can avail of the outcomes of the roadmap to define strategic investment plans for research and developments of required signalling technologies enabling the deployment of VC to the market. In terms of the societal implications, the developed roadmaps help in understanding the required costs, time to deployment and the impact on the environment. Particularly, the scenario-based roadmaps show how the introduction of the VC technology can change the modal shifts between available transport modes and railways. Consequently, modal shifts would have an overall implication on energy consumption, CO_2 emissions and costs. The findings of this paper can also be used by the society for internal learning to redesign an intervention, improve approaches to interact with customers, or deliver an action or step-change. The identification of the scenario-based roadmaps as well as the SWOT analysis can support in developing tailored interventions to achieve better outcomes.

The SWOT was useful in determining the required step-changes for migrating from the current state to the future state towards deploying VC for each market segment. Based on the MCA results (MOVINGRAIL, 2020a; Aoun et al., 2021), we found that the urban market segment is ranked first in terms of cost and capacity. This is because this railway market is the simplest in terms of infrastructure layout and operation and therefore requires less investment and operational costs. In addition, since trains operate autonomously on a single track that does not involve complexities in land profile, the CO_2 emissions can be reduced. Metro systems also have the ability to transport a lot of passengers with short headways. With the implementation of VC, capacity benefits will increase to very frequent train services (e.g. every 30 s). In terms of regulatory approval, as automated metro systems are already implemented in an increasing number of cities worldwide, such as London, Lille, Beijing and Singapore, this process takes relatively less time than for other railway markets. This is mainly due to the same characteristics that enabled Automatic Train Operation Grade of Automation 4 (ATO GoA4) in these metro systems, such as slower speeds, closed environments and no to limited crossing tracks.

The future time horizons are associated with uncertainties represented in the roadmaps. In the framework from Courtney et al. (1997) where the levels of uncertainty can be related to timeframes, the research conducted by Kahn and Weiner (1967) seems to fit Level 2 of the Courtney et al. framework (options and branching pathways), while the definition of Troch et al. (2017) looks more relevant to Level 3. Our paper relates to the Kahn and Weiner (1967) definition as the end point is clear (EU goals), with the timing and impacts to achieve these goals uncertain, represented by optimistic and pessimistic scenarios for five different market segments.

Two main toolkit configurations are identified based on the following. On one hand, when strategic planning is dominated by future uncertainty, future-oriented scenarios can be used to resolve this uncertainty, which will define an end state towards which a roadmap can be developed. These scenarios have common and different elements and can potentially be combined to create branching pathways. On the other hand, when future uncertainty is not dominant, a baseline roadmap can be developed subject to a sensitivity analysis using scenarios, which leads to mitigations and options. Our paper relates to both toolkit configurations since the uncertainty arises from the fact that we are not sure whether by 2050 VC can be deployed to all market segments given the various challenges that need to be resolved for its deployment. On the other hand, depending on the complexities involved by each market segment, durations are affected by optimistic and pessimistic scenarios.

The challenges faced by the stakeholders represent different perspectives on the feasibility and challenges of the VC technology itself, the value and usability of VC for the railway market customers, and the skills and competences for creating and developing the VC concept. In addition, although the participants had different opinions about the durations for each step-change, the workshop helped in developing a consensus among all the stakeholders based on both expert and scientific judgement.

The technology roadmap developed in this paper can be used by other groups of people or fields to make decisions, or customers who are interested in the deployment of VC in the railway market. Other disciplines and applications such as logistics, supply chain, aviation and road transport could follow similar approaches for roadmapping and for the introduction of a new technology or process from start to market uptake. Furthermore, given the susceptibility of the developed framework to support a wide range of scenarios and case studies, it can help to plan and coordinate technological developments at any organizational, national or international level. Additionally, the roadmapping methodology defined in this paper can be used as input to decision makers where synchronisation and flexibility are enabled for redefining focus and direction, based on the variability of inputs from a SWOT analysis, MCA results and stakeholders.

Future recommendations include the enhancement of visuals that support the development of roadmaps based on the considered technology and its requirements. In addition, a limitation concerns the use of the same level of priority of the step-changes to all the market segments. This might not always be adequate since different stakeholders may have diverse needs and priorities depending on the investigated scenario for each market. Therefore, the concept of dynamic scenarios can be introduced to allow for more flexibility with the dependencies between step-changes, priorities, scenarios and market segments. Moreover, the developed framework in this paper can be integrated with other management tools and methods to provide a deeper investigation of systems' dynamics and areas from different sociological and technological fields. For instance, the integration of a Technology Development Envelope (TDE) can support the determination of an optimum path of technology development to maximize its benefits.

8. Conclusions

This paper developed a technology roadmap for the implementation of Virtual Coupling (VC) with a particular focus on the mainline market segment. It aimed at capturing operational, technological and business differences between traditional railway signalling systems and future train-centric signalling systems, as well as identifying potential optimistic and pessimistic scenario-based roadmaps to migrate railway operations to next-generation signalling.

The main challenges of VC were identified along with the required step-changes to the safety, communication and control technology, interlocking, Vehicle-to-Vehicle communication, cooperative train protection and control, and integrated traffic management. A Swimlane was developed by associating step-changes identified by stakeholders in a survey and workshop to assess priorities and time order for a set of future operational and technological steps, as well as business actions relative to the implementation of VC. This was supported by means of a gap analysis that consists of determining steps that must be undertaken to improve a present state towards a desired state. Particularly, the results of a SWOT analysis could be adapted to highlight the enablers for the implementation of VC and to generate ideas on how the gaps can be closed in different market segments through a list of step-changes.

The results of a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) Multi-Criteria Analysis (MCA) were used to define the priorities of the step-changes and to explore quantitatively optimistic and pessimistic scenarios for the development of VC to different market segments. The paper focused on the impacts of five prominent factors for the deployment of new transportation technologies, namely demand, CO_2 emissions, capital and operational costs, and regulatory approval. For all market segments, the need for an initial investment might not be well received by infrastructure managers and local governments. Results showed that both optimistic and pessimistic scenarios fulfilled the target of deploying VC by 2050, except for the pessimistic scenario of mainline railways where VC could only be deployed by 2054. The main bottleneck is here the development of integrated cooperative train operation, traffic management and interlocking for train convoys. This market segment would also involve high coordination between railway undertakings and infrastructure managers to enable VC 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.

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 can therefore be used as a tool for stakeholders to setup strategic investment plans which can steer the technological developments, and the necessary regulations facilitating the migration to VC rail operations.

The proposed approach helps in effectively visualizing a future action plan according to plausible future scenarios. This is particularly important when companies attempt to manage market and technology activities for both strategic planning and technology management. In practice, companies can use the developed roadmapping methodology at a corporate level for the management of toolkits to foster business growth and organizational changes. The integration of SWOT, MCA, expert judgement, gap analysis and scenarios in the framework also provides a means for addressing corporate challenges and exploring new opportunities. Moreover, the developed roadmap framework provides a coherent and holistic architecture within the development and evolution of not only the VC system but also other dynamic businesses or systems where step-changes can be explored, mapped and interpreted based on distinct scenarios. Therefore, the methodology developed in this paper is generic and can be adapted to different business processes and integrated to other management frameworks and disruptive technological game changers. As a next research step, the interactions of the essential system components for VC will be investigated in a system safety and performance analysis.

CRediT authorship contribution statement

***Joelle Aoun*:** Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - Original draft, Writing - Reviewing and Editing.

***Egidio Quaglietta*:** Writing - Reviewing and Editing, Supervision, Project administration, Funding acquisition.

***Rob M.P. Goverde*:** Validation, Writing - Reviewing and Editing, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

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Joelle Aoun is a PhD candidate at the Digital Rail Traffic Lab of the Department of Transport and Planning (T&P) at Delft University of Technology (TU Delft), the Netherlands, and the representative of her department at the PhD Council. She is a civil engineer graduated from the Holy Spirit University of Kaslik (Lebanon) and specialized in transportation (1st Grade Hons). Over the past years, Joelle got enrolled in several internships related to different civil engineering fields in structure and transportation. She carried out site supervision and design estimation for structural projects in Lebanon. She also participated in the integration of a feasible public bus transport system with the Keserwan-Ftouh Federation of Municipalities (Lebanon). In Greece, she worked on a project involving the operational and safety performance investigation of skew superelevation runoff. In 2018, Joelle was the President of the American Society of Civil Engineers (ASCE) at the Holy Spirit University of Kaslik (USEK) in Lebanon, and she received a Certificate of Commendation for being awarded to the top 5% of all Student Organizations in the world.

Joelle's PhD is about designing and assessing train-centric railway signalling and operations. She worked on the EU H2020 Shift2Rail funded projects MOVINGRAIL and PERFORMINGRAIL which delivered breakthroughs for the deployment of train-centric signalling by defining operational implications, developing testing methods for Moving Block, assessing impacts of Virtual Coupling, and addressing safe operational principles and specifications. Her PhD main interests are on multi-criteria impact assessment for market potential and operational scenarios for Virtual Coupling. She also works on analysing and defining novel operational principles to enable safe train separation, and on defining roadmaps for technological forecasting and social change.

Egidio Quaglietta is Assistant Professor in Railway Traffic Management at TU Delft and co-director of the Digital Rail Traffic Lab. He has been leading research on digital rail innovations including Moving Block and Virtual Coupling signaling for several EU projects as MOVINGRAIL, PERFORMINGRAIL and SORTEDMOBILITY. His experience in the field of railway signaling started in 2008, obtaining a PhD degree on simulation-based signaling optimization. Later on Egidio worked as R&D engineer for several prominent railway companies such as the Italian railway system supplier Ansaldo STS (now Hitachi STS) and the British railway infrastructure manager "Network Rail". Among his industrial experiences, he has led a workstream of the R&I program "Digital Railway" as well as the sub-project on "Operations for Enhanced Capacity" for the EC FP7 project Capacity for Rail (C4R). He has developed the simulation tool EGTRAIN and his main interests are in the areas of railway traffic and infrastructure optimization, innovative signaling technology and automated railway operations. He is a member of the Institution of Railway Signal Engineers (IRSE).

Rob M.P. Goverde is a Professor of Railway Traffic Management & Operations and Director of the Digital Rail Traffic Lab at Delft University of Technology. He received the MSc degree in Mathematics from Utrecht University, the Netherlands, in 1993; the Engineering Doctorate (EngD) degree in Mathematical Modelling and Decision Support from Delft University of Technology in 1996; and the PhD degree in Railway Transport from Delft University of Technology in 2005. His research topics include railway timetabling, railway traffic management, disruption management, automatic train operation, train control and railway signalling. He cooperated in many international research projects including the EU projects ON-TIME, MOVINGRAIL, RAILS, PERFORMINGRAIL and SORTEDMOBILITY. Dr. Goverde is President of the International Association of Railway Operations Research (IAROR), Editor-in-Chief of the Journal of Rail Transport Planning & Management, Associate Editor of the IEEE Transactions on Intelligent Transportation Systems, and Fellow of the Institution of Railway Signal Engineers (IRSE).