Infrastructure Capacity in the ERTMS Signaling System

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Abstract

This article describes the main differences between level 1-3 in the new European signaling standard ERTMS and conventional signaling systems focusing on communication differences, the ability to look ahead and braking curves. Based on this description, the capacity differences between level 1 and 2 are investigated for theoretical as well as real-life cases using line headway calculation models developed for the study.

The results show ERTMS level 2 generally has shorter headways than level 1 and hence higher capacity. However, in homogeneous operation where the braking distance is well-adapted to the block lengths, level 1 can have shorter headways than level 2 due to less system delays. The results also show that Level 2 due to continuous update of the Movement Authority (MA), result in higher capacity than level 1 for longer block sections and lower speeds.

The article discusses that a 1:1 replacement of conventional signaling with ERTMS can lead to loss of capacity as the ERTMS braking curves are likely to be longer. The article also discusses how extra capacity can be gained with ERTMS as it is possible to look more block sections ahead.

Keywords

Railway capacity, Signaling, ERTMS, ETCS, Braking curves

1 Introduction

ERTMS is the new signaling standard in Europe but has also been adapted (with some modifications) in other parts of the world (mainly Asia). ERTMS consists of a standardized control system ETCS (European Train Control System) and a communication standard GSM-R (Global System for Mobile communication for Railways).

ERTMS exists in five different basic levels: Level 0-3 and level NTC (National Train Control). Level 0 enables trains equipped with ERTMS to operate on infrastructure not equipped with ERTMS, and where there is no alternative train protection or warning system. Level NTC enables trains with ERTMS to operate on infrastructure where the national train control system needs to be operated. The pure ERTMS levels range from the simplest at level 1 to the most advanced at level 3 – and some hybrid versions as well as adaptions to other markets like the Chinese. This article focuses on ERTMS level 1 and 2.

In general, ERTMS level 1 is similar to a conventional multi-aspect signaling system with ATP (Automatic Train Protection) where the train is updated discretely with new movement authority at balises (potentially with infill by balises, loops or radio). In ERTMS level 2, the communication between train and infrastructure is updated continuous allowing the train's movement authority to be continuously updated and shown to the driver. Level

3 is a moving block system with no (or only limited) train detection in the track needed why the position of the train is continuously sent from the train and a train integrity system is needed. The different signaling systems are compared in Table 1.

Table 1: Comparison of different signaling systems.

	Conventional	**Conventional multi-aspect**	**Level 1**	**Level 2**	**Level 3**
Train control	Possible	Possible	Included	Included	Included
Communication	Discrete (infill possible)	Discrete (infill possible)	Discrete (infill possible)	Continuous	Continuous
Signal aspects	2 (Red/green)	3+	Movement authority	Movement authority	Movement authority
Signal visibility	Needed	Needed	Usually needed	Not needed	No signals
Train detection in track	Needed	Needed	Needed	Needed	Limited (on train and turnouts)
Train integrity	Not needed	Not needed	Not needed	Not needed	Crucial
Train position	Known in block section	Known in block section	Known in block section	Known in block section but can be more exact	"Exact" position known

With few exceptions, higher levels of ERTMS result in increased level of capacity which is covered by numerous publications, e.g. UNIFE (2014). Capacity of different levels of ERTMS (and variations within different levels of ERTMS) is well examined e.g. UIC (2008). Higher levels of ERTMS generally leads to higher capacity as illustrated in Figure 1.

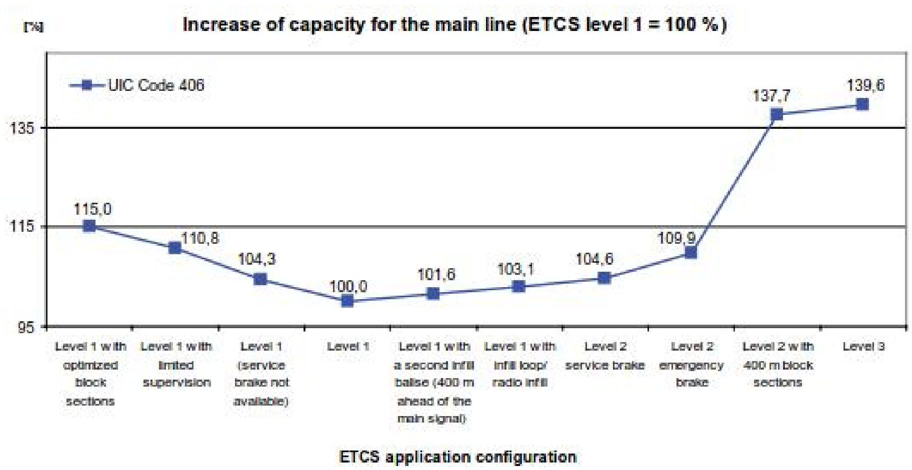

Figure 1: Influence of different ETCS levels on line capacity (UIC, 2008).

Increased capacity is often used as one of the selling points for implementing ERTMS.

However, capacity is often lost when going from multi-aspect conventional signaling to ERTMS (e.g. Goverde et al., 2013), especially if converting the signaling in a 1:1 ratio. This is mainly due to more conservative braking curves and because the multi-aspect conventional signaling system has been “optimized” to increase capacity. For the simpler single-aspect conventional signaling, there will usually be a gain in capacity when implementing ERTMS as the ability to read signal aspects further than one block section ahead is introduced.

This article describes the main differences in ERTMS that affects infrastructure capacity. Based on a line headway calculation models developed for this study, the article analyses infrastructure capacity of ERTMS level 1 and level 2 for both theoretical and practical cases.

2 ERTMS and Infrastructure Capacity

ERTMS is, as shown in Table 1, similar to conventional signaling. However, especially the differences in communication, the ability to look more block sections ahead and the braking curves result in changed infrastructure capacity. The following sections describe these parameters and their impact on infrastructure capacity

2.1 Communication

The biggest differences between the different levels of ERTMS (and to conventional signaling) is within the communication. The higher level of ERTMS, the more communication is required between the train and signaling system, cf. Table 2.

Table 2: Communication differences in ERTMS.

	Level 1	**Level 2**	**Level 3**
Communication between train and infrastructure	Line Electronic Units (LEUs) and Eurobalises	Eurobalises and RBC	Eurobalises and RBC
Role of Eurobalise	Position & signal state	Position	Position
Location of train	Track detection equipment	Mainly track detection equipment	Position information from train
Movement Authority	From Eurobalise	From RBC	From RBC
Radio	Voice	Voice and data	Voice and data

The differences in communication result in discrete update of the movement authority to the train driver in level 1 but continuous update in level 2 and 3. Increased communication of position as well as train integrity system in level 3 furthermore allows moving block. This leads to the possibility of shorter headways between the trains, cf. Figure 2.

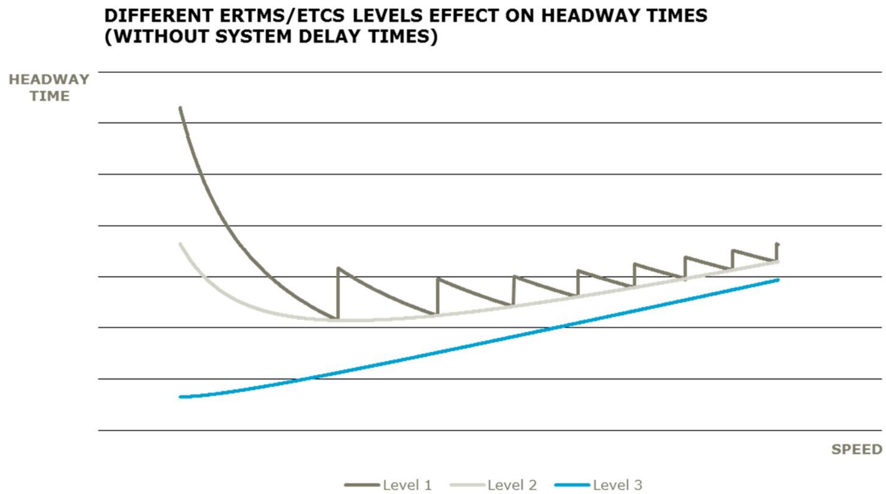

Figure 2: Headway time for different speeds and levels of ERTMS.

Figure 2 is a conceptual figure showing the minimum headway time for different levels of ERTMS depending on the speed. For level 1, the optimal headway times are when the braking distance is equal to the sum of blocks in the braking distance. Here, the headway time is the same for level 1 and 2 when system delays are not considered.

The optimal travel speed is when the minimum headway time is as short as possible. When the travel speed is below the optimal travel speed the minimum headway time can be reduced by speeding up since the block occupation time is too long. At travel speeds above the optimal travel speed, the braking distance has become too long, so that the block sections are reserved for too long time. It is not possible to have travel speeds which require looking more block sections ahead than the signaling system allows.

The increased and changed communication leads to higher communication times. The longer communication times in level 2 compared to level 1 (cf. Table 3) results in shorter headway times when the braking distance in level 1 matches the block lengths whereby level 1 in homogeneous operation can have shorter headways and hence more capacity than level 2. With infill for level 1, level 1 can result in more capacity than level 2 for a larger interval in braking distance (cf. Figure 1).

Table 3: Communication times used in the theoretical and practical calculations (Liikenevirasto, 2018).

Type	Level 1	Level 2
LEU (Lineside Electronic Unit)	0.7 sec	–
Communication delay (train to/from RBC)	–	2.65 sec
Interlocking delay (no turnouts)	5 sec	5 sec
EVC (European Vital Computer) + DMI (Driver Machine Interface)	1 sec	1 sec

2.2 Ability to Look Ahead

ERTMS gives the possibility to look more block sections ahead than conventional signaling. This due to more modern technology compared to mechanical and relay based signaling systems, where it in the electronic signaling system is easier—and less expensive—to look more block sections ahead. Besides, ERTMS has cab signaling which ensure the Movement Authority (MA) is shown to the driver on the Driver Machine Interface (DMI) in the cab. The number of signal aspects that can be communicated to the driver is therefore no longer a restricting factor.

The length of block sections in conventional (multi-aspect) signaling systems, where it is only possible to look few block sections ahead, are determined by the need to be able to stop the train within the length of the block sections indicated to the driver. This restricts how short the block sections can be for conventional signaling systems. If a train is unable to stop within the signal aspect given, the train's speed will need to be limited.

For ERTMS, where it is possible to look more block sections ahead, it is possible to have shorter block sections allowing for shorter headways. Furthermore, it is no longer needed to limit a train's speed due to the signaling system. This can potentially allow for faster freight trains resulting in higher capacity and/or faster high-speed trains on the infrastructure.

2.3 Braking Curves

As an ATP system, ETCS monitors the train's speed and position to ensure that the train does not run above the allowed speed or pass a given movement authority. This is achieved by calculating a braking curve for the train taking the braking performance, gradients, uncertainties and various correction factors into account. If the driver does not brake the train within the supervised limits of the calculated ETCS braking curve, the onboard ETCS equipment will intervene to brake the train.

In ETCS, the braking curve calculated is denoted the emergency brake deceleration (EBD) curve. It is also possible to use the (full) service brake deceleration (SBD) curve before emergency braking is initiated. This is preferred for comfort and as the emergency brake can damage the rolling stock and the track. However, in ETCS it is not a requirement to use the SBD curve.

In Figure 3 an example deceleration is shown including the EBD curve and the different supervision limits and interventions. When the train approaches a speed restriction the driver will be given an indication (I) that tells the driver to initiate braking to prevent driving faster than the permitted speed (P) as the permitted speed shown to the driver is decreasing. If the driver fails to brake according to the permitted speed an additional audible warning (W) is given before the onboard equipment intervenes and either initiate full service braking intervention (SBI) or emergence braking intervention (EBI). From the intervention to the EBD curve is reached, time is added to account for speed measurement inaccuracies and a possible acceleration during the brake build up time before the full braking performance is achieved. Furthermore, additional distance (time) is added for inaccuracies in the location of the train. The onboard equipment calculates a location confidence interval that ensures a safe location of the train as shown in Figure 3 (max safe front). The confidence interval is calculated as (up to) ±(5m+5%s) where s is the distance travelled since the last location balise (where the location confidence is reset) (UNISIG, 2015).

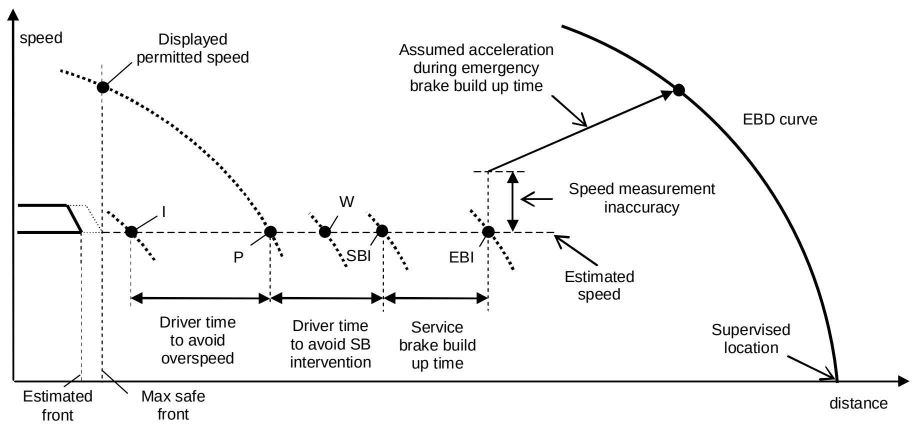

Figure 3: Emergency brake deceleration (EBD) and supervision limits (ERA, 2016).

The emergency brake deceleration (or full-service brake deceleration) curve itself is not easily calculated. Traditionally, brake weight percentage (BWP) has been used to define the braking performance of trains. This means that the nominal braking performance of train in terms of deceleration values (m/s^2) are not always available. Furthermore, the braking curves of many conventional signaling system are calculated based on the brake weight percentage, e.g. the Danish ATC system. To ensure easier transition to ETCS, ETCS offers two models for calculation of the braking curve (ERA, 2016; ERA UNISIG, 2016). One is the lambda model based on the brake weight percentage (denoted lambda, λ), the other is the gamma model based on the nominal braking performance of the train. Both yields safe braking curves that are subsequently corrected for gradients based on data from the trackside equipment. The gamma model is used for all trains that have well defined train characteristics, i.e. train sets and push-pull trains with a defined set of cars. The lambda model is used for freight trains and trains where the nominal braking characteristics cannot be obtained.

For both models, input values are given by the railway undertaking (the train data) and the infrastructure manager (the national values). The national values supplied by the infrastructure manager may differ from country to country to account for different national safety practices. This means that the same train running from one country to another on the same kind of infrastructure might have different braking curves due to national values, although the maximum braking effort of the train does not change.

The lambda model is based on a conversion model that converts the brake weight percentage of the train (λ) to converted deceleration values in m/s^2 for different speed intervals (A_brake_converted). These deceleration values are subsequently corrected by the integrated correction factors (Kv_int, and Kr_int) from the infrastructure manager based on the train type (passenger or freight), P or G braking and the length as shown in Figure 4. The deceleration values obtained (A_brake_tuned) ensures a safe braking due to the integrated correction factors (national values) and the conversion model that has been validated trough braking tests (ERA, 2016). As the lambda model yields a conservative braking, it is likely that the EBD curve is longer than in a conventional signaling system where the braking curve calculation has been optimized as mentioned in Section 1.

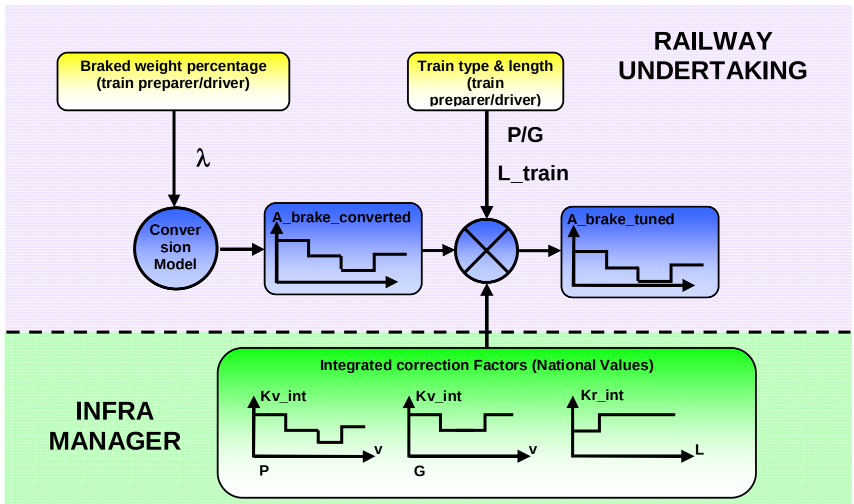

Figure 4: Braking curve estimation using the lambda model. (ERA, 2016).

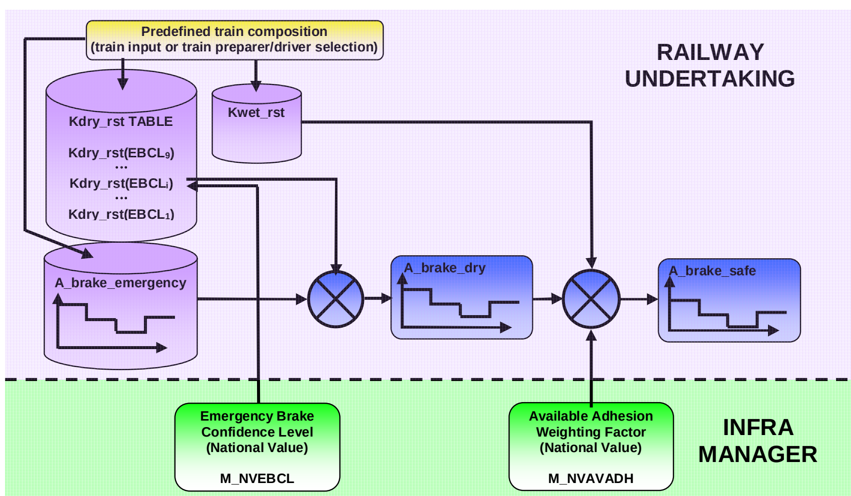

Figure 5: Braking curve estimation using the gamma model. (ERA, 2016).

The gamma model is based on the nominal braking performance of the train in terms of deceleration values m/s^2 for different speed intervals (A_brake_emergency or A_brake_service). This gives a more precise representation of the train's braking performance than the lambda model. As shown in Figure 5, the nominal emergency braking performance of the train is adjusted by the Kdry_rst value to obtain the safe braking performance on dry track (A_brake_dry). The Kdry_rst value is selected from a table of values. Each value in the table provides increasing safer brake performance. Basically, each value is tied to the probability that the train will brake according to nominal emergency brake performance multiplied by Kdry_rst on dry track. The Kdry_rst value is chosen based on the emergency brake confidence interval (M_NVEBCL), a national value provided by the infrastructure manager. This value spans from 50% to 99.9999999%, where the first ensures safe braking every second time on dry track and the latter essentially every time. Low values will result in shorter braking curves than higher values which results in improved capacity by shorter headways as well as the possibility of stopping faster at stations e.g. towards buffer stops and end of MA. For lower values (shorter braking curves) , it may be needed to addoverlaps to maintain/improve safety. The M_NVEBCL value may be optimized for capacity while maintaining overall safety when overlaps are used using a Monte Carlo approach as described by Meyer et al. (2011).

The dry brake performance of the train is subsequently adjusted to obtain A_brake_safe using both a factor for available adhesion from the infrastructure manager (M_NVAVADH) and a factor for the train describing the train's braking performance on rails with reduced adhesion (Kwet_rst).

In addition to the national values described in this section, there exist more national values that also has impact on the braking curves. We will not go into depth with these in this paper. Table 4 summarizes and compare the two different braking curve calculation models.

Table 4: Differences between lambda and gamma braking curves.

Type	**Lambda**	**Gamma**
Precision	Low/limited	High
Number of parameters	Few	Many
Generally used for	Freight trains as exact braking parameters are not known	Train units as braking performance is well-defined

The length of the braking deceleration curve, whether calculated as gamma or lambda, and the associated supervision limits has a large impact on the infrastructure capacity as the time required for braking constitutes a larger proportion of the minimum headway time compared to other signaling related parameters. This is especially the case at high speeds as shown by Abril et al. (2008). For capacity planning, the permissive (P) is mainly used for the headway calculations. The indication (I) may also be used as this will give a conservative braking length estimate in normal operation (cf. Figure 3). If the train driver drives more aggressively or ATO is used, i.e. closer to the warning speed, a decrease in headway, and thus improved capacity, can be obtained.

Comparing ECTS braking curves with conventional signaling systems, the ETCS braking curves tend to be more conservative. This is a consequence of the calculation models and the associated correction factors (national values) chosen. An infrastructure manager migrating from a conventional signaling system to ERTMS may choose nation values that result in braking curves (for different rolling stock) as close as possible to the ones in the existing conventional system. However, this will result in some braking curves being longer than in the conventional system and some braking curves being shorter. The latter is a problem as it means that safety is reduced. The national values are thus (in early evaluation phases) chosen to ensure that no braking curves are (significantly) shorter than in the conventional system. This result in ETCS braking curves being generally longer resulting in capacity loss.

3 Methodology

Our analyses of infrastructure capacity using ERTMS is divided in two parts. The first part consists of theoretical calculations for various fixed block lengths traversed at constant speed while the second part consists of practical calculations on lines with varying block lengths and speeds. In both parts we analyze the capacity gains and losses between ERTMS level 1 and 2. As described in section 2.3, the braking curves are a crucial input for both the theoretical and practical calculations. For our capacity analyses, we calculate the braking curves using the ERA brake calculation tool (ERA, 2018) as input to our headway calculation. The data and methodologies for the two parts are described in the following three sections.

3.1 Train Data

For our analyses, three types of trains are used: a freight train, an IC train and a fast/express train. Braking curves for the latter are calculated using both the lambda and the gamma model. The data for the trains is shown in Table 5. For the theoretical calculations, we only use the IC and Freight trains while all types are used in the practical calculations.

Table 5. Train data for the analyses.

Train	**Freight**	**IC**	**Fast (Lambda)**	**Fast (Gamma)**
Weight [t]	2006	462	328	
Length [m]	515	177	159	
Maximum speed [km/h]	90	200	220	
Start acceleration (m/s^2)	0.19	0.8	0.4	
Avg. deceleration (gamma) [m/s2]				1.05
Brake weight percentage (lambda) [m/s^2]	54	135	135	
Used in theoretical calculations	•	•		
Used in practical calculations	•	•	•	•

3.2 Theoretical Calculations

The purpose of the theoretical calculations is to map the capacity gains and losses between ERTMS level 1 and level 2 for various fixed block length sizes. As part of the theoretical calculations, a sensitivity analysis is also conducted for the communication delay to the radio block center (RBC) in ERTMS level 2. In this sensitivity analysis the nominal delay of 2.65 seconds (cf. Table 3) is compared with an increased delay of 7 seconds.

The calculations are defined as theoretical as the trains travel at their maximum line speed and all block sections on the line are equal in length. Thus, acceleration and braking are not considered, and the calculations are therefore most realistic on the middle of a line, not at the ends of the line.

An automated Excel tool has been set op for the theoretical calculations. The tool iterates through all combination of parameters for a line headway calculation with fixed block lengths and speeds. The minimum line headway is the minimum separation time between two trains on a line the ensures that both trains can run on the line unhindered. The parameters combined for headway calculation to form the mapping of capacity gains (and losses) are:

- Speeds: 60 to 200 km/h in increments of 10 km/h (although ERTMS can handle increments of 5 km/h)
- Block lengths [m]: 500, 750, 1000, 1200, 1600, 2000, 2500, 3000, 4000

The calculations are carried out for IC and Freight trains as described in Section 3.1. The two train types are combined to simulate both homogenous and heterogenous operation. For the headway calculations, the IC and freight trains are thus combined in all four possible ways, i.e. (1st train, 2nd train): (IC, IC), (IC, Freight), (Freight, IC), and (Freight, Freight). For ERTMS, the system reaction times shown in Table 3 are used.

3.3 Practical Calculations

As described in Section 3.2, the theoretical calculations do not take acceleration, braking, and varying block lengths into consideration. We have therefore also carried out calculations for two real-life lines in the Nordics where the acceleration, braking, all block lengths, dwell times and speed profiles are taken into consideration.

The two lines are divided into seven respectively two line sections (denoted line section 1-7 and 8-9). The line speed is in the range 130-200 km/h for the first line and 220 km/h for the second line.

As shown in Table 5, we use an IC train and a freight train as in the theoretical calculations, but also a high-speed train is used. As in the theoretical calculations, we map the capacity gains and losses between the different signaling systems for different combinations of trains taking the actual block lengths, speed profile and timetable into account. Again, the line headway forms the basis for the capacity estimation. To estimate the minimum line headway, we have developed a calculation model in C++ that uses blocking time theory (Happel, 1959) to estimate the block occupations and subsequently calculate the line headway between trains as described in Pachl (2008). Blocking time theory is the same approach as used in commercial tools (e.g. OpenTrack and RailSys). To estimate the time spent by a train in each block, we use the running time estimation model described in Jensen (2015). This model takes acceleration, braking, and the speed profile into account. The estimated train running times include timetable supplements recommended by UIC (2000). Complex train movements in junctions are not considered in the model. This is to be implemented at a later stage to make it possible to analyze the capacity gains and losses with ERTMS in major junctions in detail.

4 Results

Results of the theoretical and practical calculations are described in the next two sections based on the methodologies described in Section 3.

4.1 Theoretical Results

Based on the theoretical calculations it is confirmed that the continuous update of level 2 generally result in higher capacity than discrete update for level 1. However, the larger systems and communication delays in level 2 (cf. Table 3) decreases the capacity gain of continuous update. In case of the braking length matching the block lengths, level 1 can result in shorter headways than level 2 as continuous update has no immediate effect and level 1 has less system and communication delays, cf. Figure 6.

Homogeneous operation

Average capacity improvement with ERTMS level 2 (IC trains only)										
Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	27,5%	9,5%	20,7%	27,8%	38,8%	46,9%	54,5%	60,1%	68,1%	39,3%
70 kph	17,7%	2,3%	13,6%	20,9%	32,4%	40,9%	49,0%	55,1%	63,8%	32,8%
80 kph	9,0%	32,1%	7,0%	14,4%	26,2%	35,1%	43,6%	50,1%	59,5%	30,8%
90 kph	1,2%	23,5%	0,9%	8,4%	20,3%	29,5%	38,4%	45,2%	55,3%	24,7%
100 kph	17,6%	15,8%	33,2%	2,7%	14,7%	24,1%	33,3%	40,5%	51,0%	25,9%
110 kph	9,5%	8,6%	25,6%	37,2%	9,4%	18,9%	28,3%	35,8%	46,8%	24,5%
120 kph	2,3%	2,1%	18,6%	30,0%	4,4%	14,0%	23,5%	31,2%	42,7%	18,8%
130 kph	14,4%	21,7%	12,2%	23,3%	-0,3%	9,3%	18,9%	26,8%	38,6%	18,3%
140 kph	6,5%	13,9%	5,6%	16,4%	34,7%	4,3%	14,1%	22,0%	34,2%	16,9%
150 kph	-1,1%	6,4%	-0,9%	9,5%	27,5%	-0,7%	9,1%	17,1%	29,6%	10,7%
160 kph	6,7%	-0,6%	18,7%	3,1%	20,6%	35,3%	4,2%	12,3%	25,1%	13,9%
170 kph	-0,6%	12,2%	11,5%	24,7%	14,3%	28,6%	-0,4%	7,8%	20,6%	13,2%
180 kph	5,5%	5,2%	4,9%	17,6%	8,3%	22,4%	37,3%	3,4%	16,4%	13,4%
190 kph	-1,4%	-1,2%	-1,3%	10,9%	2,6%	16,4%	31,1%	-0,9%	12,2%	7,6%
200 kph	3,4%	8,4%	13,0%	4,9%	25,8%	10,8%	25,3%	37,7%	8,1%	15,3%
Average	7,9%	10,7%	12,2%	16,8%	18,6%	22,4%	27,3%	29,6%	38,1%	20,4%

Heterogeneous operation

Average capacity improvement with ERTMS level 2 (IC & freight trains)										
Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	15,2%	6,8%	20,3%	29,3%	21,6%	30,3%	38,7%	45,3%	55,0%	29,2%
70 kph	13,9%	10,5%	11,2%	20,1%	34,8%	23,2%	32,0%	39,0%	49,4%	26,0%
80 kph	4,0%	18,4%	3,1%	11,8%	26,4%	16,6%	25,7%	32,9%	43,8%	20,3%
90 kph	2,4%	19,3%	8,2%	4,3%	18,6%	30,3%	19,6%	27,0%	38,4%	18,7%
100 kph	10,0%	15,7%	23,5%	1,6%	16,0%	27,7%	17,2%	24,8%	36,4%	19,2%
110 kph	6,3%	12,4%	19,9%	18,0%	13,4%	25,3%	14,8%	22,5%	34,3%	18,5%
120 kph	2,9%	9,3%	16,7%	14,6%	11,1%	22,9%	12,5%	20,3%	32,4%	15,9%
130 kph	8,6%	18,6%	13,6%	11,5%	8,8%	20,7%	10,3%	18,2%	30,4%	15,6%
140 kph	4,9%	15,0%	10,5%	8,2%	25,6%	18,3%	8,0%	15,9%	28,3%	14,9%
150 kph	1,3%	11,4%	7,4%	4,9%	22,2%	15,8%	5,6%	13,5%	26,0%	12,0%
160 kph	5,0%	8,0%	16,8%	1,8%	18,9%	33,3%	3,2%	11,2%	23,8%	13,6%
170 kph	1,6%	14,2%	13,3%	12,3%	15,8%	30,1%	1,0%	9,0%	21,7%	13,2%
180 kph	4,5%	10,8%	10,2%	8,8%	13,0%	27,0%	19,3%	6,9%	19,6%	13,3%
190 kph	1,2%	7,7%	7,2%	5,6%	10,2%	24,2%	16,3%	4,8%	17,5%	10,5%
200 kph	3,5%	12,4%	14,1%	2,7%	21,5%	21,5%	13,5%	23,6%	15,6%	14,3%
Average	5,7%	12,7%	13,1%	10,4%	18,5%	24,5%	15,8%	21,0%	31,5%	17,0%

Figure 6: Capacity improvement for level 2 compared to level 1 for homogeneous operation (left) and heterogeneous operation (right) for different block lengths and line speeds.

The results in Figure 6 show that level 2 generally results in the highest capacity gains for longer block sections and lower speeds. This is because the continuous update of level 2 has more effect when trains occupy the block sections for longer time.

Comparing homogenous and heterogeneous operation, it can be seen from Figure 6 that higher capacity gains are achieved with homogeneous operation for long block sections and low speeds (red circles in Figure 6), while higher capacity gains are achieved with heterogenous operation for short block sections and high speeds (blue circles in Figure 6). This is due to variation in block occupation times where it for short block occupation times is less likely that the trains in heterogeneous operation will have braking distances matching the block lengths, while it for long block occupation times increases the probability that some trains will have braking distances better matching the block lengths.

Figure 7 shows cumulative distributions of capacity improvement from level 1 to level 2 for homogenous operation (IC trains) and heterogenous operation with four different train combinations (IC, IC), (IC, Freight), (Freight, IC), and (Freight, Freight) as described in Section 3.2.

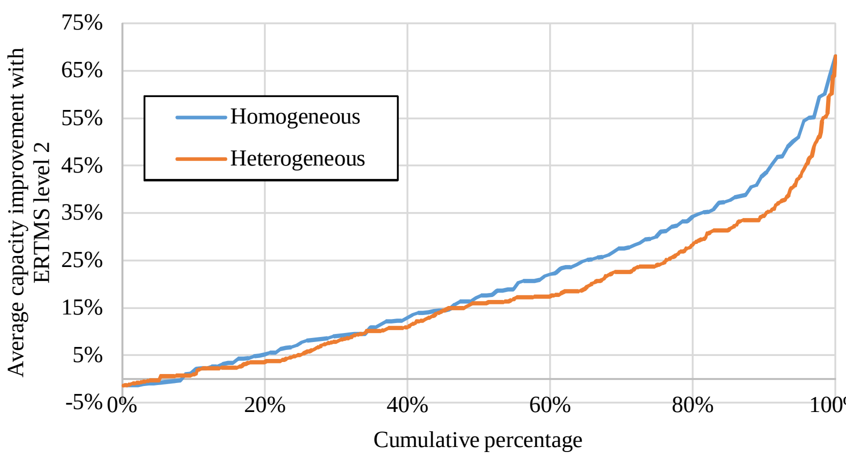

Figure 7: Cumulative capacity improvements for level 2 compared to level 1 for homogeneous operation and heterogeneous operation.

From Figure 7 and the corresponding Table 6, it is seen that the capacity gain of ERTMS level 2 vs level 1 is higher for homogeneous than heterogeneous operation. While significant capacity gains are possible, it can be observed that most train combinations have more moderate gains, and only few combinations result in loss of capacity for level 2 compared to level 1.

Table 6: Capacity improvement for level 2 compared to level 1 in percent.

	Min	5%	25%	50%	75%	95%	Max	Std. dev	Avg.
Homogeneous	-1.4	-0.6	8.0	17.6	30.5	52.1	68.1	16.3	20.4
Heterogeneous	-1.4	-0.2	5.2	15.9	24.1	42.7	68.1	13.6	17.0

ERTMS level 2 is more sensitive to delays in the communication system then level 1 as the Movement Authority (MA) is received by radio. If the movement authority is not received timely, the train headway will increase, and in worst case, the train will be emergency braked. The sensitivity of the system delay is illustrated in Figure 8 for 2.65 seconds (cf. Table 3) and 7 seconds.

Homogeneous operation – 2.65 seconds system delay

Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	27,5%	9,5%	20,7%	27,8%	38,8%	46,9%	54,5%	60,1%	68,1%	39,3%
70 kph	17,7%	2,3%	13,6%	20,9%	32,4%	40,9%	49,0%	55,1%	63,8%	32,8%
80 kph	9,0%	32,1%	7,0%	14,4%	26,2%	35,1%	43,6%	50,1%	59,5%	30,8%
90 kph	1,2%	23,5%	0,9%	8,4%	20,3%	29,5%	38,4%	45,2%	55,3%	24,7%
100 kph	17,6%	15,8%	33,2%	2,7%	14,7%	24,1%	33,3%	40,5%	51,0%	25,9%
110 kph	9,5%	8,6%	25,6%	37,2%	9,4%	18,9%	28,3%	35,8%	46,8%	24,5%
120 kph	2,3%	2,1%	18,6%	30,0%	4,4%	14,0%	23,5%	31,2%	42,7%	18,8%
130 kph	14,4%	21,7%	12,2%	23,3%	-0,3%	9,3%	18,9%	26,8%	38,6%	18,3%
140 kph	6,5%	13,9%	5,6%	16,4%	34,7%	4,3%	14,1%	22,0%	34,2%	16,9%
150 kph	-1,1%	6,4%	-0,9%	9,5%	27,5%	-0,7%	9,1%	17,1%	29,6%	10,7%
160 kph	6,7%	-0,6%	18,7%	3,1%	20,6%	35,3%	4,2%	12,3%	25,1%	13,9%
170 kph	-0,6%	12,2%	11,5%	24,7%	14,3%	28,6%	-0,4%	7,8%	20,6%	13,2%
180 kph	5,5%	5,2%	4,9%	17,6%	8,3%	22,4%	37,3%	3,4%	16,4%	13,4%
190 kph	-1,4%	-1,3%	-1,3%	10,9%	2,6%	16,4%	31,1%	-0,9%	12,2%	7,6%
200 kph	3,4%	8,4%	13,0%	4,9%	25,8%	10,8%	25,3%	37,7%	8,1%	15,3%
Average	7,9%	10,7%	12,2%	16,8%	18,6%	22,4%	27,3%	29,6%	38,1%	20,4%

Homogeneous operation – 7 seconds system delay

Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	21,7%	5,2%	16,5%	23,8%	35,1%	43,5%	51,4%	57,3%	65,7%	35,6%
70 kph	12,0%	-2,0%	9,3%	16,7%	28,4%	37,2%	45,6%	52,0%	61,2%	28,9%
80 kph	3,4%	26,2%	2,7%	10,2%	22,1%	31,3%	40,0%	46,8%	56,7%	26,6%
90 kph	-4,1%	17,8%	-3,3%	4,1%	16,2%	25,5%	34,7%	41,8%	52,2%	20,5%
100 kph	11,3%	10,2%	27,4%	-1,5%	10,6%	20,1%	29,5%	36,9%	47,9%	21,4%
110 kph	3,6%	3,2%	19,9%	31,4%	5,3%	14,9%	24,5%	32,1%	43,5%	19,8%
120 kph	-3,3%	-3,0%	13,1%	24,3%	0,3%	10,0%	19,7%	27,5%	39,3%	14,2%
130 kph	8,1%	15,5%	6,9%	17,8%	-4,3%	5,3%	15,1%	23,0%	35,2%	13,6%
140 kph	0,6%	8,1%	0,5%	11,1%	29,3%	0,4%	10,3%	18,3%	30,7%	12,2%
150 kph	-6,5%	1,0%	-5,6%	4,6%	22,3%	-4,5%	5,4%	13,5%	26,2%	6,3%
160 kph	1,0%	-5,6%	13,1%	-1,5%	15,7%	30,2%	0,6%	8,8%	21,6%	9,3%
170 kph	-5,8%	6,6%	6,3%	19,1%	9,5%	23,7%	-3,9%	4,3%	17,3%	8,6%
180 kph	0,0%	0,0%	0,0%	12,3%	3,8%	17,7%	32,5%	0,0%	13,1%	8,8%
190 kph	-6,5%	-6,1%	-5,8%	6,0%	-1,6%	11,9%	26,4%	-4,1%	8,9%	3,2%
200 kph	-1,8%	3,2%	7,8%	0,2%	20,6%	6,6%	20,8%	33,1%	5,0%	10,6%
Average	2,2%	5,4%	7,3%	11,9%	14,2%	18,3%	23,5%	26,1%	35,0%	16,0%

Heterogeneous operation – 2.65 seconds system delay

Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	15,2%	6,8%	20,3%	29,3%	21,6%	30,3%	38,7%	45,3%	55,0%	29,2%
70 kph	13,9%	10,5%	11,2%	20,1%	34,8%	23,2%	32,0%	39,0%	49,4%	26,0%
80 kph	4,0%	18,4%	3,1%	11,8%	26,4%	16,6%	25,7%	32,9%	43,8%	20,3%
90 kph	2,4%	19,3%	8,2%	4,3%	18,6%	30,3%	19,6%	27,0%	38,4%	18,7%
100 kph	10,0%	15,7%	23,5%	1,6%	16,0%	27,7%	17,2%	24,8%	36,4%	19,2%
110 kph	6,3%	12,4%	19,9%	18,0%	13,4%	25,3%	14,8%	22,5%	34,3%	18,5%
120 kph	2,9%	9,3%	16,7%	14,6%	11,1%	22,9%	12,5%	20,3%	32,4%	15,9%
130 kph	8,6%	18,6%	13,6%	11,5%	8,8%	20,7%	10,3%	18,2%	30,4%	15,6%
140 kph	4,9%	15,0%	10,5%	8,2%	25,6%	18,3%	8,0%	15,9%	28,3%	14,9%
150 kph	1,3%	11,4%	7,4%	4,9%	22,2%	15,8%	5,6%	13,5%	26,0%	12,0%
160 kph	5,0%	8,0%	16,8%	1,8%	18,9%	33,3%	3,2%	11,2%	23,8%	13,6%
170 kph	1,6%	14,2%	13,3%	12,3%	15,8%	30,1%	1,0%	9,0%	21,7%	13,2%
180 kph	4,5%	10,8%	10,2%	8,8%	13,0%	27,0%	19,3%	6,9%	19,6%	13,3%
190 kph	1,2%	7,7%	7,2%	5,6%	10,2%	24,2%	16,3%	4,8%	17,5%	10,5%
200 kph	3,5%	12,4%	14,1%	2,7%	21,5%	21,5%	13,5%	23,6%	15,6%	14,3%
Average	5,7%	12,7%	13,1%	10,4%	18,5%	24,5%	15,8%	21,0%	31,5%	17,0%

Heterogeneous operation – 7 seconds system delay

Speed/Block length	500 m	750 m	1000 m	1200 m	1600 m	2000 m	2500 m	3000 m	4000 m	Average
60 kph	11,1%	3,5%	16,9%	26,0%	18,8%	27,6%	36,3%	43,0%	53,0%	26,2%
70 kph	9,7%	6,9%	7,9%	16,8%	31,5%	20,5%	29,4%	36,6%	47,2%	22,9%
80 kph	-0,1%	14,2%	-0,2%	8,5%	23,1%	13,8%	23,0%	30,4%	41,5%	17,1%
90 kph	-1,6%	15,0%	4,7%	1,0%	15,3%	27,0%	16,8%	24,4%	36,0%	15,4%
100 kph	5,6%	11,5%	19,2%	-1,6%	12,6%	24,4%	14,4%	22,1%	33,9%	15,8%
110 kph	2,0%	8,2%	15,7%	14,0%	10,1%	21,9%	12,0%	19,8%	31,8%	15,1%
120 kph	-1,3%	5,3%	12,5%	10,7%	7,8%	19,6%	9,7%	17,6%	29,8%	12,4%
130 kph	4,1%	14,1%	9,6%	7,6%	5,5%	17,3%	7,5%	15,4%	27,8%	12,1%
140 kph	0,6%	10,6%	6,5%	4,4%	21,7%	15,0%	5,1%	13,1%	25,6%	11,4%
150 kph	-2,8%	7,2%	3,6%	1,3%	18,3%	12,6%	2,8%	10,8%	23,4%	8,6%
160 kph	0,7%	4,0%	12,6%	-1,7%	15,2%	29,4%	0,5%	8,5%	21,2%	10,0%
170 kph	-2,5%	9,9%	9,3%	8,3%	12,2%	26,3%	-1,7%	6,3%	19,1%	9,7%
180 kph	0,3%	6,7%	6,3%	5,0%	9,4%	23,4%	16,0%	4,2%	17,0%	9,8%
190 kph	-2,8%	3,7%	3,5%	2,0%	6,8%	20,6%	13,1%	2,2%	15,0%	7,1%
200 kph	-0,6%	8,3%	10,1%	-0,8%	17,6%	18,0%	10,3%	20,4%	13,1%	10,7%
Average	1,5%	8,6%	9,2%	6,8%	15,1%	21,2%	13,0%	18,3%	29,0%	13,6%

Figure 8: Capacity improvement for level 2 compared to level 1 with system delay of 2.65 seconds (left) and 7 seconds (right) for different block lengths and line speeds, for homogeneous operation (top) and heterogenous operation (bottom).

Figure 8 shows higher system delays reduce the capacity gain of level 2 compared to level 1, and higher system delays have significant impact on short block sections and high speed. This is because the system delay has higher impact when trains occupy the block sections for shorter time.

4.2 Practical Results

Applying the headway calculation model on real-life railway lines and timetables with freight, IC and fast trains, it is seen in Table 7 that the decrease in capacity consumption for level 2 vs level 1 is limited to 1-10% with an average of 3%.

Table 7: Capacity consumption for different line sections for level 1 and 2.

	Level 1	Level 2	Difference
Line section 1	45%	44%	1%
Line section 2	46%	43%	3%
Line section 3	59%	49%	10%
Line section 4	50%	47%	3%
Line section 5	41%	39%	2%
Line section 6	56%	54%	2%
Line section 7	60%	59%	1%
Line section 8	61%	59%	2%
Line section 9	43%	42%	1%
Average	51%	48%	3%

The results in Table 7 are for different line sections on two different railway lines that have had a 1:1 replacement of conventional signals with ERTMS. The reasons for the limited capacity gain for level 2 compared to level 1 are short block sections on the line sections and high degree of heterogeneity with less potential for improving the headways, cf. Figure 9.

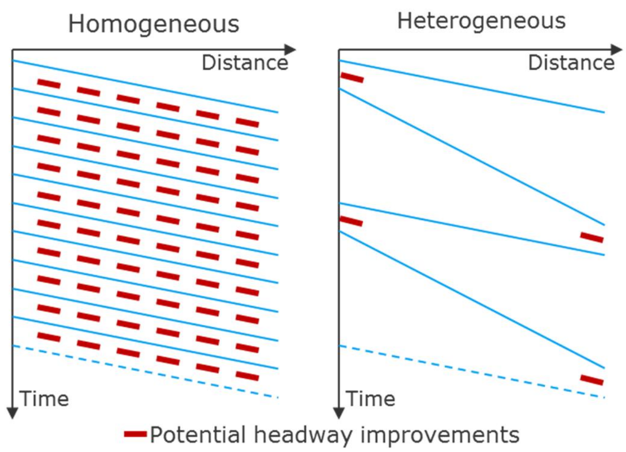

Figure 9: Potential for headway (block occupation) improvements for homogeneous and heterogeneous operation.

As an example, for line section 4, homogeneous operation would have yield 18%, 14%, 45%, and 12% for operation with purely Freight, IC, Fast (Lambda) and Fast (Gamma) respectively, cf. Table 8.

Table 8: Improvement in line headway for a real-life case example for level 2 vs level 1 for line section 4 (cases with homogeneous operation marked with bold).

2nd train / 1st train	Freight	IC	Fast (Lambda)	Fast (Gamma)
Freight	**18%**	3%	1%	2%
IC	19%	**14%**	24%	8%
Fast (Lambda)	27%	26%	**45%**	12%
Fast (Gamma)	27%	26%	45%	**12%**

Two different ETCS braking curve calculation methods exist, lambda and gamma, as described in section 2.3. The lambda calculation is used when nominal brake performance data is not available for the more detailed gamma calculation. However, as seen in Table 8 for the fast train, the choice of braking curve model can have significant influence on the headways and hence capacity. In Table 8, the Fast train has well-adapted braking distance for the block lengths with the gamma braking curve. However, if the braking curves is calculated with the lambda braking curve model, a more significant capacity improvement from level 1 to level 2 would have been observed for this specific train type. This is due to slightly longer braking curves calculated using the lambda model resulting in reservation of an extra block section.

The higher capacity gain from level 1 to level 2 for the lambda braking curves thereby illustrate the effect of the continuous update of the Movement Authority (MA) in level 2 in the current case.

5 Discussion

The theoretical results have shown potential for large capacity gains for level 2 compared to level 1, especially for infrastructures with long block sections and low speed. For homogenous operation, we have observed moderate capacity gains in our real-life case examples when comparing level 1 and level 2. However, only small realized gains in capacity from level 1 to 2 have been identified in our real-life case examples for heterogeneous operation. It is therefore relevant to examine solutions for capacity improvements for different line sections e.g. by adding infill (loops, radio and/or balises) to level 1.

This article has focused on the differences between ERTMS level 1 and 2 systems. However, when changing from conventional signaling to ERTMS, it is essential to examine the potential loss in capacity when the braking curve calculations change which generally lead to longer braking curves and hence loss in capacity. Here it is important to choose the right national values for the braking curves to ensure as high capacity as possible with ERTMS – or limit the capacity loss converting to ERTMS. An example of an important national value is the emergency brake confidence level used in the gamma calculation – both important for infrastructure capacity and safety. Another parameter that greatly affects the braking in ERTMS, and thus the capacity, is the use of the service braking interface. Not using this interface improves capacity as braking intervention is initiated later, although this is not advisable as describe in Section 2.3.

When deciding on the ERTMS architecture, 1:1 replacement of the conventional signaling or overlay may not be options due to loss of capacity. For heavily utilized line sections, ERTMS' advantages over older signaling systems can be used. This is especially the possibility of shorter and more flexible block sections as ERTMS generally can look further ahead and optical signals are not needed. This both allow shorter headways and possibility of higher speed for the (freight) trains with reduced braking capabilities.

ERTMS can potentially be used with Automatic Train Operation which can reduce operation cost for the TOC and lead to increased infrastructure capacity. The extra capacity is achieved by a more uniform driving behavior, including braking, making it possible to optimize block lengths and driving behavior.

6 Conclusions

This article has described the main differences between ERTMS level 1-3 and conventional signaling systems. Based on this description, the capacity differences between level 1 and 2 have been investigated for theoretical as well as real-life cases using a line headway calculation model developed for the study.

The results illustrate that ERTMS level 2 generally has shorter headways than level 1 and hence higher capacity. In homogeneous operation where the braking distance is well-adapted to the block lengths, level 1 can have shorter headways than level 2 due to less system delays.

Level 2 has the highest capacity gains over level 1 for longer block sections and lower speeds. This is because the continuous update of level 2 has more effect when trains occupy the block sections for longer time. Heterogeneous operation generally reduces the capacity gain for level 2 compared to level 1 in case of long block sections and low speed while the capacity gain for homogeneous operation is increased for short block sections and high speed as the disadvantage of discrete update of the Movement Authority (MA) in level 1 thereby is reduced.

1:1 replacement of conventional signaling to ERTMS can lead to loss of capacity as the braking curves are likely to be longer for ERTMS why longer headways occur. However, extra capacity can be gained with ERTMS as it is possible to look more block sections ahead resulting in shorter and more flexible block sections and potentially higher speed for (freight) trains with reduced braking capabilities.

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