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Research Article

ERTMS/ETCS Level 3: Development, assumptions, and what it means for the future

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ABSTRACT: The purpose of this paper is to categorize the research on Level 3 and Hybrid Level 3; map how the research focus on ERTMS Level 3 has developed over time; summarize key assumptions in research on Level 3 and Hybrid Level 3. This study uses a scoping review approach. This review method provides a comprehensive overview of the literature in a selected field. The literature searches in this study were primarily conducted in Scopus and Web of Science and were complemented with a follow-up search in Google Scholar. The topics are divided into two thematic areas: Effects on the Railway System and Technical Requirements. The thematic area Technical Requirements is further divided into the following subcategories: train, trackside, and communication. The effects on the railway system are measured using performance indicators: capacity, stability/robustness, and safety. ERTMS Level 3 has developed from a pure Level 3 to Hybrid Level 3. Hybrid Level 3 represents a pragmatic solution, but it may emerge as a threat to the long-term objective of the Level 3 moving block. Studies of Level 3 are based on a moving block solution, while studies of Hybrid Level 3 are mainly based on virtual sub-sections. Both Level 3 and Hybrid Level 3 studies tend to make assumptions that risk missing wider aspects of the railway system. There is also a need to correctly represent different ERTMS Level 3 configurations to ensure expected capacity gains. For a better understanding of the development and future path of ERTMS Level 3, it is interesting to study the following aspects: the historical development of ERTMS Level 3 research, the assumptions made about ERTMS Level 3, and the conditions and restrictions under which ERTMS Level 3 will be implemented. Assumptions and simplifications are necessary for modeling work, but there is also a need to highlight underlying assumptions in analyses of different ERTMS Level 3 configurations.

KEYWORDS: ERTMS, ETCS, Level 3, Hybrid Level 3, moving block, virtual sub-section

1 Introduction

Safety systems have been developed to ensure safety in railway networks and reduce the risk of accidents caused by human errors. These systems are intended to prevent operations that jeopardize safety, such as train drivers exceeding established safety speed limits or passing red traffic signals (Pachl, 2002). It is EU policy that current national safety systems for member states in the EU will be replaced by a common system: the European Rail Traffic Management System (ERTMS). ERTMS is a traffic management system that will simplify travel and cross-border transport within Europe since, currently, most European countries have their own safety systems. As part of ERTMS, the European Train Control System (ETCS) will enable cross-border traffic (EEIG ERTMS Users Group, 2020. In this paper, ERTMS will be used to refer to both ERTMS and ETCS. ERTMS has three levels of implementation: Level 1, Level 2, and Level 3 (Pachl, 2020). The purpose of this paper is to map the existing research on ERTMS Level 3.

To understand the advantages of Level 3, we need to understand Level 2, the most common ERTMS implementation level. Level 2 is a radio-based system with some physical trackside equipment (most importantly, track-based train detection). In Level 2, signaling and movement authorities (MA), which give permission for a train to move from one point to another, are displayed to the train driver in the cab (EEIG ERTMS Users Group, 2020). The train continuously sends data reporting its exact position and direction to the Radio Block Centre (RBC) (Bloomfield et al., 2012). In contrast, Level 3 is a fully radio-based system without any trackside equipment. In Level 3, the RBC continuously receives data on the position of each train and calculates the smallest possible train distances at any time. With Level 2, the movement authorities are determined for fixed blocks so that a track section between two fixed points cannot be used by two trains at the same time. With Level 3, accurate and continuous position data are provided to the control center by the train rather than by track-based detection equipment. Because trains continuously monitor their own positions, tracks are no longer separated into fixed blocks, and trains can utilize blocks that move along the train ("moving blocks"). Compared to Level 2, Level 3 has the advantage of reduced costs for trackside equipment and capacity improvement (EEIG ERTMS Users Group, 2020).

The moving block solution is currently being developed and standardized, which has opened the door for different technical solutions for ERTMS Level 3. One of these is virtual block, often referred to as virtual sub-sections (VSSs). The VSS solution

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Abbreviations

ATO	Automatic Train Operation
ETCS	European Train Control System
ERTMS	European Rail Traffic Management System
GNSS	Global Navigation Satellite System
GSM-R	Global System for Mobile communications – Railway
HL3	Hybrid Level 3
L3	Level 3
MA	Movement Authorities
MB	Moving Block
RBC	Radio Block Center
TIMS	Train Integrity Monitoring System
TTD	Trackside Train Detection
VSS	Virtual Sub-Section

addresses the challenges of implementing moving blocks, which resemble the physical fixed blocks of Level 2 but without trackside equipment. By shortening the length of virtual blocks, capacity performance can be like that of moving block systems (EEIG ERTMS Users Group, 2020). Virtual blocks allow trains with Level 3 systems and those with older systems to operate on the same lines during transition periods. Such a hybrid implementation is often called Hybrid Level 3 (HL3). However, it is important to note that the term hybrid solution is not exclusively used to refer to VSSs. "Hybrid solutions" can also relate to moving blocks (Furness et al., 2017). A pure Level 3 system (*pure* in the sense that it only allows trains with Level 3) can be implemented with VSSs. As shown in Fig. 1, there are four different types of ERTMS Level 3:

- Level 3 with moving block (L3 + MB)
- Level 3 with virtual sub-section (L3 + VSS)
- Hybrid Level 3 with moving blocks (HL3 + MB)
- Hybrid Level 3 with virtual sub-section (HL3 + VSS)

There is a fifth type called overlay, but it is rarely used and will therefore not be included in this paper. There is a tendency to use Hybrid Level 3 as a synonym for all types of VSS implementation, while Level 3 often refers to moving block systems. In this paper, ERTMS Level 3 refers to all four solutions.

For a better understanding of the development and future path of ERTMS Level 3, it is interesting to study the following aspects: the historical development of ERTMS Level 3 research, the assumptions made about ERTMS Level 3, and the conditions and restrictions under which ERTMS Level 3 will be implemented. To address these issues, this paper reviews the academic literature on ERTMS Level 3. The literature review will map the research on Level 3 and Hybrid Level 3 and address the following research questions:

- How can we categorize the research on Level 3 and Hybrid Level 3?
- How have the topics and focus of research on ERTMS Level 3 developed over time?
- What are the key assumptions of research related to Level 3 and Hybrid Level 3?

2 Method

This study uses a scoping review approach (Gough, 2007). This review method provides a comprehensive overview of the literature in a selected field. The review process is described in detail in this section and illustrated in Fig. 2.

2.1 Search and sorting

It is common to use a structured review process to map previous research. The reasoning of significance can be conducted following generic standards or constructed from specific questions set by the reviewer, as is the case for this study (Gough, 2007). ERMTS is a relatively new research field and moving blocks and VSSs are also new concepts for the railway sector. Thus, we find it important to categorize the different subjects of related studies. We find it relevant to distinguish between studies related to the technical development of the signaling system and those looking at its effects on the railway network.

The literature searches in this study were primarily conducted in Scopus and Web of Science and were complemented with a follow-up search in Google Scholar (search criteria given in Table 1). To be included, the papers had to be clearly railway-related and include ERTMS and Level 3/hybrid in the title or abstract. To further specify the search, the keyword *ETCS* was discarded, as it generated several non-railway-related papers. Four searches were conducted (Table 1). The last two included studies of moving blocks and VSSs and variants of these terms (fixed virtual block, virtual block, etc.). All relevant results from the first, third, and fourth searches were included in the second search. The second search was therefore the basis for further review, with 95 papers.

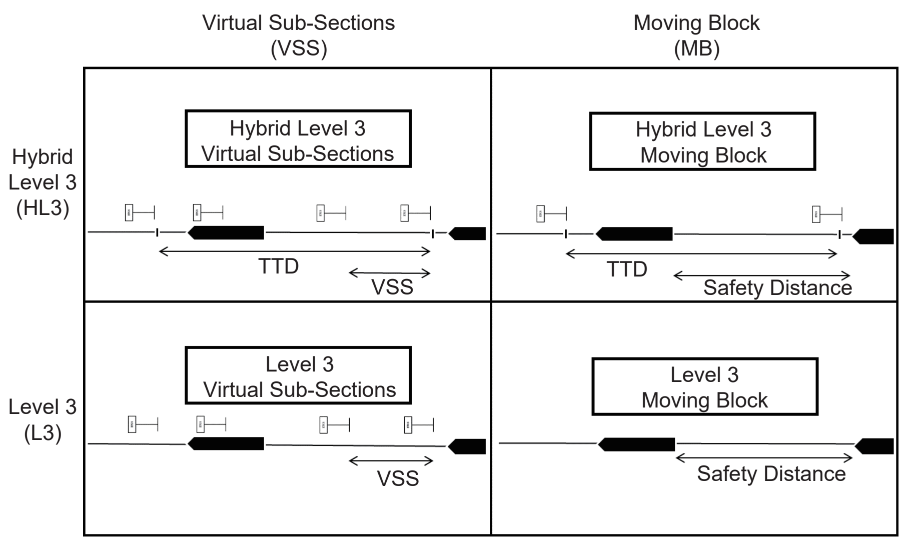

Fig. 1 Different ERTMS Level 3 concepts, including track-based train detection (TTD), virtual sub-section (VSS), and moving block safety distance.

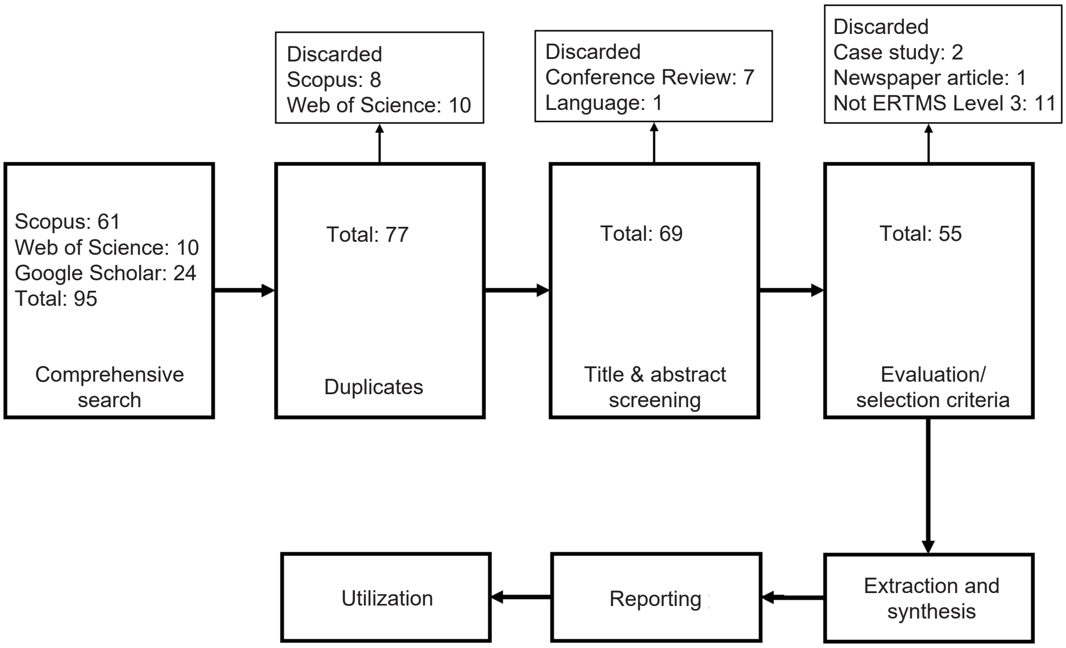

Fig. 2 Process map, with the total number of publications at different stages.

Table 1 Keywords and search results (query string shown here corresponds to Scopus; an equivalent string was used for Web of Science and Google Scholar)

	Scopus	Web of Science	Google Scholar
TITLE-ABS-KEY({etcs} AND (hybrid OR "level 3"))	84	27	—
TITLE-ABS-KEY(ertms AND (hybrid OR "level 3"))	61	10	24*
TITLE-ABS-KEY(ertms AND moving block)	25	4	**
TITLE-ABS-KEY(ertms AND virtual block)	11	5	**

Note: * The number of results after initial screening. ** Not searched for in Google Scholar (generated too many irrelevant results).

2.2 Screening and evaluation

The search generated 95 results. The screening step excluded eighteen duplicate papers. Abstract screening discarded eight papers: one for not having sufficient English in the abstract to be categorized and seven for being conference reviews. Fourteen papers were discarded after evaluation: two case studies, one newspaper article deemed not relevant, and eleven that only mentioned Level 3 in the background section. Finally, a total of 55 papers remained for extraction and synthesis.

2.3 Extraction, mapping, and categorization

After the extraction step, the literature addressed the following topics:

Train

• Train Integrity Monitoring System (TIMS) in general

• A specific Global Navigation Satellite Systems (GNSS) solution for TIMS

• Distance and speed control related to the moving block system

Signaling and communication

• GSM-R, specifically the communication between the train and the signaling system

• Virtual balises (removal of physical balises) as part of Level 3

• Virtual coupling, specifically technical solutions that could increase the capacity gain of Level 3

Railway system

• Design validation, including formal methods and models

• Railway network performance, including capacity and headway calculation, simulations, and modeling

These topics address different aspects of ERTMS Level 3, as shown in Fig. 3. TIMS, GSM-R, and virtual balises all relate to technical aspects of Level 3. Design validation refers to system specification verification, and formal methods and models are commonly used in studies on this topic. Network performance is measured using capacity, headway, or punctuality, using either calculation or simulation methods. Several studies examine how distance and speed can be monitored to ensure traffic flow. Virtual coupling is technically an adjacent research area, but in some cases, it is regarded as an extension of Level 3.

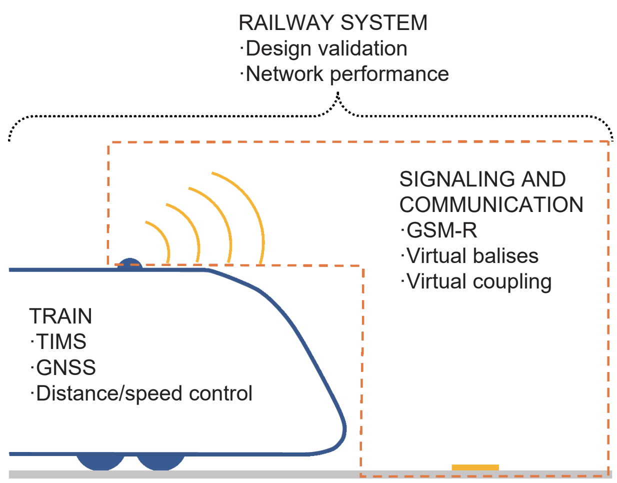

Fig. 3 Research directions of ERTMS Level 3 and how they relate to different parts of the railway system.

3 Categorizing studies

3.1 Thematic areas

The topics above can be divided into two thematic areas: *Effects on the Railway System* and *Technical Requirements*. The terminology introduced in Fig. 1 can also be used to categorize the studies: Level 3, Hybrid Level 3, VSS, and moving block. Further, some studies reference both moving blocks and VSSs, and thus an additional group was introduced: *L3 (independent of MB or VSS)*.

The thematic area *Technical Requirements* is further divided into the following subcategories: train, trackside, and communication. The effects on the railway system are measured using performance indicators: capacity, stability/robustness, and safety. Capacity refers to the utilization of railway infrastructure. Stability/robustness addresses railway network stability, robustness, and resilience. Safety refers to risk and hazardous situations in the railway network. Table 2 shows the studies sorted according to the terminologies described above.

Table 2 shows that there are no studies explicitly focusing on the *Trackside* category. This is reasonable, since the purpose of Level 3 is to remove trackside equipment and thus eliminate failures. However, trackside equipment is a central part of railway signaling, and removing this category in the early stages may be too hasty. Furthermore, there are no studies related to Hybrid Level 3 moving block (HL3 + MB). Three studies (Snook et al., 2021; Besani et al., 2015; Ranjbar et al., 2021) discuss both *Technical Requirements* and *Effects on the Railway System*; therefore, they are counted twice in Table 2.

3.2 Development of Ertms Level 3: Timeline and origin

Fig. 4 shows how research on Level 3 has developed over time. It highlights a shift in research topics from pure Level 3 to hybrid solutions. ERTMS Level 3 is first mentioned in research papers as a hybrid solution of Level 3 (Dachwald et al., 2001). This implies that the concept of hybrid solutions has been a potential research subject as long as pure Level 3, although Hybrid Level 3 was not addressed again until 2018. Hybrid solutions have gained considerable attention since the first release of the concept paper “Hybrid ERTMS/ETCS Level 3: Principles” in 2016 (EEIG ERTMS Users Group, 2020).

As seen in Fig. 4, most studies on pure Level 3 focus on moving blocks, while some include aspects related to Level 3 independent of technical solutions. Only a few studies, published in 2012, 2019, and 2021, studied pure Level 3 with VSSs.

Fig. 5 shows the number of papers by country of origin based on the first author’s affiliation. Most papers are from the Europe. The Chinese Train Control System (CTCS) and the North American Positive Train Control (PTC), which resembles ERTMS, are not included in this literature review. There are, however, some similarities and differences between these systems and ERTMS/ETCS. The main purposes of all such safety systems are interoperability, safety, reliability, easy maintenance, and reduced costs (Ning et al., 2010). CTCS also uses GSM-R as a standard. Similar to ERTMS/ETCS, CTCS has different levels, with CTCS Level 4 corresponding to ERTMS Level 3. However, CTCS Level 4 is currently a moving block solution, and there is no alternative solution for positioning the trains, compared to balises for ERTMS. The North American PTC does not have a moving block solution, but an “advanced PTC” (alternatively PTC 2.0) is being considered to provide support for a virtual or moving block solution (Diaz de Rivera et al., 2020). However, for PTC to be equivalent to ERTMS Level 3, it would require more sophisticated and reliable communications and network capabilities than those being implemented for the current PTC system (Diaz de Rivera et al., 2020).

3.3 Technical requirements

A central part of the moving block concept is that the block reliably reports its track position as it moves with the train. Lazarescu and Poolad (2021) claim that all trains need to constantly and reliably report both train integrity and track position without infrastructure support to ensure that trains are

Table 2 Overview of the number of papers

	Technical requirements			Effects on railway system		
	Train	Trackside	Communication	Capacity	Stability/ robustness	Safety
L3 + MB	4	0	9	12	11	4
L3 + VSS	0	0	0	2	0	1
L3 (independent of MB or VSS)	2	0	2	1	2	1
HL3 + MB	0	0	0	0	0	0
HL3 + VSS	1	0	1	5	0	13

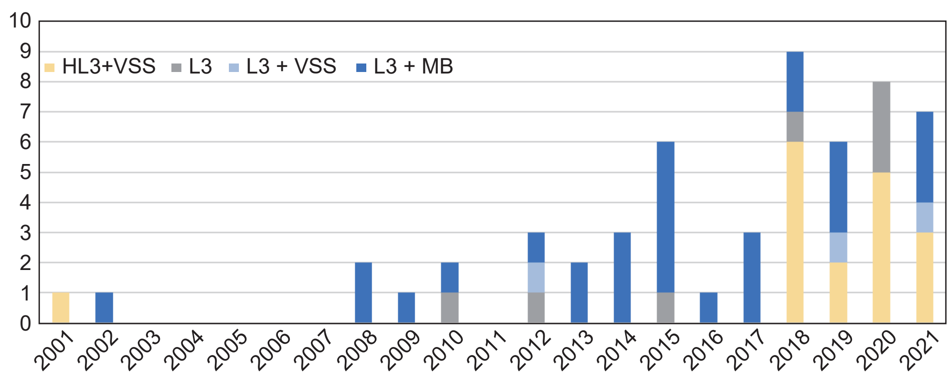

Fig. 4 Timeline of papers studying different technical solutions: Hybrid Level 3 with Virtual Sub-Section (HL3 + VSS); Level 3 independent of technical solution (L3); pure Level 3 with Virtual Sub-Section (L3 + VSS); pure Level 3 with Moving Block (L3 + MB).

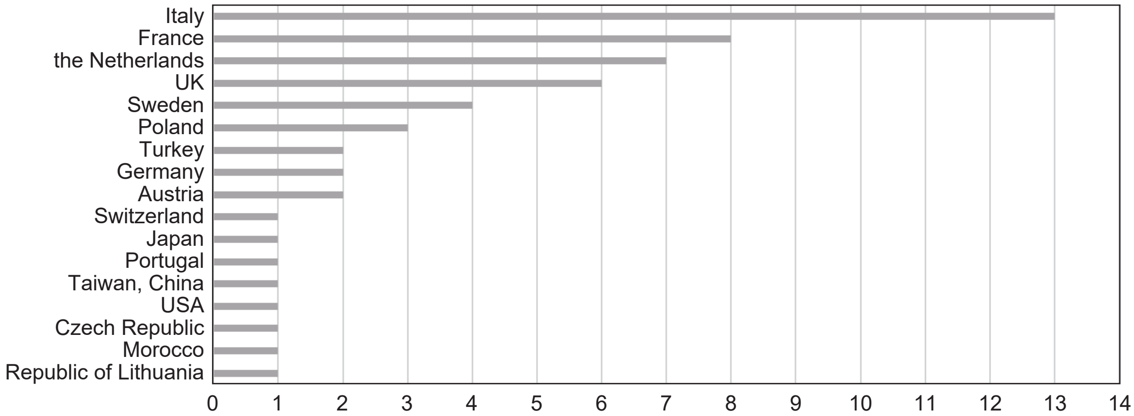

Fig. 5 Number of papers by country/region of origin.

complete, and no wagons are lost. For long freight trains with individual wagons, self-monitoring is a complex task. Loco-hauled passenger trains with a fixed composition and multiple-unit trains also have challenges, though they are not as severe as those of long freight trains (i.e., a train with no wagons cannot lose a wagon). Neri et al. (2014) classify the technical solutions for train integrity into two categories:

1) Systems that rely on devices at the end of the train; for example, a brake air pipe pressure reduction detector (changes in the air pressure used for the brakes can indicate the loss of a wagon), an acoustic wave transmitter or radio transmitter (to confirm that the last wagon is still there), and a GNSS localizer (to confirm the location of the last wagon).

2) Systems that do not need devices at the end of the train; for example, ultrasonic systems (to confirm the train composition), the detection of spacing and number of wheels (to confirm that all wagons are still connected), the injection of acoustic signals (to detect deviations indicating the loss of a wagon), and the monitoring of parameters on the leading wagon (to detect deviations in the parameters).

Using GNSS to perform the integrity function on a train has gained some attention. GNSS is a tried and proven technique, and, as Neri et al. (2014) describe, it could be used to effectively monitor train integrity with sensors at the last wagon. Another advantage of GNSS is that it can accurately locate the position of a wagon in cases of failure when a train is split into two sections. However, GNSS has problems with accuracy and reliability (Ikonomakis et al., 2022), for example, in tunnels and urban environments. To address these problems, Neri et al. (2014) propose combining GNSS with additional sensors to provide a cost-effective train integrity monitoring system. Lazarescu and Poolad (2021) propose using wireless sensors on all wagons that are independent of GNSS. These sensors confirm that all couplings are connected, securing train integrity. It should be noted that the problems regarding GNSS are not railway-specific. Promising future research from other transport-related fields may provide solutions to the problems of GNSS (Yan et al., 2021).

Communication between the train and the RBC is a vital component of ERTMS and of moving blocks in particular. If communication failures occur and messages are lost, the train must stop, even if the track ahead is free (Carnevali et al., 2015). To understand why, we need to look at the fundamentals of moving block communication. The basic principle is that a transmitter sends the position of a preceding train to the RBC, and the RBC returns a corresponding MA to the following train. This procedure creates a safe distance between the two trains. Several failures may occur in the communication process between the train and the RBC (Kochan and Koper, 2020). According to Biagi et al. (2017), failures can be caused by burst noise (leading to the communication channel being temporarily inaccessible), connection losses (due to failures in hardware components), or handovers between communication areas (when a train passes the border of a GSM-R cell). In addition, as highlighted by Carnevali et al. (2015), the GSM-R communication channel is a source of unreliability because of almost unavoidable data transmission errors. Biagi et al. (2017) conclude that the greatest risk of communication failures occurs at handovers between GSM-R cell borders. A minor communication disruption could still affect train operation. A following train may then need to engage emergency brakes, which would cause delays (Carnevali et al., 2015) and have major impacts on the railway network's capacity (Jansen et al., 2008).

Despite these risks of failure, the overall capacity improvement of a pure Level 3 system still positively impacts railway capacity compared to traditional signaling (Jansen et al., 2008). Jansen demonstrates this with a stochastic model of the communication system complemented by a simple track layout of the railway system.

The aim of Level 3 is to decrease failures by reducing the physical trackside components (EEIG ERTMS Users Group, 2020). Nevertheless, balises will still exist as part of train positioning. Presently, ERTMS Level 2 and Level 3 trains obtain their position by combining reference balises with on-board odometry to calculate the distance traveled from the last balise. Most ERTMS installations already have this system in place. Beguin et al. (2018), Basile et al. (2019), and Marais et al. (2018) propose removing balises to decrease the number of possible failures and reduce installation costs. When using GNSS for train positioning, virtual balises would reduce the need for physical balises.

Reliable TIMS and communication are essential for both VSS and moving block systems (Sassi et al., 2020), indicating that the same solutions could be applied to both of these ERTMS Level 3 concepts. With a hybrid solution, a working TIMS is not a prerequisite (Snook et al., 2021). The basic principle of Hybrid Level 3 is that it accommodates trains with different levels of ERTMS: ERTMS and TIMS-equipped trains (i.e., Level 3), ERTMS trains not fitted with TIMS (i.e., Level 2), and trains not equipped with ERTMS (Hoang et al., 2018). Due to the limitations of GSM-R communication, a train may disconnect from the system. Hybrid Level 3 helps mitigate this problem by using Level 2 as a backup (Furness et al., 2017).

3.4 Effects on the railway system

Capacity can be measured by calculating the number of trains on a line or the total time the track is occupied by trains (Coviello et al., 2014). Another common way of measuring capacity is to measure the railway network's robustness to disturbance, that is, the capacity margins that provide the network leeway in case of delays (Valentinovič and Sivilevičius, 2017). Koning (2002) demonstrates that Level 3 with moving blocks has a higher capacity than both Level 2 and Level 3 with fixed blocks. Using empirical results, Lai and Wang (2012) also show that Level 3 with moving blocks (both pure and Hybrid Level 3) positively affects capacity. They emphasize that moving blocks can improve the capacity on a line, but the total capacity gained in the network may be insignificant because of the constraints of the track layout at stations. This highlights a problem, in that most studies only investigate the effects of the railway line (Coviello et al., 2014). Omitting the effects of stations (and all types of nodes) in the railway network is problematic and may cause one to overlook capacity bottlenecks or misjudge the gains of Level 3.

Moving blocks allow two consecutive trains to move as close to each other as possible. An important aspect of moving blocks is thus to correctly model two following trains while ensuring accurate estimates of the capacity and safety of the line (Durmus et al., 2012). To fulfill this modeling aspect of moving blocks, Durmus proposes a model that can successfully handle disturbances of two consecutive trains. By using train characteristics and dynamics (length, location, speed, and acceleration) and considering the braking distance, the capacity and safety of moving block systems can be estimated.

Additional information can be used to increase the stability of Level 3 moving blocks—for example, timetable changes and updated speed profiles (Besani et al., 2015). This could help mitigate concerns about congestion caused by trains with different speed profiles. Liu (2016) demonstrates the importance of additional information for moving blocks by optimizing parameters for timetable planning to enable smooth traffic flows. For example, Liu et al. (2015) model moving blocks with a safety distance of 2,000 m for fast trains and 1,000 m for slow trains. This distance can be shortened to increase capacity, but with the trade-offs of decreasing safety and traffic flow (and *vice versa*).

It is common to study the effect of moving blocks on a double-track line, focusing mainly on the effect on headway (i.e., block occupation). Coviello et al. (2014) study the effect of moving blocks on a single-track line and examines how to use them to increase capacity on a congested line. However, Coviello does not consider trains traveling in the same direction at different speeds, which impacts the capacity of both single- (in cases of platooning) and double-track lines. It is especially challenging on mixed traffic lines that combine slow-moving freight trains with fast-moving passenger trains. This means that the effect of moving blocks on capacity is greater for lines with similar types of trains (i.e., trains with the same speed), such as metro systems, high-speed lines, and freight passages (Schön et al., 2013). The capacity of the GSM-R system can be a limiting factor, and lines are usually divided into areas that manage limited numbers of trains, with a maximum of ten (Bersani et al., 2015). However, the limitations of the GSM-R system should not be a limiting factor to the line's capacity (Bersani et al., 2015).

The capacity gains of moving blocks could be improved even further by optimizing the onboard braking curve. Emery (2008) found that the braking distance can be added to the safety distance between following trains without compromising safety, leading to increased capacity gains. According to Emery, this solution could save significant time in cases of disturbance and would be especially interesting in the case of high-speed trains (which have long braking distances).

In theory, virtual coupling could be implemented in association with moving blocks to boost capacity gains even further (Flammini et al., 2021). Virtual coupling could be implemented in parallel with any signaling system (Flammini et al., 2018). Di Meo (2020) highlights the importance of speed control for successfully implementing virtual coupling. They propose a cooperative driving scheme using train-to-train communication for trains that are coupled virtually (meaning, in practice, platooning with an extremely short distance). Because of this, virtual coupling can be regarded as a step beyond moving blocks and is sometimes called Level 4 (Di Meo et al., 2020). Nevertheless, there is a need to evaluate the feasibility and performance of virtual coupling to ensure operability in diverse scenarios (for example, mixed traffic) and operating conditions (Di Meo et al., 2020). It is unclear whether the capacity gains from virtual coupling are sufficient to motivate the implementation of the technology (Quaglietta, 2019). Quaglietta (2019) notes that the operational principles of virtual coupling have not yet been fully defined, which makes estimates of the capacity effects uncertain. With this in mind, Quaglietta et al. (2020) compute virtual coupling's potential for headway decreases by 77% and 43% compared to Level 2 and Level 3, respectively.

Moving blocks could be combined with automatic train operation (ATO)—self-driving trains—to improve capacity even further (Emery, 2008). The combination not only allows planners to use shorter buffer time during timetable construction but also has the potential for time savings during traffic disturbance (Emery, 2008).

VSS systems allow for a higher degree of freedom than fixed block systems (ERTMS Level 2), as they are not dependent on physical components. Therefore, VSSs can achieve higher capacity on railway lines by using short block distances (Dachwald, 2001), increasing the efficiency of the train schedules (Willie, 2021). However, exploiting this potential is a non-trivial task that mainly relies on manual labor to determine the length and position of the virtual blocks (Willie et al., 2021). Wille et al. (2021) propose a method for automating this process through infrastructure designs (block lengths, location) and timetable creation. An early study by Koning (2002) notes that a Level 3 fixed block system (corresponding to VSSs with the same block sections as a Level 2 fixed block system) performs worse than a Level 2 system (and, by extension, a Level 3 moving block system). Therefore, using the same block section lengths for VSS as for Level 2 is not recommended, and some optimizations are needed to exploit the capacity potential. By reducing the length of the virtual blocks, the performance can be similar to that of moving blocks (Jansen, 2019). The user handbook *Hybrid ERTMS/ETCS Level 3: Principles* (EEIG ERTMS Users Group, 2020) states that compared to moving block, VSSs are not fundamental to the Hybrid Level 3 concept but represent a pragmatic approach, as VSSs have less impact on existing trackside systems.

VSS could decrease headway. Cuppi et al. (2021) found that compared to traditional signaling, VSS reduced headway between two trains with the same speed from 5 to 3 min. Retaining trackside detection also has its benefits, as it could improve system performance (i.e., capacity) because it provides a faster release of VSSs (Snook et al., 2021). This is also an argument for splitting the TTD blocks into smaller VSSs instead of splitting a line into a completely new VSS (Jansen, 2019).

Beyond capacity benefits, VSSs also have economic advantages. Dachwald et al. (2001) claim that Level 3 can have a significant impact towards fully exploiting infrastructure capacity, leading to both micro- and macro-economic gains. As VSSs are more suitable for a hybrid solution, the cost required to upgrade conventional signaling systems could be reduced (Ranjbar, 2021). A hybrid solution also has the benefit of a more robust signaling system (compared with a pure Level 3 system) since Level 2 serves as a backup (Furness et al., 2017).

Several studies have used formal methods to examine safety requirement verifications. Event-B was used by Mammar et al. (2020, 2018), Tueno Fotso et al. (2020), Dghaym et al. (2020, 2018), Ait Wakrime et al. (2018), and Fischer and Dghaym (2019). Other examples of formal methods include Abstract State Machine (Gaspari et al., 2019), mCRL2 Toolset (Bartholomeus et al., 2018), Spin (Arcaini et al., 2020, 2018), and Electrum (Cunha and Macedo, 2020).

4 Assumptions and conditions

4.1 Summary of existing studies

The reviewed studies have explicit or implicit assumptions that may influence their analyses and conclusions. Tables 3 and 4 summarize the assumptions of the literature regarding moving blocks and VSSs. Whether or not working train integrity (TIMS) exists is one issue. If a TIMS is assumed, a working TIMS solution is a requisite for the study, regardless of the type of technical implementation. In the cases where TIMS is not assumed to exist, it is either not fully developed (for example, studies of technical aspects of TIMS) or unreliable (TIMS creates disruptions in the network).

Another common assumption is related to whether communication disruptions have a minor effect on the railway network, or if the effects of such disruptions are handled explicitly. Communication disruptions could also include other failures beyond those between the train and the RBC. In the case of virtual coupling, train-to-train communication represents another potential area for transmission failures.

Safety distance is another interesting parameter in studies of moving blocks (Table 3). Safety distance refers to the space between two consecutive trains and affects the minimum possible headway of the track. For VSSs and Level 2 fixed blocks, block length is another interesting parameter, as shown in Table 4.

4.2 Discussion

The majority of studies, regardless of Hybrid or Level 3, assume that either TIMS is solved or that communication failures have insignificant effects (Fig. 6). As seen in Tables 3 and 4, TIMS is commonly assumed to be solved. This is especially true in studies of moving blocks and those that do not address TIMS specifically. Most authors of Level 3 moving block studies treat TIMS as a prerequisite. For Hybrid Level 3, it is more complex. We know that TIMS is not solved for some trains in hybrid systems, as these trains still have Level 2 installed. Thus, for a hybrid solution, an important factor for capacity relates to the number of trains in the railway network that will have a working TIMS. Few papers consider the proportion of trains with and without TIMS. The assumption has less impact in test cases where only two trains are involved but it will have a major impact on larger railway networks.

Generally, communication failures are assumed to have a minor effect on the network. Thus, when failures occur, these disturbances are assumed not to affect the railway network's performance. To study the effect of Level 3 on robustness, we must consider all types of disturbances, including failures in infrastructure, signaling systems, dwell times, and communication. For simulations of railway networks, it is important to include the effects of communication failures during operations, which are rarely addressed in the reviewed studies.

The defined safety distance values between moving blocks vary between studies. Studies of virtual coupling stand out for having extremely short safety distances. Virtual coupling imitates two trains being coupled physically with the intention of having as short a safety distance as possible. As virtual coupling has not been fully developed, the applied values for safety distance should be considered theoretically. If we instead look at moving block studies, a few assumptions stand out. One frequent assumption is that only a default value is used for safety distance. This is problematic, especially for simulations of railway networks as various types of rolling stock. Assuming only one value for the safety distance is an over-simplification other than for test case studies of specific scenarios, such as two trains with the same performance driving on a double-track line. To simulate moving blocks on a railway network with different types of rolling stock, a wider range of safety distances must be represented.

The VSS solution provides flexibility in the number of blocks that a line can be divided into and the lengths of those blocks. However, as seen in Table 4, block lengths for virtual blocks are rarely stated. In addition, some studies state that the lengths of VSSs are assumed to be the same across the whole system. Arcaini et al. (2020) argue that the lengths of VSSs should be defined in a system specification. When simulating a railway network using predefined lengths for all blocks, length will affect capacity, especially around stations where the allowed speed is lower than on main line sections. The reason simulations use only one length for VSSs may vary, but for most cases, it seems to be for simplicity.

Table 3 Assumptions for modeling of Level 3 with moving blocks and/or virtual coupling. Train length corresponds to normal/fast train; slow train in parentheses if mentioned

Ref.	ERTMS Level 3 concept	Middleic	Method	TIMS assumed solved?	Assumed minor effect of communication failures?	Train length	Safety distance
Abed (2010)	L3 + MB	Performance	Overview of effects on performance	Yes	Yes	—	—
Allota (2015)	L3	TIMS	Concept testing	No	Yes	—	—
Babczyński and Magott (2014)	L3 + MB	GSM-R	Simulation (Monte-Carlo)	Yes	Yes	—	5,000 m
Babczyński and Magott (2015)	L3 + MB	GSM-R	Probability calculations	Yes	No	3,000 m*	—

(Continued)

Ref.	ERTMS Level 3 concept	Middleic	Method	TIMS assumed solved?	Assumed minor effect of communication failures?	Train length	Safety distance
Basile et al. (2019)	L3 + MB	TIMS (GNSS)	Modeling (Simulink/UPPAAL)	No	No	—	—
Beguin et al. (2018)	L3 + MB	Distance/speed control	Safety appraisal method	Yes	No	—	—
Besani et al. (2015)	L3 + MB	Distance/speed control	Control method	Yes	Yes	—	—
Biagi et al. (2017)	L3 + MB	GSM-R	Modeling of communication failures	Yes	No	4,100 m*	5,000–6,000 m
Carnevali et al. (2015)	L3 + MB	GSM-R	Modeling of communication failures (non-Markovian)	Yes	No	—	4,000 m
Chiappini et al. (2010)	L3	Design validation	Formal method	Yes	Yes	—	—
Coviello et al. (2014)	L3 + MB	Performance	Headway and capacity calculation (RailSys)	Yes	Yes	296 m/ 740 m	—
Di Meo et al. (2020)	L3	Virtual coupling	Numerical analysis method	Yes	Yes	190 m	2,000 m
Durmus et al. (2012)	L3 + MB	Distance/speed control	Modeling (Batches Petri Nets)	Yes	Yes	320 m	7,500 m
Durmus et al. (2013)	L3 + MB	Distance/speed control	Simulation	Yes	No	400 m	1,000 m
Emery (2008)	L3 + MB	Distance/speed control	Concept formalizing	Yes	No	400 m	40 s/ 1,800 m**
Flammini et al. (2018)	L3	Virtual coupling	Stochastic capacity modeling	Yes	Yes	—	100 m
Flammini et al. (2021)	L3 + MB	Virtual coupling; Performance	Capacity analysis (SAN)	Yes	Yes	200–600 m	200 m
Jansen et al. (2008)	L3 + MB	GSM-R; Performance	Simulation	Yes	No	—	111 s/ 4,900 m**
Kochan and Koper (2020)	L3	Design validation	Formal method	Yes	Yes	—	—
Koning (2002)	L3 + MB	Performance	Headway calculations and punctuality simulation	Yes	Yes	—	77 s/ 3,400 m**
Lai et al. (2012)	L3 + MB & L3 + VSS	Performance	Capacity calculation (UIC 406 method)	Yes	Yes	—	—
Lazarescu and Poolad (2021)	L3 + MB	TIMS	Concept testing (field test)	No	Yes	—	—
Lindström (2012)	L3	GSM-R	Theoretical development	Yes	No	—	—
Liu et al. (2015)	L3 + MB	Distance/speed control	Simulation (TrackULA)	Yes	Yes	250 m (75 m)	2,000 m (1,000 m)
Liu (2016)	L3 + MB	Distance/speed control	Discrete-time simulation model	Yes	Yes	250 m (75 m)	200 m (100 m)
Marais et al. (2018)	L3 + MB	Virtual balises	Video-based tool	Yes	Yes	—	—
Neri et al. (2014)	L3 + MB	TIMS (GNSS)	Monte Carlo simulation	No	Yes	2,500 m	—
Neri et al. (2015)	L3 + MB	TIMS (GNSS)	Simulation	No	Yes	—	—
Platzer and Quesel (2009)	L3 + MB	Design validation	Formal method	Yes	No	—	—
Quaglietta (2019)	L3 + MB	Virtual coupling	Simulation (EGTRAIN)	Yes	Yes	—	117 m
Quaglietta et al. (2020)	L3 + MB	Virtual coupling	Simulation (EGTRAIN)	Yes	Yes	—	15 s/ 670 m**
Ruscelli et al. (2017)	L3 + MB	GSM-R	Theoretical development	Yes	No	—	—
Sassi et al. (2020)	L3	TIMS	Safety requirements analysis	No	Yes	—	—
Schön and Streitzig (2013)	L3 + MB	TIMS	Capacity evaluation	No	Yes	—	—
Valentinovič and Sivilevičius (2017)	L3 + MB	Performance	Capacity calculation	Yes	Yes	—	—

Note: * Sum of train length, safety margins, and braking distance. ** Calculated with an average speed of 160 km/h.

Table 4 Assumptions regarding modeling of Level 3 with VSSs (both hybrid and pure). Train length corresponds to normal/fast train; slow train in parentheses if mentioned

Ref.	ERTMS Level 3 concept	Topic	Method	TIMS assumed solved†	Assumed minor effect of communication failures	Train length	Block length (TTD)	Block length (VSS)
Arcaini et al. (2018)	HL3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Arcaini et al. (2020)	HL3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Ait Wakrime et al. (2018)	HL3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Bartholomeus et al. (2018)	HL3 + VSS	Design validation	Formal method	No	No	—	—	—
Boudi et al. (2019)	L3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Cunha et al. (2020)	HL3 + VSS	Design validation	Formal method	No	No	—	—	—
Cuppi et al. (2021)	HL3 + VSS	Performance	Headway and capacity calculation (Opentrack)	Yes	Yes	—	900–1,350 m	350–450 m
Dachwald et al. (2001)	HL3 + VSS	Performance	Concept	No	Yes	—	—	—
Dghaym et al. (2018)	HL3 + VSS	Design validation	Formal method	No	No	—	—	—
Dghaym et al. (2020)	HL3 + VSS	Design validation	Formal method	No	No	—	—	—
Fischer et al. (2019)	HL3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Gaspari et al. (2019)	HL3 + VSS	Design validation	Formal method	No	Yes	—	—	—
Jansen et al. (2018)	HL3 + VSS	Performance	Simulation (RailSys)	Yes	Yes	69–324 m††	—	100–500 m
Lai et al. (2012)	L3 + MB & L3 + VSS	Performance	Capacity calculation (UIC 406 method)	Yes	Yes	—	—	—
Mammar et al. (2018)	HL3 + VSS	Design validation	Formal method	No	Yes	—	—	—
Mammar et al. (2020)	HL3 + VSS	Design validation	Formal method	No	Yes	—	—	—
Ranjbar et al. (2021)	HL3 + VSS	Performance	Simulation (RailSys)	Yes	Yes	—	—	100–200 m
Snook et al. (2021)	HL3 + VSS	Design validation	Formal method	Yes	No	—	—	—
Tueno Fotso et al. (2020)	HL3 + VSS	Design validation	Formal method	Yes	Yes	—	—	—
Vergroesen et al. (2020)	HL3 + VSS	Performance	Simulation (RailSys)	Yes	Yes	76–569 m	—	100–200 m
Wille et al. (2021)	L3 + VSS	Performance	Simulation	Yes	Yes	100–700 m	2,500 m	500 m

Note: † Trains with Level 3. †† Values for passenger train. Freight train used in study, but no length specified.

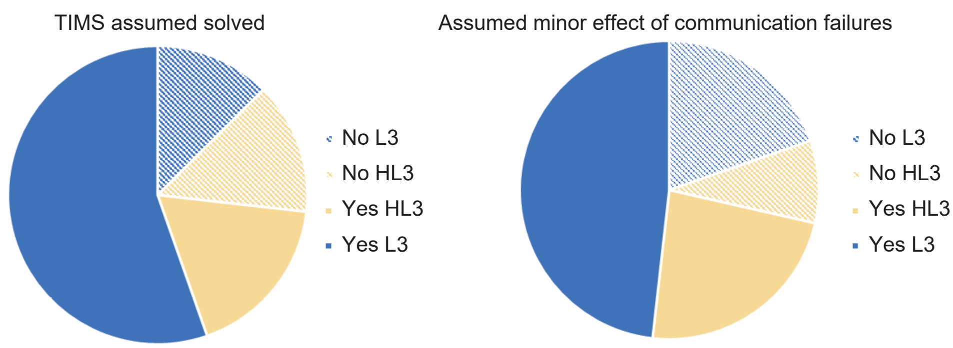

Fig. 6 Left: Share of all papers that assume TIMS is solved or not. Right: Share of all papers that assume that communication failures have a minor effect on the railway network or not.

With a fixed block length, VSSs can be generated for the entire line, making model implementation more manageable. Still, it is not always clear that this is done for simplicity, and in the worst case, it could give planners the impression that all VSSs should be the same length. However, VSSs should have different lengths to maximize the positive effects on headway. To model VSSs, different lengths of blocks should be included. As Jansen writes (Jansen, 2019, p. 60), "The block length or length of the virtual subsections should be adjusted to the expected train speeds or train speed differences to improve the headways of successive trains."

If we address the different block lengths, there remains the question of minimum and maximum lengths of VSSs. Jansen (2019) addresses this question, specifying that VSSs should have a minimum length of 200 m, but allow a minimum of 100 m in specific cases. They also state that the sections should be no longer than 5,000 m but do not clearly explain how these lengths are derived.

There is also the question of how many blocks a train can occupy. Most studies assume that a Level 3 train occupies two VSSs at most, regardless of the train length. This is not always the

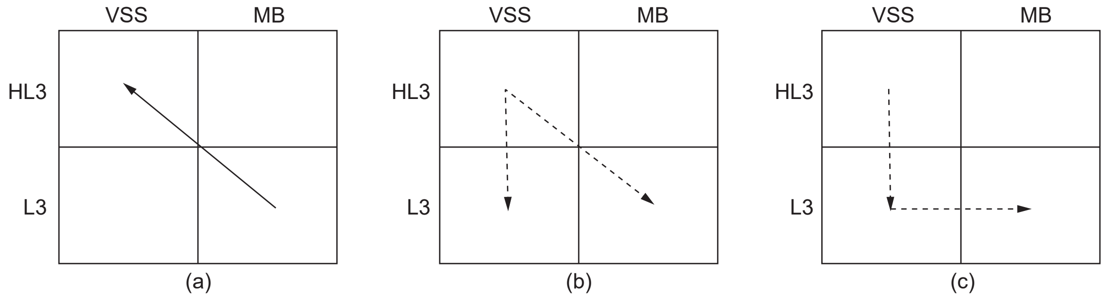

Fig. 7 (a) Development of Level 3, (b) potential path for development, and (c) alternative path.

case; the number of VSSs occupied should be defined by the subsection lengths and train length and should therefore not have an upper limit. Therefore, ideally, simulations should not assume a maximum occupation of two block sections as a prerequisite.

There are some noteworthy assumptions regarding the development of Hybrid Level 3. No studies address whether a hybrid system with VSSs is intended to evolve into a complete Level 3 system with moving blocks. When it comes to capacity gains, we can assume that the incentive for this transition would be small since VSSs generate a similar performance to moving blocks (or, at least, this is assumed).

4.3 Development and future path of Level 3

Fig. 7(a) depicts the development of research on ERTMS Level 3, showing that the research focus has shifted from pure Level 3 with moving blocks to a hybrid solution with VSSs.

Fig. 7(b) shows two different potential paths for ERTMS Level 3. One path points to pure Level 3 with VSSs and returns to the original Level 3 moving block configuration. If every train has a working TIMS, Hybrid Level 3 with VSSs may evolve into a pure Level 3, which creates an alternative path for the development of ERTMS Level 3, as illustrated in Fig. 7(c).

Given that Level 3 with moving blocks is the long-term objective of ERTMS implementation, Hybrid Level 3, as an intermediate concept, may represent a risk; compared to VSSs, moving blocks may not provide sufficient gains in capacity and stability to justify the cost of upgrading the system.

5 Conclusions

This study reviewed and categorized previous research on ERTMS Level 3. Regarding the first research question, the reviewed studies have different areas of focus related to Level 3 and Hybrid Level 3. The studies are categorized into several different topics and further categorized into two thematic areas: technical solutions and effects on the railway system.

The second research question relates to the development over time of research on ERTMS Level 3. ERTMS Level 3 has developed from a pure Level 3 with moving blocks to a Hybrid Level 3 with VSSs because the implementation of the latter is regarded as more achievable. However, there are still some issues regarding the future development of ERTMS Level 3. As an intermediate step, Hybrid Level 3 represents a pragmatic solution, but as a substitute, it may emerge as a threat to the long-term objective of Level 3 moving block.

Finally, the third research question addresses the key assumptions of the mapped research on Level 3 and Hybrid Level 3. Studies of Level 3 are based on a moving block solution, while studies of Hybrid Level 3 are mainly based on VSSs. Both Level 3 and Hybrid Level 3 studies tend to make assumptions regarding methods and scenarios that risk missing wider aspects of the railway system. For example, capacity studies primarily consider railway lines and tend to disregard the details of stations and junctions. There is a need to study the effect of different safety distances for moving blocks as well as VSS lengths, as there are no standardized values. Assumptions and simplifications are necessary for modeling work, but there is also a need to correctly represent different ERTMS Level 3 configurations to ensure that ongoing investments materialize into the expected capacity gains.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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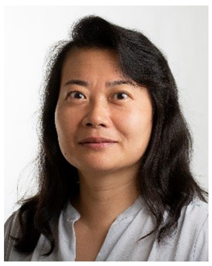

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