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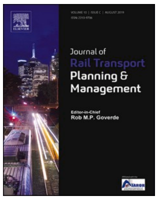

Impact of signalling system on capacity – Comparing legacy ATC, ETCS level 2 and ETCS hybrid level 3 systems

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ABSTRACT

Most railways use fixed block technology, which could be replaced with moving block technology with associated high cost. It is therefore interesting to gradually upgrade the signalling system exploiting hybrid technologies. This paper aims to investigate the impact on capacity of various signalling systems (including fixed block technology and hybrid technology) using a microscopic simulation tool under scheduled (static) conditions without considering probability functions. To perform comparative analysis between European Train Control System (ETCS) Hybrid Level 3, ETCS Level 2, and the Swedish ATC2 legacy system, three signalling system scenarios are designed and capacity consumption is considered as a performance indicator. The study was performed on the central section of Stockholm's commuter train network with peak hour conditions from the 2020 timetable. The results show that ETCS L2 delivers lower capacity consumption in total compared to the ATC2 legacy system. ETCS Hybrid Level 3 with existing trackside train detection and partially shortened block sections delivers lower capacity consumption compared to ETCS L2 and ATC2. The implementation of hybrid solutions such as ETCS Hybrid Level 3 in addition to allowing for gradual upgrading of signalling systems to the next generation (moving block system) can improve capacity of high-density commuter lines.

1. Introduction

High demand for railway transport has led to traffic congestion and nearly overloaded railway networks (Aoun et al., 2020) with related impact on economic attractiveness (Abril et al., 2008). Currently implemented signalling systems (in terms of a conventional signalling system with cab signalling system, fixed block technology, and moving block technology) along the railway considerably impacts the available capacity and capacity utilization along the railway (Goverde et al., 2013). European Railway Traffic Management System (ERTMS) is a set of standards including GSM-R, and European Train Control System (ETCS). ETCS level 3 and Train Integrity Monitoring (TIM) can facilitate full moving block (ERTMS Users Group, 2018).

These preconditions require upgrading the rolling stock with onboard equipment to obtain maximum performance – which is a cost challenge in the short term. In this situation, it is more convenient to upgrade the signalling system gradually by using hybrid solutions (Ranjbar and Olsson, 2020) such as ERTMS Level 3 Fixed Virtual Blocks, with Trackside Train Detection (TTD) (known as Hybrid level 3) which would allow both TIM-fitted and unfitted trains to run on the same line, but the maximum performance would be accomplished with all running trains equipped with TIM (Furness et al., 2017).

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As capacity consumption is an important performance consideration (Verkehrswissenschaftliches Institut, 2008) and decision-making indicator (UIC, 2013), this study aims to investigate the impact on capacity consumption of different signalling systems using a microscopic simulation tool under static conditions (without disturbances and changing variables within the defined time period). In order to distinguish high-density commuter lines from non-high-density commuter lines, the Capacity Consumption (CC) value of the block section with highest CC was considered as a capacity indicator along the line. CC values were defined as follows:

- CC $>$ 100% critical section with no residual capacity (congested sections);
- 80% $<$ CC $<$ 100% with low residual capacity;
- CC $<$ 80% with sufficient residual capacity for additional trains (UIC, 2013).

One purpose is to verify the impact on capacity consumption and minimum headway of upgrading the legacy system to ETCS level 2 and hybrid level 3. The layout of the current physical block sections is kept, but in ETCS HL3 block sections are shortened by using virtual block sections. This can improve capacity without considerable additional cost for configuration of new physical block sections.

To carry out the comparative analysis, three different scenarios were modelled for southbound trains in the central section of the commuter train network in Stockholm using the microscopic simulation tool RailSys. The study is based on the Swedish national RailSys model provided by Trafikverket (Swedish Transport Administration). In this study, the base model is configured to various signalling systems in order to achieve the study's goal. The three scenarios created are:

- Scenario 1 – based on current conditions with the legacy ATC2 signalling system.
- Scenario 2 – the line and trains are upgraded to ERTMS/ETCS L2, signals are replaced with marker boards but the location and length of the block sections remain the same as in scenario 1.
- Scenario 3 – the line is upgraded to Hybrid Level 3 (HL3) assuming the existing physical block sections (excluding sections with movable components) are divided into Virtual Sub-Sections (VSSs between 100 and 200 m).

The three scenarios developed are based on timetables under scheduled condition, i.e., static conditions without perturbations. A static analysis involves running a nominal simulation without any stochastic variable – all trains run according to the timetable. In static methods, probability functions such as travel time delays are constant over the time (Warg & Bohlin, 2016). Static methods are suitable for evaluating the travel time and headway enhancements of high-capacity signalling (Markewicz, 2013). Static methods are one of the common approaches to examine the impact of different signalling systems on capacity. By evaluating reduction of minimum headway and capacity consumption based on blocking sequences easily, it is possible to demonstrate the impact of signalling systems on capacity (Peterson, 2017).

This paper is structured as follows: Chapter 2 provides a brief overview of various implementation levels of the ERTMS, the Swedish ATC2 signalling system, and braking principles. Chapter 3 covers the literature related to capacity studies. Chapter 4 contains explanations about headway and capacity consumption. Chapter 5 explains the case line overview. Chapter 6 describes the simulation settings and scenarios. Chapter 7 presents the results of study, and finally, chapter 8 contains the conclusions.

2. Background

This chapter provides a brief overview of the various implementation levels of the European Railway Traffic Management System (ERTMS), and an introduction to the Swedish ATC2 signalling system and ETCS braking principles. We briefly introduce level 1 and 2 but have main focus on level 3. In addition, we mention level NTC where trains equipped with ERTMS/ETCS are operating on lines with a national signalling system.

3. European Train Control System level 1 (ETCS L1)

ETCS L1 is a spot transmission train control system, a cab-signalling system that overlies on existing signalling system and typically relies on trackside signals. The speed of trains is continuously monitored to protect the train from overspeed (considering speed limits) and override the limits of Movement Authority (MA), (Havryliuk, 2017). ETCS L1 relies on conventional Trackside Train Detection system (TTD). Axle counters and track circuits are main components of conventional TTD systems. TTD transmits the status of the railway to external systems (interlocking and control center). Line Electronic Unit (LEU) translates received telegrams from interlocking and transmits them to the switchable balises to update the train in the Movement Authority (MA). To enhance capacity and updating the MA in advance, extra balises can be implemented between main and distant signals to communicate infill or transform the system to a semi continuous train control system by implementing loop or radio infill. In addition, this avoids trains running under release speed limits (ERTMS User ERTMS USERS GROUP, 2016).

4. European Train Control System level 2 (ETCS L2)

ETCS L2 is a radio-based train control system that overlies existing signalling systems and relies on conventional TTD systems for train integrity and track vacancy detection. ETCS L2 provides a bidirectional communication between Infrastructure and vehicle (I2V) using the radio communications network, Global System for Mobile Communication-Railway (GSM-R) and secure radio transmission protocol by Euroradio (Bloomfield et al., 2012). In ETCS L2, the trackside signals are optional where fall-back and balises have responsibility for position referencing (Cuppi et al., 2021). The stop marker board will indicate the end of each block section. A radio block centre (RBC) communicates to the MA based on information received from the interlocking to the train via radio transmission system. Balises and odometer ERTMS L2 using high frequency MA updates (near to real-time) via Euro radio provides more reliable operation at higher speeds (ERTMS User ERTMS USERS GROUP, 2016). Depending on operational principles, stop marker boards (SMB) and lineside marker boards (LMB) can be implemented.

5. European Train Control System level 3 (ETCS L3)

The ERTMS Users Group (EUG) in deliverable D5.1 Moving Block System Specifications introduces four types of ETCS Level 3 Moving Block Systems: 1) Full Moving Block, without TTD; 2) Full Moving Block, with TTD; 3) Fixed Virtual Blocks, without TTD; 4) Fixed Virtual Blocks, with TTD, (ERTMS Users Group, 2019). (In this study, ERTMS Level 3 Full Moving Block System abbreviated to L3 FMB and Fixed Virtual Blocks, with Trackside Train Detection as described in (ERTMS Users Group, 2018) is designated Hybrid level 3 (HL3)). Level NTC (train equipped with ERTMS/ETCS operating on a line equipped with a national system).

5.1. *European Train Control System level 3 full moving block system*

In ETCS Level 3 Full Moving Block Systems (L3 FMB), the Movement Authority (MA) releases by Radio Block Centre (RBC) based on Train Integrity Monitoring (TIM) and the position reported by train. The ETCS on-board computer continuously calculates the braking curves considering safety margins based on Confirmed Safe Rear End (CSRE) and Confirmed Rear End (CRE) of the train ahead and danger points such as level crossings or points. The L3 FMB allows trains to operate with shorter safe distances (decreasing minimum headway), which increases capacity. In addition, transferring the task of TTD systems using track circuit and axle counters for trains equipped with TIM and positioning system brings reduction of trackside equipment, and implementation and maintenance cost (ERTMS Users Group, 2019).

The moving-block principle cannot be applied to moveable elements, such as switchpoints. Transferring the responsibility of train detection and TIM from TTD systems to on board systems requires continuous radio connection between the train and trackside, where disconnection due to degraded situation, intentional restart of RBC, or switching to shunting mode, the RBC would lose the actual location of train which would be challenging (ERTMS Users Group, 2018).

5.2. *European Train Control System hybrid L3 (HL3)*

The Hybrid Level 3 (HL3) concept exploits the capability to use limited implementation of physical block sections and subdivide them into shorter Virtual Sub Sections (VSSs) bringing reduced implementation and maintained cost. VSS is a new concept that is defined as a division of physical block sections into shorter VSSs which are stored in the logic of trackside equipment. Note, the sections with moveable elements cannot be subdivided into VSSs. In fixed Virtual Blocks with Trackside Train Detection (TTD) systems, the principles of ETCS L2 are kept, whereby both trains equipped with TIM or trains not equipped this way can run on the same line. TTD and Positive Train Detection (PTD) are responsible for train detection on physical block sections and Virtual Sub-Sections (Furness et al., 2017; ERTMS Users Group, 2018).

6. European Train Control System braking principles

According to (EUROPEAN RAILWAY AGENCY ERTMS UNIT, 2020), control command and signalling systems are not in charge to manage braking systems on rolling stock, but instead it is responsible to monitor train location and to avoid overspeed in relation to the target speed, preventing overrun of target points End of Movement Authority (EOA) and supervised Location, (EUROPEAN RAILWAY AGENCY ERTMS UNIT, 2020). ETCS onboard units constantly estimate supervision limits in real time. Supervision limits consist of: Indication (I), permitted speed (P), Warning (W) and Service Brake Intervention (SBI). The curve of the distance against speed during deceleration is called braking curve (for service braking this is called the service brake deceleration curve). Emergency Brake Deceleration (EBD) is a deceleration curve based on the application of emergency brake (to stop at target distance in a worst case, that is supervised location, SvL). Emergency Brake Intervention (EBI) is based on worst-case scenarios assuming the dynamic feature of trains, brake build up time, actual speed and error in calculation of speed. Indication (I) is one of the key elements of supervision limits in ETCS that provides information about the location for applying the brake to avoid overspeed and application of SBI by the train (if this option is active on train). ETCS onboard units used to calculate braking curves needs input parameters such as ETCS fixed values which are constant and provided in (ERTMS User ERTMS USERS GROUP, 2016) information related to the train (train length, brake performance, correction factors, and the brake build-up time) and related to infrastructure characteristics (location of wayside equipment, target speed, and target distances). The input parameters regarding features of infrastructure and the trains are fundamental for estimation of EBD (Havryliuk, 2017).

ETCS on-board units calculates the guaranteed EBD curve (parabolic curve) based on two main constituents of deceleration which are (EUROPEAN RAILWAY AGENCY ERTMS UNIT, 2020; ERTMS User ERTMS USERS GROUP, 2016):

> “A_brake_safe” that is deceleration applied by emergency brake as deceleration against speed.
>
> “A_gradient” which is the produced acceleration or deceleration by uphill or downhill slope.

Asafe (v, d) = A_brake_safe (v) + Agradient(d).

In order to fulfil the requirements of guaranteed emergency brake, correction factors should be considered: Kdry_rst, that is related to confidence level on dry rails and Kwet_rst is related to estimated loss performance due to reduced adhesion between wheel and rail. National safety level can be adjusted by means of such corrections factors.

Usually, in legacy systems like ATC2, the deceleration values are not easily available. Therefore, the brake percentage (depending on the train's arrangement and category) may be converted to the deceleration value (m/sˆ2). In ERTMS/ETCS, to simplify this issue in legacy systems, two types of braking models can be defined. Trains with fixed arrangement and a known train set are categorized as a gamma model. Also trains which are capable of >200 km/h have to be specified by means of gamma model. Trains with variable composition (freight trains) and without predefined brake characteristics are categorized as a lambda model (Landex and Jensen, 2019).

In total, the required input data for ETCS braking curve calculation are as follows:

- Train data: Before initiation of mission the ETCS onboard unit should be setup according to the train's characteristics (several factors related to braking, traction models, the train's length, and similar), fixed values and national values.
- Infrastructure data: Characteristics of infrastructure such as uphill/downhill slope percentage, speed retractions, position of signals and similar.

For more information see (EUROPEAN RAILWAY AGENCY ERTMS UNIT, 2020; ERTMS User ERTMS USERS GROUP, 2016; ERA, ERTMS EUROPEAN RAILWAY AGENCY ERTMS UNIT, 2020).

7. Definitions and general rules

Overlaps are the additional distance beyond the main signals. These are designed to ensure safety to prevent passing signals at danger by long trains with low braking performance and such. In railways overlaps may be based on two different principles: 1) Overlap with full distance from danger points, 2) Danger points located in overlap areas protected by a main signal (e.g., station home signal) with approaching singles before them (Pachl, 2020). In ATC2, full overlap distance beyond the main signal is required.

Release speed is the maximum permitted speed to the EOA without intervention of Automatic Train Protection (ATP). ATP protects the train against overspeed considering the maximum permitted speed and overrunning signals at danger (Evans, 1996). In ATC2, for shorter protection distances the release speed could decrease to 10 km/h (Trafikverket, 2015, 2019; Trafikverket, 2015a,b). The release speed for the block sections relevant in this study is 40 km/h. In ERTMS L2, implementation of optical signals is optional (for fall back), and marker boards indicate the border between block sections and potential stopping points for end of movement authority (Sun et al., 2020).

8. Swedish ATC2 signalling system

ATC2 is the Swedish signalling system that can be interfaced with ETCS by a Specific Transmission Modul (STM) at the National Train Control System (NTC) level. ATC2 is almost equivalent to ETCS L1 – that is a spot transmission-based cab signalling system that could be optionally equipped with simple loop or radio infill. Such an upgrade would provide semi-continuous communication between the train and rolling stock for upgrading movement authority in advance before reaching the main signal.

At the NTC level, ATC2 is integrated with ETCS using the STM. To reduce unnecessary brake intervention the STM monitors speed limits and braking curves. To avoid restrictive braking curves in NTC, STM has its own predefined patterns for brake interventions and this results in lower capacity consumption and shorter minimum headway in some legacy signalling systems compared to ETCS. Overall, applying national rules in STM are helpful to reduce the unnecessary deceleration and acceleration for uphill and downhill gradients and helps to gain better results in terms of capacity consumption in legacy systems. ATC2-STM monitors the braking pressure in order to provide some information to the driver and increasing capacity (Trafikverket, 2014).

The current Swedish ATC2 system provides information through signal balises at fixed positions and these are mostly found at main signals. If an "Expect stop" information is transmitted to a train, the onboard ATC-system monitors that the train reduces its speed to a certain release speed before the target point, after which the driver is solely responsible for braking the train to stop ahead of the signal. The release speed most often used in Sweden is 40 km/h but can also be 10 km/h at certain locations or in specific situations. If the signal has changed to "Proceed" after the train passes the last point transmitting signal information, then the train must still reduce its speed to the release speed, pass the signal balise group (BG) and receive updated information (Trafikverket, 2015, 2019). This is the most obvious disadvantage with a discrete system like the Swedish ATC2 as compared to systems that provide continuous updates. This situation may be addressed by using infill balises, which give repeated information from the BG at the next main signal, thus they can update a previously received "Expect stop" to "Expect proceed" and contribute to a better train flow. As described earlier, both an ETCS L2 and HL3 configuration transmits signal information continuously via radio (ERTMS Users Group, 2018; ERTMS User ERTMS USERS GROUP, 2016).

9. Literature review

European Rail Traffic Management System (ERTMS) contributes to improvement of interoperability, safety, and capacity. To reach complete interoperability, fulfil safety requirements, and enhance capacity in the European railways, ERTMS should overcome several challenges such as interaction of human and machine factors, technical specifications and requirements, implementation costs, operating rules and concerted testing procedures for interoperability and validation of products from different suppliers. Capacity enhancement depends on several factors such as characteristics of infrastructure (topology, length of block section in fixed moving block system), rolling stock (length and braking performance), operational rules, heterogeneity or homogeneity in traffic, timetables, and signalling systems. Due to the dependency of capacity on several factors (as above) calculation of railway infrastructure capacity is complex (Dicembre & Ricci, 2011).

There is a trade-off between the number of trains operating on a given line and quality of service (Abril et al., 2008). Increasing the number of trains running on a rail route road result in accumulation of primary delays, lower quality of service, and unreliable timetables. To create robust and stable timetables, and prevent propagation of minor delays (e.g., due to increased station dwell time), time supplements could be allocated to running times between two stations. To avoid or reduce secondary delays or knock-on delays, buffer times could be assigned to a minimum headway. Allocation of unnecessary time supplements and buffer times could have negative impact on available capacity on line (Parbo et al., 2016).

There are several common methods for calculating capacity of railway infrastructure depending on the purpose of a study. These methods are generally categorized into Analytical methods, optimization methods, and simulation methods. Analytical methods use mathematical expressions and are suitable for obtaining preliminary results, and they are usually straightforward and less time consuming. Optimization methods are useful to find better results from some optimization viewpoints for congested schedules and infrastructure, and for simulation methods that are highly capable of graphical presentation but they are time consuming (for more details please have look at Abril et al., 2008; Kontaxi and Ricci, 2009).

For instance, the compression method is an analytical method that is suitable for calculation of an infrastructure's capacity consumption (utilized capacity) based on blocking time sequences. This method has been provided by the International Union of Railways (UIC) to standardize capacity evaluation for international corridors (UIC, 2013). UIC 406 is based on blocking time sequences (time for route formation, time for visual distance, required approaching time from distant signal or indication point to the block section, travel time along the block section, clearing time which depends on train's length and release time) as introduced by Oskar Happel in 1959 (Jensen, 2015; Lindner and Jörn, 2010; Landex et al., 2008).

Optimization methods apply tactical solutions such as rescheduling, adding trains, and compressing timetable (compression method), changing order of train departures, and rerouting to improve capacity (Landex et al., 2008; Sameni, 2012). For instance, for traffic planning Petersen applied an analytical method of mean running time on a single-track line with heterogeneous traffic. For that study, he assigned priority to overtaking, and departure times are random uniform variables within the defined time period (Petersen, 1974).

Computing capacity consumption can apply the blocking time model to the study in two ways: 1) First, calculating the average minimum headway of the line considering actual traffic characteristics (mixed traffic and related frequencies) and multiplying by the number of trains. In this approach the timetable is not necessary, only the frequency of the mixed trains within a given time period; 2) Second, using an existing timetable and modelling blocking time sequences to then move the trains as close as possible with no buffer time – known as the compression method (Lindner and Jörn, 2010). Capacity consumption is the ratio between occupation time within the defined time period. Note that occupation time contains the complete blocking time sequence and is different from physical occupation time of the block section (Goverde et al., 2013; UIC, 2010; Pachl, 2002; Verkehrswissenschaftliches Institute, 2008).

Modelling railway environments with variety of technologies, traffic flow and signalling systems (conventional, cab signalling, fixed block, and moving block systems) require adequate tools such as simulation (Stankaitis et al., 2017). Simulation methods help to model railway environments more precisely and near real world but they are time consuming and require volumes of input data. In general, simulation tools are categorized as either microscopic and macroscopic models. Microscopic tools consider the details of infrastructure, vehicle, and timetable, where macroscopic models are simplified and suitable for network optimization (Borndörfer and Lamorgese, 2018; Johansson, 2021).

Previous similar studies were reviewed to verify the impact of signalling systems on capacity (Goverde et al., 2013). 2013 specify the importance of signalling systems and investigate the influence of various signalling systems on capacity consumption by performing comparative analyses in both scheduled (using compression method) and dynamic disturbed (using Monte Carlo simulation setup) conditions. Their findings verify that ERTMS L2 with shorter block sections delivers lower capacity utilization compared to Dutch NS′54/ATB.

A. Dicembre and S. Ricci use the OpenTrack microscopic simulation tool to study the interaction of timetables with features of infrastructure, specifically the length of block sections in urban railway settings. Their findings illustrate the length of block sections significantly impact the minimum headway and infrastructure capacity so shorter block sections deliver shorter minimum headway and higher capacity (Dicembre & Ricci, 2011). Koning uses the simulation in his study to compare the performance of ERTMS level 2 fixed block, ERTMS level 3 moving block, and ERTMS level 3 with fixed blocks. The Results of his study show that ERTMS L3 FMB has higher performance compare to the ERTMS L2 and L3 fix block systems. ERTMS L2 is slightly more efficient in terms of capacity performance than the L3 fix block system (Koning, 2002).

Studies conducted by VIA Consulting & Development GmbH and published by UIC show average occupation time in ERTMS level 2 and 3 compared to ERTMS L1 in different scenarios including concerning Service Brake Intervention (SBI) availability (reduces the capacity) and unavailability. ERTMS L1 limited supervision with balise in the vicinity of distant signal delivers lower capacity consumption compared to Full Supervision (FS). ERTMS L1 equipped with infill and extra balises by providing movement authority in advance can improve capacity (see Table 1). In total, the location of indication points influences capacity consumption, as much as the distance from the target distance deceleration starts (in advance) but which increases running time and capacity consumption. Shortening the block sections with ERTMS L2 can improve capacity considerably (UIC, 2013). In his master's thesis (Jansen, 2019), Jansen compares ERTMS Hybrid Level 3 (assuming different block section lengths with existing and limited implementation of track vacancy proving equipment) to ERTMS L2 and the Dutch legacy signalling system (NS′54/ATB).

These findings show that ERTMS HL3 with shorter block sections and limited implementation of TTD is more efficient compared to legacy systems (12.3%), ERTMS L2 (2.6%), less efficient compared to HL3 with 500m VSS and existing TTD (1.3%) and HL3 with VSS up to 100m and existing TTD (5%) in terms of occupation time rate (see Table 2).

10. Minimum headway and capacity consumption

Evaluation of line capacity in order to approximate future upgrades is a complex procedure. Headway-based methods are commonly used to calculate capacity, most of which use the blocking time model (Lai et al., 2015). Minimum headway is the minimum required time interval between two following trains (Pachl and Thomas White, 2004; Wang et al., 2020) and is the basis for estimating capacity (FTIA, 2019). Evaluating minimum headway using blocking time sequences requires calculating the blocking time components, which include: 1) Sighting distance and reaction time (in conventional signalling systems with cab a signalling system to observe the signal aspect), 2) Route setting time, 3) Approaching time from distant signal to main signal (in a conventional signalling system), and from indication point to main signal (in cab signalling systems), 4) Physical block occupation time (dependent on permitted speed), 6) Block section clearing time (which depends on the length and overlap of rolling stock), and 7) Block section release time.

The UIC 406 measures capacity consumption using the compression method based on route occupation time. Route occupation time is based on minimum headway (headway-based method) without considering any gaps between trains. In other words, time supplements and buffer times are not considered. To provide acceptable quality of service with the compression method, the additional time must be defined, as described in UIC code 406. The added time depends on the timetable and delays, making it difficult to calculate. Therefore, UIC code 406 proposed additional time rates that vary depending on the type of line and peak/off-peak hours. Note, the time supplements and buffer times are independent of additional times and they can be added during scheduling.

Formulas for calculation of occupation time and capacity consumption are (UIC, 2013):

$$\text{Occupation time } [\%] = \frac{\text{Occupation Time}}{\text{Defined time period}} * 100\%$$

The next section provides an overview of calculating minimum headway using HL3, ETCS L2, and ATC2 with certain assumptions used to simplify calculation.

In order to prevent instability and propagation of knock-on delays in general and at such line sections (in this study) adding suitable buffer time (assigning insufficient buffer time results an unstable timetable and lengthy buffer time reduces the capacity) to capacity consumption is recommended.

11. Comparing minimum headway in a hypothetical case between ATC2, ETCS L2, and ETCS HL3

This section gives examples of the expected impact different signalling systems (HL3, ETCS L2 and ATC2) have on headway with given assumptions used to simplify calculation, for a part of railway line. The examples are based on blocking time sequences in a headway-based model. Headway based models are suitable for calculating infrastructure's capacity with heterogeneous traffic and they are commonly based on blocking time models (Lai et al., 2015; Wang et al., 2020).

Figs. 1–3 clarify the systems discussed in this paper – Swedish legacy system ATC2, ETCS L2 and ETCS HL3 and how these can differ in terms of minimum headway. This illustrates three examples using common parameters. Minimum headway (also technical headway) is the shortest possible time between two trains at a specific location without the rear train having to initiate braking due to a

Table 1

Average performance rates different signalling systems with variety of configurations at junctions (UIC, 2013).

Level	Description	Performance Rate [%]
ETCS L1	Balise Group (BG) at distant signal with SBI unavailable	95.6
ETCS L1	BG at max.& mean distance (SBI available)	96.6
ETCS L1	Limited supervision	98.0
ETCS L1	BG at Max. distance from distant signal (SBI unavailable)	100.0
ETCS L 1	BG at max. distance (SBI unavailable)	102.0%
ETCS L1	BG at max.& mean distance enhanced block sections + Radio Infill (SBI unavailable)	103.8%
ETCS L1	BG at max.& mean distance enhanced block sections + Infill loop (SBI unavailable)	104.0
ETCS L2	Speed change at switches (SBI available)	104.4
ETCS L2	Speed change at signal (SBI unavailable)	104.5
ETCS L2	Speed change at switches (SBI unavailable)	104.6
ETCS L2	Speed change at switches with optimized blocks (SBI unavailable)	106.4
ETCS L3		131.4%

Table 2
Capacity consumption rate different signalling systems (Jansen, 2019).

Level	Description	Occupation time Rate
NS′54/ATB-EG		84,0%
ERTMS L2		74,3%
ERTMS HL3	500m VSS & existing TTD	70,4%
ERTMS HL3	VSS up to 100m, existing TTD	66,7%
ERTMS HL3	VSS up to 100m, reduced TTD	71,7%

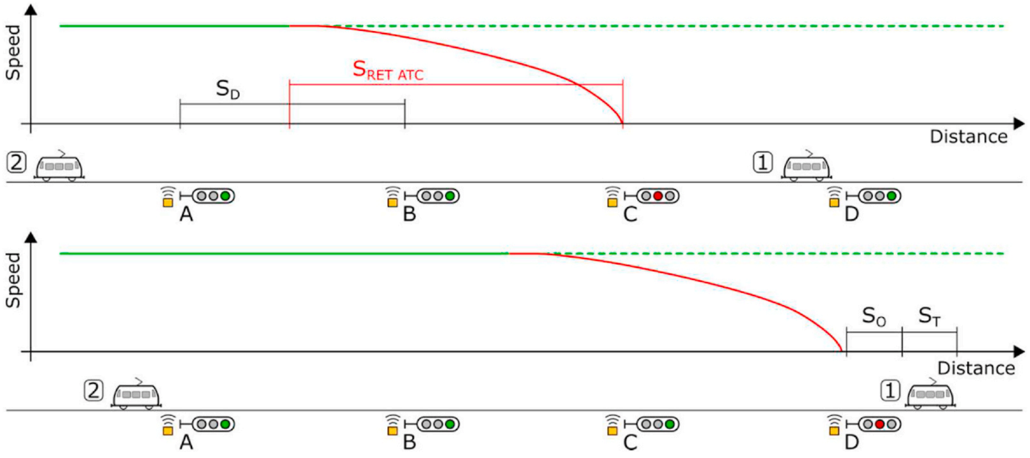

Fig. 1. Minimum headway in the Swedish ATC2, fixed block sections with non-continuous updating.

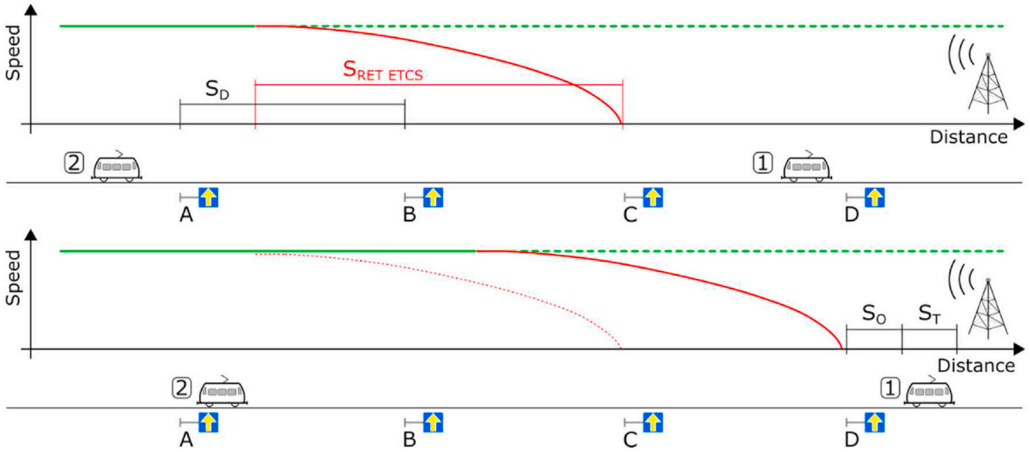

Fig. 2. Minimum headway in ETCS L2, fixed block sections with continuous updating.

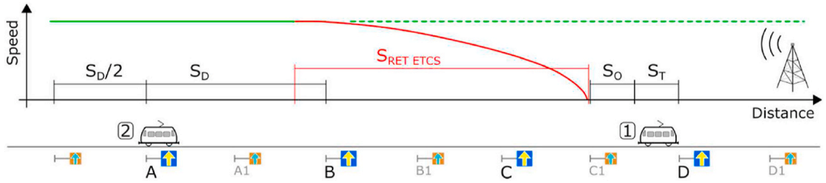

Fig. 3. Minimum headway in ETCS HL3, fixed block sections condensed by virtual Sub-Sections sections with continuous updating.

restriction caused by the front train. This is a somewhat theoretical concept since the minimum headway could not be expected to work in practical operation with the condition that the rear train is not affected by a restriction. However, it is useful for studying where the longest minimum headways occur since they dimension the train flow possible and indicate where improvements could be targeted. A planned (scheduled) headway can also be related to the minimum headway, thereby indicating a buffer time.

In each example two trains (1 and 2) are running in the same direction and at the same speed 80 km/h (V_0), the block section distance (S_D) is 400 m, and no gradients exist. Train length (S_T) is set to 100 m. The braking distance for the ATC2 case ($S_{RET\ ATC}$) is determined to 600 m, including the distance needed for pre-warning and brake application. The braking distance for the ETCS cases ($S_{RET\ ETCS}$) is determined to 660 m, this includes the same pre-warning and brake application time as in the ATC2 case.

In all cases the block section distance (S_D) is insufficient for braking from 80 km/h to 0 – whereby – the braking must be initiated on the previous section.

The distance S_O is the distance between the rear of train 1 and the previous signal point which is required to be free for the systems to allow a route for the next train to be set to that signal point. In the Swedish ATC2, the distance S_O represents where train 1 must clear an opposing signal before a route can be set to the signal point in that direction, the typical distance is 100 m (Trafikverket, 2015, 2019). In ETCS L2 and HL3 the distance S_O can represent an overlap that is defined as the distance between EOA and SvL needed for emergency braking (McNaughton 2011), and thus avoiding braking curves to the signal point in question being too restrictive. This will also include system reaction time components (route setting, release time, and system response time) (FTIA, 2019). This time is assumed to be 6 s for ATC2 ($T_{S\ ATC}$). For ETCS L2 a transmission time of 6 s is added, so the total time becomes 12 s ($T_{S\ ETCSL2}$). The transmission time consists of transmission from interlocking to RBC, movement authority generation, sending this to the train and computing time onboard. In the ETCS HL3 case an additional time of 4 s is added to $T_{S\ ETCSL2}$, and this accounts for transmission of data from the train to RBC and the addition of location error to train length when clearing a virtual section. This gives that the total time used in this case is 16 s ($T_{S\ ETCSHL3}$). Time estimates are inspired by Buker et al. (2019) and Hennig et al. (2021).

Fig. 1 shows a setup with ATC2. In the first situation, train 1 is at the end of section C–D. The following train (2) can at this time have a route up to signal C but not further since this would violate the principle of only one train per block section (Pachl, 2002). Train 2 could be closer to train 1 than shown in the figure. Assume has passed signal A and is on section –B when train 1 vacates section C–D and the route for train 2 is extended to D, then this information would not reach train 2 before it passes the signal BG at B and by this time it would be within the established braking curve. The braking curve will be cancelled at this point (B) and train 2 can accelerate again, but this would not represent a free flow minimum headway. To avoid this from happening, consider the next situation where train 1 has just vacated section C–D. As soon as the route for train 2 is extended to signal D, it can pass the BG at A and receive this information.

The minimum headway can be established by calculating the running time between signal A and D with addition for S_O, S_T and system reaction time ($T_{S\ ATC}$). For simplification, the sighting distance for a driver to be able to perceive a changed signal aspect is not considered here. With the listed assumptions the minimum headway for Fig. 1 is:

$$Minimum\ Headway\ ATC2 = \frac{(S_D + S_D + S_D) + S_O + S_T}{(V_0/3.6)} + T_{S\ ATC} \approx 69\ s$$

Fig. 2 shows the same setup but with ETCS L2 instead of ATC2, where among other things, the optical signals have been replaced with marker boards, but the block sections remain the same. Again train 1 is just about to pass board D and at this moment train 2 has movement authority (MA) up to board C. A short while later, train 1 has vacated section C–D and cleared distance S_O, movement authority for train 2 is extended to board D.

Since the MA can be continuously updated (unlike in ATC2), at this moment train 2 can be almost at the location where the braking curve targeting board C begins (reflecting the previous MA). The front of train 1 is at the distance $S_D + S_O + S_T$ from board C. Brake intervention is avoided if the route to board D is set and MA is transmitted and received by train 2 before it reaches this location. The minimum headway according to the Fig. 2 scenario can now be determined to be:

$$Minimum\ Headway\ ETCS\ L2 = \frac{S_{RET\ ETCS} + S_D + S_O + S_T}{(V_0/3.6)} + T_{S\ ETCSL2} \approx 69\ s$$

The third scenario describes a situation with ETCS HL3 installed (Fig. 3). It is based on the same L2 setup as in the second scenario, but the existing block sections are split in two equidistant shorter VSSs. Assuming both trains are level 3 compatible, they can both release virtual and fixed block sections (level 2). The minimum headway according to the Fig. 3 scenario becomes:

Fig. 3 assumes that train 1 has just vacated section C–C1, thus the MA for train 2 can be extended to virtual marker board C1. Since the VSSs are assumed to be half of the existing L2 sections, i.e. 200 m, the next release including the system reaction time ($T_{S\ ETCSHL3}$) occurs after train 1 has run another 200 m. Train 2 thus needs a minimum separation of 200 m to the brake intervention point according to Fig. 3. These conditions lead to that the minimum headway in this scenario can be determined as:

$$Minimum\ Headway\ ETCS\ HL3 = \frac{S_D/2 + S_{RET\ ETCS} + S_O + S_T}{(V_0/3.6)} + T_{S\ ETCSHL3} \approx 64\ s$$

Regarding the ETCS HL3 scenario in Fig. 3, if train 1 is operated as an ETCS level 2 train, then the section release can only occur at the boards of level 2 sections by axle counter objects. The headway will then be the same as in the pure level 2 case in Fig. 2, regardless of whether train 2 is operating as level 2 or 3. One of the key features with HL3 is that level 2 and 3 trains can be mixed, but the train integrity for level 2 trains is checked when it passes the level 2 marker boards.

These examples highlight the differences between the three setups and how these can affect headway. Although ETCS L2 has an advantage over ATC2 in continuous updating this does not improve headway due to the longer system time and longer braking distance. In this case, the advantage of ETCS HL3 is attenuated by further extended system time compared to ETCS L2 resulting in just a small improvement in headway.

The calculated minimum headways hold for these scenarios with specific train speed, braking distances, block section distance, and system time assumptions. If the parameters change, the minimum headway will normally also change. The combination of these is of great importance and it can sometimes be favourable and sometimes unfavourable, especially with ATC2 where threshold effects can occur and affect the minimum headway significantly due to the non-continuous updating (updating only at fixed locations).

If, for example, S_D is increased from 400 m to 500 m ATC2 headway increases from 69 to 83 s and the ETCS L2 headway from 69 to 73 s. If S_D is decreased to 300 m, ATC2 headway decreases to 56 s and the ETCS L2 headway to 64 s. In the last example, ETCS L2 thus gets a larger headway than ATC2, and this is since the braking distance for ATC2 is a multiple of the block distance length and can be said to be optimized for this specific case.

If, for example, the slope is changed from 0 to $-10‰$, the braking curve distances become longer, and this will increase the minimum headway in the ETCS L2 and HL3 cases given the assumptions used in these examples. This could also affect the ATC2 scenario if the longer braking distance extends over more than two block sections. However, if the braking distance still fits in two block sections, the minimum headway would remain the same for ATC2.

The ATC2 scenario in Fig. 1 can be improved (minimum headway can be reduced) by inserting an infill BG at a strategic location within each block section. In reality, the block section lengths, trains, and speeds will vary. A setup with block lengths, infill balise groups, and so on could work well for a specific train type but work less well for another in terms of minimum headway.

These examples visualize and describe the minimum headway concept where both trains run with the same speed. If a station or other stop is introduced, this likely becomes dimensioning, and if so, the minimum headway will increase. This effect can be seen in the headway analysis presented for the Stockholm City Line further in this paper.

Table 3 summarizes the calculated minimum headways and percentage for the hypothetical cases with ATC2, ETCS L2, and ETCS HL3.

12. Case line overview

In this study to verify the influence different signalling systems based on various technologies (that is, fixed block and hybrid signalling technology) may have on the capacity, a part of the Stockholm commuter line with high frequency of traffic was considered as a case study. Table 4 presents brief information about stations section lengths and scheduled dwell time at each station.

The line studied includes Stockholm City Line that is a commuter railway tunnel with two stations inaugurated in 2017. The defined reference time is 2 h (between 4 and 6 p.m.) during peak hours for southbound traffic flow from Solna to Älvsjö. The section of interest is about 13 km double track line included Stockholm city line (7.4 km), which is dedicated to commuter trains with fixed composition.

The city line is normally only operated by commuter trains. The line connects to existing train paths on the inner tracks north of Tomteboda övre and in the south at Stockholms södra (Trafikverket, 2019a,b). Dwell time at Stockholm City is normally limited to a maximum of 2 min (120s). Fig. 4 shows the schematic track layout used by commuter trains in normal operation, in and surrounding the central area of Stockholm. Tracks normally used by other than commuter trains are not visible in the figure, expect on the section Sundbyberg–Huvudsta which is currently a double track operated by a mix of train categories. Fig. 5 shows part of a peak period timetable for southbound trains through the central section. Figs. 6–8 repectively show the infrastructure model in scenario 1, 2 and 3.

13. Capacity assessment

This section briefly overviews the RailSys settings in this study. The analysis is made using RailSys version 11, infrastructure description version 2020 (from Trafikverket) and timetable in 2020 (T20). The results are based on occupation time (considering blocking time sequences) of each individual block section extracted from RailSys. The analysis is based on static method without considering probability functions and changing variables within the defined time period.

14. Scenario 1

Considering abovementioned principles, scenario 1 represents the current situation of the line, whereby it is equipped with ATC2 and relies on trackside signals with assigned overlap based on the Swedish national RailSys model provided by Trafikverket. The release speed is set to 40 km/h.

Table 3
Theoretical minimum headways and the ratio of minimum headways ETC2 and HL3 to ATC2.

Signalling system	Theoretical Minimum headway [s]	Minimum headway compared to ATC2%
ATC2	69	100
ETCS L2	69	100
HL3	64	93

Table 4
Case study.

Station ID	Station name	Section length [km]	Scheduled dwell time [s]
So	Solna	0.0	60
TmÖ	Tomteboda övre	1.7	
Sod	Stockholm Odenplan	2.1	60
Sci	Stockholm City	1.6	120
Sst	Stockholms södra	2.5	42
Åbe	Årstaberg	2.5	42
Äs	Älvsjö	2.7	42

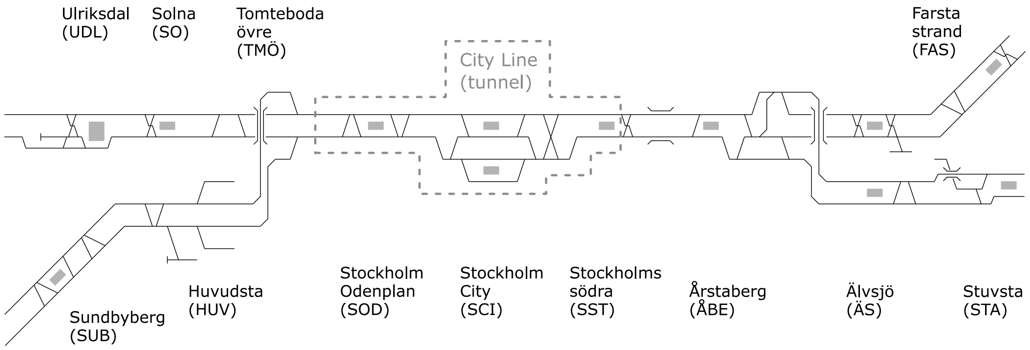

Fig. 4. Schematic track layout through central Stockholm showing tracks normally used by commuter trains. Tracks normally used by other trains which pass central Stockholm over ground are not shown.

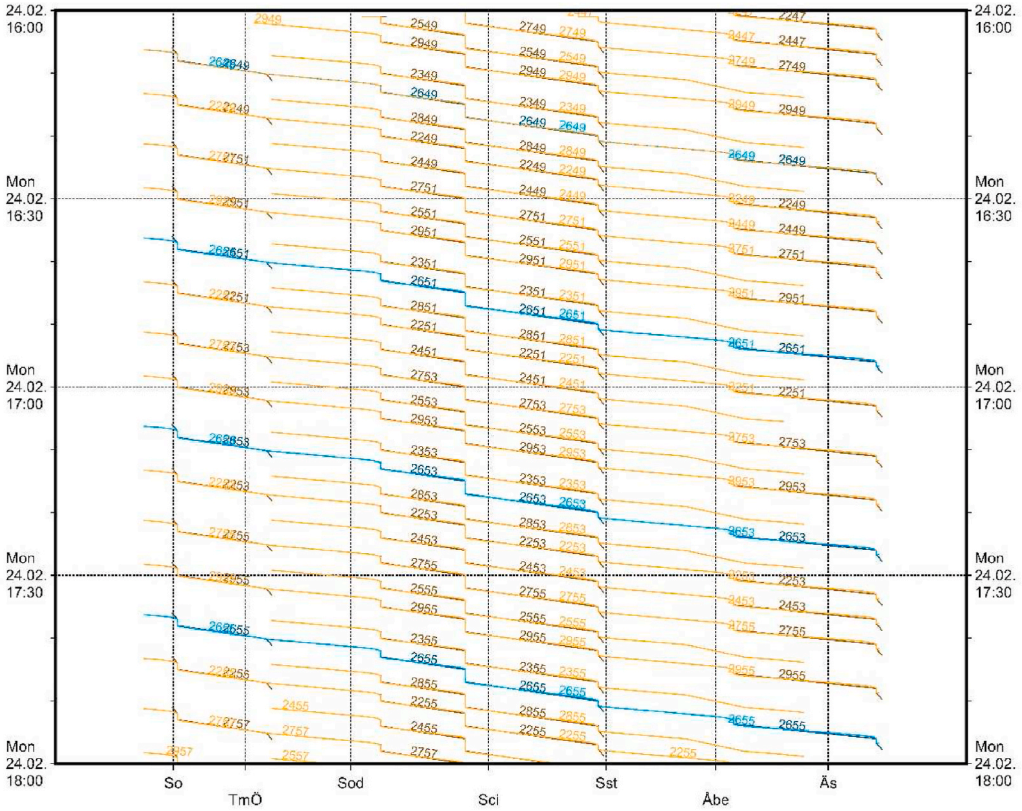

Fig. 5. Case study, timetable view in RailSys (Solna–Älvsjö).

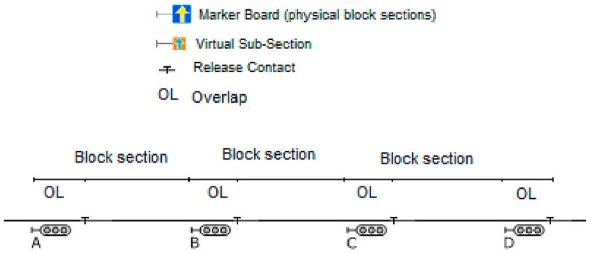

Fig. 6. Infrastructure model in scenario 1.

Fig. 7. Infrastructure model in Scenario 2.

Fig. 8. Infrastructure model Scenario 3.

15. Scenario 2

In scenario 2 the signals are replaced with marker boards and use 100 m overlap and 40 km/h release speed. It is possible to have shorter overlaps, but this would affect calculation of braking curves, they become more restrictive, which results in lower deceleration and longer running times. The brake percentage depends on the train composition and type. For trains without predefined composition (lambda trains), brake percentage can be converted into a deceleration value (m/s2) for the service brake distance (SBD) based on information provided by the infrastructure manger (in Sweden this is Trafikverket). In these ETCS signalling system scenarios, the preoccupation is set to indication (See 2.4 European Train Control System braking principles) to minimise the driver based braking curve. An alternative would have been to use the setting "*permitted*", where deceleration is based on P-curve (permitted speed curve) which could result in shorter blocking time. In RailSys the fixed parameter based on the European Rail Agency (ERA) is applied – the time between warning supervision limits and SBI 2s, driver reaction time is between permitted speed and SBI 4s.

16. Scenario 3

In scenario 3 the line is upgraded to Hybrid Level 3 (HL3) assuming the existing physical block sections are divided into VSSs between 100 and 200 m except sections with moveable elements. The other settings (relating to marker boards, overlaps ARE 100m, the release speed is set to 40 km/h, preoccupation is set to indication, and lambda braking model) are similar to scenario 2.

17. Analysis results

This section contains the results of the study using the above assumptions and settings.

Fig. 9 shows the occupation time rate of each block section in scenario 1. Signal SCI M 123 relates to the scheduled stop at the Stockholm City station for one of the two platform tracks available for this direction. In normal operations, trains use the two tracks alternately. The occupation time rate is the proportion of occupation time to defined time period in percent. Capacity consumption is the ratio of occupation time plus additional time to the defined time period (2 h or 7200 s) along the given route (Solna-Älvsjö) with the ATC2 legacy system – which is 43% (UIC, 2013).

In scenario 2, it is assumed that the line and trains are equipped with ERTMS/ETCS L2 exploiting bidirectional radio communications system, wayside optical signals are replaced with marker boards. The lengths of block sections are kept as before to verify the impact of ETCS L2 on minimum headway and block section occupation time without modification of infrastructure.

Fig. 10 illustrates that ETCS L2 delivers shorter minimum headway on sections with constant speed but on end sections (before stations while decelerating to the end of movement authority) trains start to decelerate earlier compared to ATC2 due to more restrictive braking curves. This results in longer braking distance/time, higher minimum headways, and capacity consumption on these specific sections on approach to the EOA compared to the ATC2 legacy system.

In scenario 2 the total occupation time rate for a single train to run on the studied route during the reference time (7,200s) is 39%, which is a 4% enhancement compared to ATC2.

In scenario 3 the line is upgraded to ERTMS Hybrid Level 3 with existing TTD equipment. The physical block sections are divided into VSSs of 100–200 m.

Fig. 11 illustrates the speed profiles for ATC2 and ETCS L2 together with the vertical profile (right y-axis) for the section. Triangles

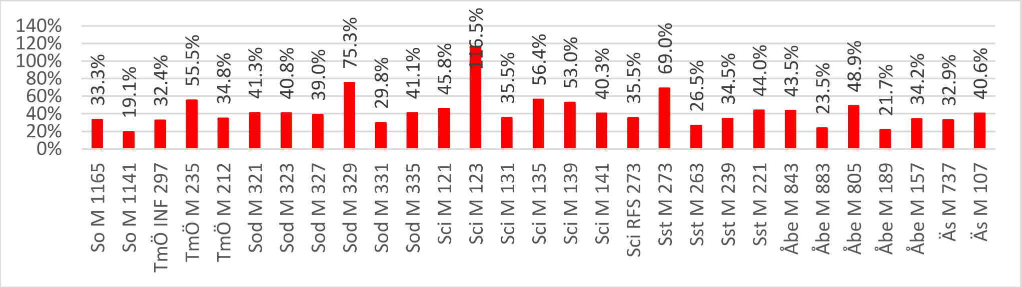

Fig. 9. Occupation time [%] ATC2.

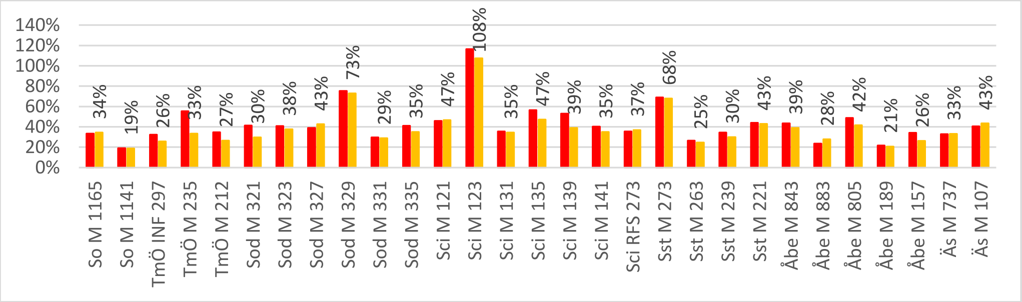

Fig. 10. Occupation time [%] ERTMS L2 vs ATC2.

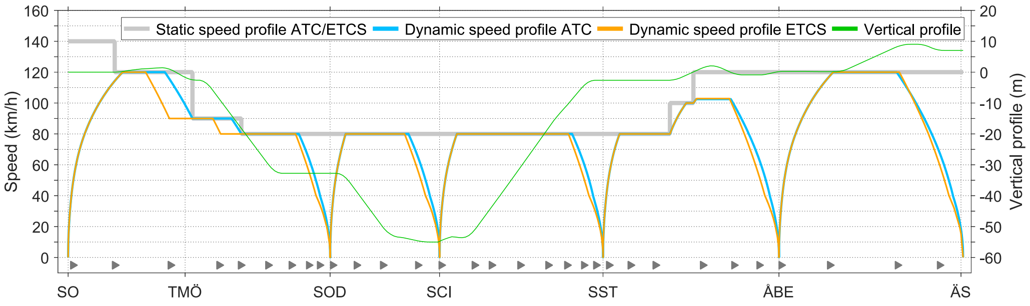

Fig. 11. The figure shows static and dynamic speed profiles for ATC2 and ETCS for southbound trains together with the vertical profile (right y-axis). Triangles indicate signal/marker board locations.

indicate signal and marker board locations, assumed to be same for both systems in this case study. The ETCS L2 braking is more restrictive to the end of authority (EOA) and limit of authority (LOA) locations compared to the current ATC2-system, which increases the total running time. The more restrictive braking modelled for ETCS L2 allows the minimum headway to be higher for sections with braking compared to ATC2.

By shortening block sections HL3 delivers lower minimum headway and capacity utilization performance. In total, 37% capacity consumption along the studied line indicates considerable enhancement −14% and 9% capacity gains compared to ATC2 and ETCS L2, respectively.

Table 5 Presents the results in summary and illustrates that the HL3 with existing trackside train detection equipment divided into short VSSs of 100–200 m length delivers higher performance compared to the legacy system (ATC2) and the ERTMS L2, 14% and 9%

Table 5
Summary of results.

Signalling system	Occupation Time [s]	Occupation time [%]	Capacity Consumption [%]	Minimum headway [s]	Ratio of Headway % (Compared to ATC2)
ATC2	3090	43	51	104	100
ETCS L2	2805	39	46	94	90
HL3	2247	31	37	77	74

capacity gains, respectively. ETCS L2 due to restrictive braking behaviour (train starts to decelerate earlier) targeting to end of authority brings higher travel time and minimum headway compared to the legacy system. Generally, ETCS L2 delivers better performance, about (9%) capacity gains compared to ATC2.

18. Conclusions

This paper examines the possibility to improve occupation time and capacity consumption using a new concept, HL3, that combines fixed block technology with moving block technology to enable running trains either with or without train integrity monitoring systems to operate on the same line. This could help gradually move towards a next generation signalling system. The primary contribution of this study is to verify the impact of different signalling systems on capacity of high frequency commuter train lines in undisturbed and static conditions. The capacity consumption was considered as a performance indicator for evaluating impact of signalling system on capacity. To approximate the possible capacity gains on commuter train lines, a comparative analysis between HL3, ETCS L2, and ATC2 is conducted. The study was performed on a high frequency commuter train line in Stockholm using a microscopic simulation tool combined with theoretical calculations for a hypothetical case.

The difference in headway time is larger in the theoretical calculations (section 4.1) compared to the analysis using RailSys. The simplified hypothetical assumptions in the theoretical example ignore train and infrastructure characteristics, sighting distance, and approaching time. RailSys considers train and infrastructure characteristics and their interaction with the timetable. Produced results by RailSys are more precise and reliable comparing to analytical approaches.

Findings are in line with previous studies showing considerable capacity gains are possible using HL3 with shortened block sections compared to ETCS L2, and the ATC2 legacy system.

This study adds that HL3 could be a suitable solution for specific cases such as high frequency traffic commuter train lines with dense signalling.

The study findings show that signalling systems, length of block sections, and contributing factors to braking curve considerably impact capacity. In total, ETCS L2 delivers lower capacity consumption but ETCS produces longer running time and braking distance due to input values that are not adapted to local infrastructure and this consequently leads to higher capacity consumption during braking at the end of movement authority compared to ATC2. The study results establish that HL3 can reduce capacity consumption and improve capacity compared to ETCS L2 and ATC2.

The railway industry currently tends to favour hybrid solutions because they provide flexibility of operation by allowing running trains with or without TIM, and further, the gradual upgrading of signalling systems. For future development of signalling systems to the next generation (moving block systems) implementation of hybrid solutions such as ETCS Hybrid Level 3 may be suitable on commuter train lines.

For future work analysing the capacity effects of HL3 on lines with heterogenous traffic considering delays under perturbated conditions may demonstrate these benefits under more realistic conditions.

Credit author statement

Vahid Ranjbar: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Visualization; Roles/Writing - original draft; Writing - review & editing. **Nils O.E. Olsson:** Conceptualization, Funding acquisition, Supervision; Resources; Writing - review & editing., **Hans Sipilä:** Conceptualization, Resources; Software; Formal analysis; Supervision; Validation; Visualization, Writing - review & editing.

Declaration of competing interest

None.

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