Rosberg and Thorslund
European Transport Research Review (2022) 14:18
https://doi.org/10.1186/s12544-022-00542-5

European Transport
Research Review

ORIGINAL PAPER

Open Access

Radio communication-based method for analysis of train driving in an ERTMS signaling environment

Tomas Rosberg* and Birgitta Thorslund

Abstract

Background: ERTMS is an important project improving cross-border interoperability throughout Europe by a single rail signaling standard. One advantage following this development is a standardized radio signaling, which can be tracked by logging the data transfer using the ETCS protocol between Radio Block Center and train. This means that a broad spectrum of train driving can be analyzed in terms of for example driving behavior, signal planning and capacity in a new efficient way.

Methods: In this paper a radio-based protocol method to achieve this, is presented and applied for studying braking characteristics in terms of meeting point design. The aim was to design, apply and validate a radio-based train data collection method to enable cost-efficient and avoid time-consuming train data collections. To enable comparison between the results from the suggested radio-based method and traditional methods, a verification measurement was performed. Three different alternatives of speed calculation were validated. These were based on: Train Position Report speed; calculation of average speed based on reported train position; processed reported train position forming the average speed. The best alternative was then applied to examine deceleration towards different signal targets at single-track meeting points.

Results: The results from this study suggest that the ETCS Level 2 protocol is a feasible way to collect train dynamics data. The method is time saving when it comes to train driver behavior studies where several trains and drivers are needed to get significant results. Comparison with traditional GPS method suggest that the method is valid. Most promising is the alternative using processed train position.

Keywords: ERTMS, ETCS, Signaling, Radio-based, Train dynamics, Braking characteristics

1 Introduction

The next generation signaling system, European Rail Traffic Management System (ERTMS) and the connected European Train Control System (ETCS) is an important industrial project to improve cross-border interoperability throughout Europe by creating a single rail signaling standard [17]. For a successful transition, there is a need for more knowledge of the effects of this new signal system on capacity, signal planning, and timetable design. Specifically, there is a knowledge gap in terms of train driver behavior effects on these aspects, which is addressed in a previous paper [19]. Investigating concerns related to train driver behavior is of major importance before the full ERTMS roll-out, and capturing experiences of the ERTMS pilot lines is thus essential.

Within the scope of exploring how capacity, signal systems, and driving behavior interact, a previous lineside signaling study, using traditional measurement methods with GPS, revealed that the margins to unconditional ATP braking is high and that the braking differs depending on the signal target. Further, the on-track measurements show significantly lower acceleration and

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*Correspondence: tomas.rosberg@vti.se
VTI, Olaus Magnus väg 35, 58195 Linköping, Sweden

deceleration compared to capacity tools used, resulting in differences between measured and simulated running time [18]. Studies from the UK have investigated the impact of train driving behavior for lineside signaling, contributing to the knowledge base for their national system [7, 11]. The lack of data on how trains are driven on ERTMS lines has been highlighted [15] and increased understanding of train driver behavior related to the new European system is essential for smooth international collaboration.

Transition from lineside to in-cab signaling introduces a major change in driving practice, turning the driver focus from the lineside signals outside the cab to the DMI-information inside [14]. Studies exploring driving behavior on ERTMS equipped lines, suggest effects on both capacity and driveability. For example, it has been shown that on sections with ERTMS compared to sections with lineside signaling, drivers tend to cruise at a lower speed relative the permitted speed [15] and that retrofitted Swedish ERTMS lines can be improved in terms of drivability and line capacity [9]. Several DMI issues have also been raised during the ERTMS development [20] and there is an uncertainty in how the driver interacts with the ETCS braking curves [19]. RailSys, one of the capacity assessments tools used by several European infrastructure managers, assumes that the driver follows the permitted braking curve [25]. However, this is not compulsory, and the braking pattern could equally well be connected to the less restrictive indication curve, or some mix between these. This is an unresolved issue that influences the line capacity. These findings all point at a need for more understanding of how the driver operates in the new ETCS environment and one way is to measure train dynamics in real traffic flow.

Measuring train dynamics with GPS equipment with good signal coverage is a method with high sampling rate (typically 10 Hz) and high accuracy for speed and acceleration (typically ±0.1 km/h and ±0.01 m/s^2 for a train application [16]). However, GPS-data collection is time consuming and not optimal for investigating and measuring train patterns. Another traditional approach to examine train driver behavior is to collect train dynamics data from onboard equipment, which have several drawbacks such as being time consuming from technical, juridical, and logistical aspects. One study from Great Britain have focused on operational phases (acceleration, cruising, coasting, and braking) with data input from on-train data recorders of diesel multiple unit trains [15]. In the Netherlands track occupation field data have been used to estimate the train trajectory and driving behavior [2]. On the iron-ore line in northern Sweden capacity analysis has been performed with input from train data recorders [10]. In these studies, the measurement method is not in focus and thus not presented in detail. ERTMS signaling enables a new possibility when it comes to data collection; the juridical data recorder (JRU) logging train events standardized by IEEE Standard 1482.1-1999 [8]. The JRU[1] records the actions of the driver, train conditions and signal parameters. Still there might be juridical issues, since the train operator owns the data stored onboard the train. Another advantage with ERTMS (from Level 2) is the standardized radio signaling [27], which can be tracked by logging the data transfer between RBC and train. Using this opportunity for data collection means that a broad spectrum of train driving, including both freight and passenger trains, can be analyzed in terms of driving behavior, signal planning, capacity, etcetera in a new efficient way.

Approximately 70% of the Swedish rail network consist of single-track [24]. One challenge that would benefit from efficient measurement methods is the design of single-track meeting points, enabling faster train meets. This problem has been addressed by modelling the total meeting delay time, where the braking for trains stopping in the siding is a key component [6]. Alternative train-paths, including new and modified meeting points, at the Iron Ore Line in Sweden have also been investigated and evaluated [4]. However, these models and investigations do not address driver impact on train braking, nor a possible impact of stopping points with different release speeds.

From a Swedish perspective, there are signal planning rules connected to single track meeting points. Tracks with protective points (turnouts), preventing a vehicle from reaching a certain track, implies that all ETCS signaling points protected by the turnout will have a release speed at 40 km/h. If no protective points exist, a protection distance of at least 200 m is necessary to avoid signaling points (marker boards) with a release speed of 15 km/h. Whether or not the release speed affects the driver and thereby the capacity is a topic that needs to be addressed. Another meeting point signal situation is when the train has no restrictive speed or stop signal, however is scheduled to stop according to the timetable. This can occur when the train route is clear without any occupation in the preceding block section. In the light of the upcoming broad ERTMS roll-out, examining preferred signal planning principles is of great interest. The consequences of signal points with different release speeds on capacity and timetable design needs to be investigated.

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[1] From baseline 3 in ERTMS Level 2 the JRU is named *On-board recording device*.

This paper presents a radio-based protocol method using the data traffic between RBC and train. The method is also applied on investigation of meeting point design. Using this ETCS protocol data for different analysis is not unique, however not widely employed. For example, ERTMS traces have been used to build up scenarios for evaluating the ERTMS telecommunication system [21].

Monitoring the signaling system is one of the essential parts of the ETCS data management [22]. Commercial suppliers offer systems for telecom, traffic, network, and quality of service analysis, which includes radio-data. The method presented in this paper uses ETCS traces to estimate train dynamics focusing on train speed and deceleration measurements. To our knowledge, no attempt has been made previously to use this radio-signaling to measure train dynamics and driving behavior. The main purpose of ETCS is to provide train safety, and the suggested method does not propose any changes in that domain, rather enabling a new way of observing train dynamics via the ETCS protocol.

The aim was to design, apply and validate a radio-based train data collection method to enable cost-efficient and avoid time-consuming train data collections. The following research questions have been formulated to reach this aim:

1. How should a radio-based train data collection method be designed to enable efficient train data collections?
2. How is the deceleration effected by signaling points with different release speeds?

The background and theory of ERTMS is described in Sect. 2. This is followed by a presentation of the methodology for the radio protocol-based measurement and for the examination of deceleration in Sect. 3. The results displayed in Sect. 4 are elaborated and discussed in Sect. 5 together with methodological aspects and future work. In Sect. 6 the conclusions drawn from the results are presented.

2 Background

In this section background information essential for understanding the concept of ERTMS is presented. This includes an overview of the radio communication followed by descriptions of each component involved.

The ERTMS technical layers consist of the European Train Control System (ETCS) and the provider for data communication Global System for Mobile Communications–Railway (GSM-R). This concept is a standardized generation of train control and signaling, which includes the automatic train protection (ATP), supervising the train speed and breaking [23]. Practically the ETCS is an on-board computer-based system, which compares the maximum permitted speed with the trains' actual speed [20]. For speed control, ETCS interacts with track and radio systems to provide the cab signaling. Technical and operational requirements for interoperability demand coordinated interfaces between equipment and applications and requires convergence from several national railway systems into a single system [20].

ETCS involves three core levels of technical operation; level 1–3. This study is focused on operation with level 2, however could be performed equally well in the context of level 3 or hybrid level 3. The paper presents how ETCS radio data can be used for train dynamics measurements, understanding the actual train driving behavior, in a system where the train movements are monitored by the radio block center (RBC). Other research covers odometry solutions [5, 12] and deficiencies in ETCS signaling [28], which are out of the scope of this paper.

2.1 ERTMS Level 2 radio communication overview

The data bearer service GSM-R works as the data path to connect the On-Board Unit (OBU) and the Radio Block Center (RBC) and the infrastructure operator manages the system from the Operation and Maintenance (O&M) software. The data bearer provides a data transmission link for up- and downlink ETCS messages between the OBU and RBC, see Fig. 1.

The signaling can be simplified according to Fig. 2 and split into the following three main blocks; application block, communication protocols, and wireless technology.

The main aim for the ATP application is providing railway safety. EuroRadio provides a safe connection between two ETCS units. A few middle layer protocols are also specified by the ERTMS specification [27] which are shown as OSI protocols (Open Systems Interconnection) in Fig. 2. With an ERTMS signaling system the communication between train and RBC is performed via ETCS messages. The format is based on variables and packets and defined in the System Requirements Specification [27].

From the driver perspective the train route is initiated by the movement authority (MA) message is transmitted from RBC to the train via GSM-R and is presented as speed and route data in the driving machine interface (DMI). From the Eurobalises, train position is calculated via the odometer system. In traditional odometry, the train distance is measured by recording wheel rotations, which means that wheel geometry and roadbed affects the accuracy. For ETCS, the accuracy is often increased by combining several types of sensors. A synchronization of the platform and infrastructure is essential and is performed at every Eurobalise [1].

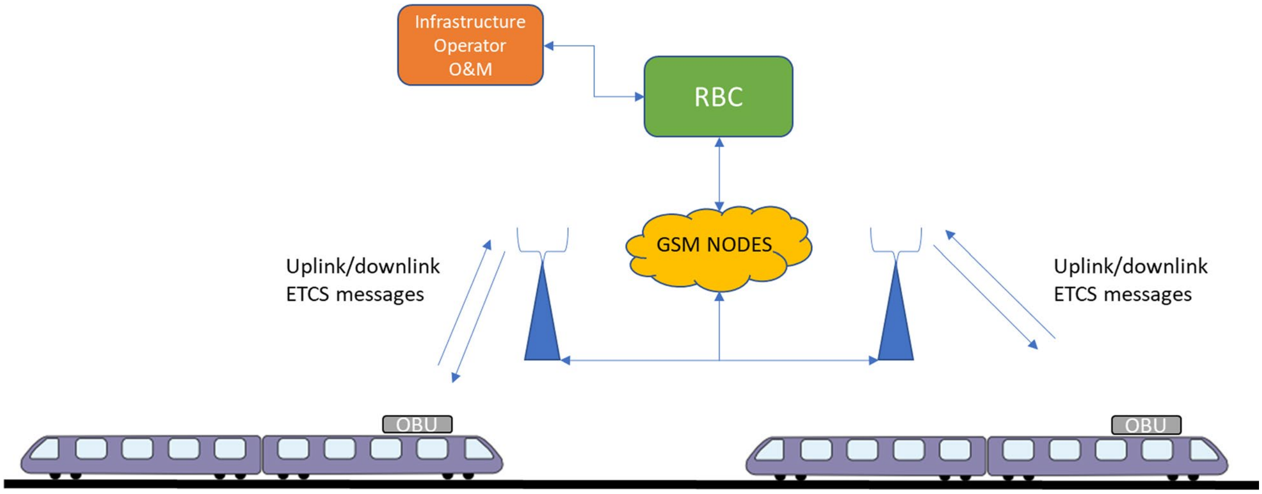

Fig. 1 ERTMS Level 2 radio communication overview

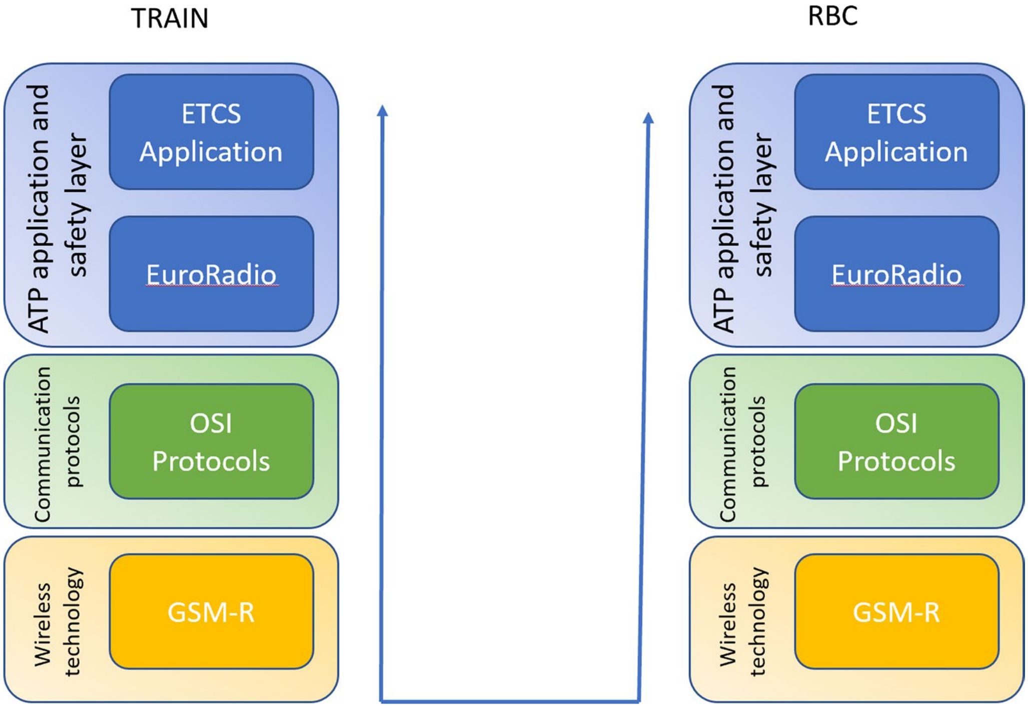

Fig. 2 Communication architecture, inspired by Pinedo et al. [13]

2.2 ETCS messages

The first step in the signaling between OBU and RBC is to establish an ETCS connection. It is initiated by the train with message *Initiation of a communication session*, *RBC System Version* and finally *Session Established*. The next step is to exchange capabilities and configuration of the train and RBC, which is done with the four additional messages: *Validated Train Data, Acknowledgement of Train Data*, the first *General message* and its corresponding *Acknowledgement*. From this point the establishment is complete and normal operation proceeds until the session is ended. *General messages* are sent by the RBC, which are acknowledged by the train. The train asks for permission to run with *Movement Authority Request* and the RBC sends *Movement Authority (MA)* to allow the train to start or continue moving. This proceeding is

Table 1 Connection establishment signaling

Time	Message no	ETCS message	Direction
08:28:30.532	155	Initiation of a communication session	Uplink
08:28:31.147	32	RBC/RIU System Version	Downlink
08:28:33.034	159	Session Established	Uplink
08:28:33.285	129	Validated Train Data	Uplink
08:28:33.436	136	Train Position Report	Uplink
08:28:33.840	8	Acknowledgement of Train Data	Downlink
08:28:33.890	24	General message	Downlink
08:28:33.928	24	General message	Downlink
08:28:35.740	146	Acknowledgement	Uplink
08:28:36.041	146	Acknowledgement	Uplink
08:28:39.256	136	Train Position Report	Uplink

Table 2 Summary of variables of interest

Variable	Explanation	Message/packet
V_MAXTRAIN	Maximum train speed (km/h)	Validated train data/validated train data
V_TRAIN	Train speed (steps of 5 km/h)	Train position Report/position report
T_TRAIN	Trainborne clock (s)	
NID_LRBG	Identity of last relevant balise group (no)	Movement authority/no packet (included in message head)
NID_BG	Balise identity	Movement authority/linking
D_LINK	Distance to next balise group in train route (m)	
D_LRBG	Distance between the train and the last balise group (m)	Movement authority/international static speed profile
D_STATIC	Distance to next speed change (m)	
V_STATIC	Allowed speed (km/h)	

also acknowledged by the train with an *Acknowledgment of Train Data*. The first *General message* configures the interval of which the train is expected to send its position. The train fulfills by sending a *Train Position Report (TPR)*. An example of the start of the signal flow is shown in the real message trace in Table 1. The MA Request and MA are normally sent at a later stage when the train driver requests a train route, and the dispatcher sets the current route.

In this study two messages are of extra interest, *Movement Authority* and *Train Position Report*. The MA is a transmitted downlink, direction RBC to OBU, and includes packets *Level 2/3 Movement Authority*, *Linking, International Static Speed Profile.* These packets include the reference balise, balise route positions, and driver speed profile. For the train to track messages in the uplink direction, TPR packet *Position Report* contains information of the position and speed. Combining these messages generates a speed-distance graph.

The variables in Table 2 are described in the following sections. For a full explanation see SUBSET 026 [27].

2.2.1 Packet—position report

By the variables V_TRAIN (train speed) and D_LRBG (distance from last balise group), a speed-balise relation can be achieved. However, V_TRAIN is given with a low resolution (5 km/h), which will have a major impact on speed-distance accuracy. The time between two location reports (T_CYCLOC) is given by the RBC in a General Message and the packet *Position Report Parameters.*

2.2.2 Packet—linking

With the linking part of the MA, it is possible to replace the balise identity from packet Position Report with a distance. Combining the variables NID_BG (balise id) and D_LINK (distance to next balise group) with the position report reveals the speed distance relation.

2.2.3 Packet—international static speed profile

This packet includes the allowed speed profile. The speed changes in the train route are indicated by discontinuities in speed, related to balise positions. D_STATIC (distance to next speed change) and V_STATIC (allowed speed) together with linking information gives the allowed speed-distance information.

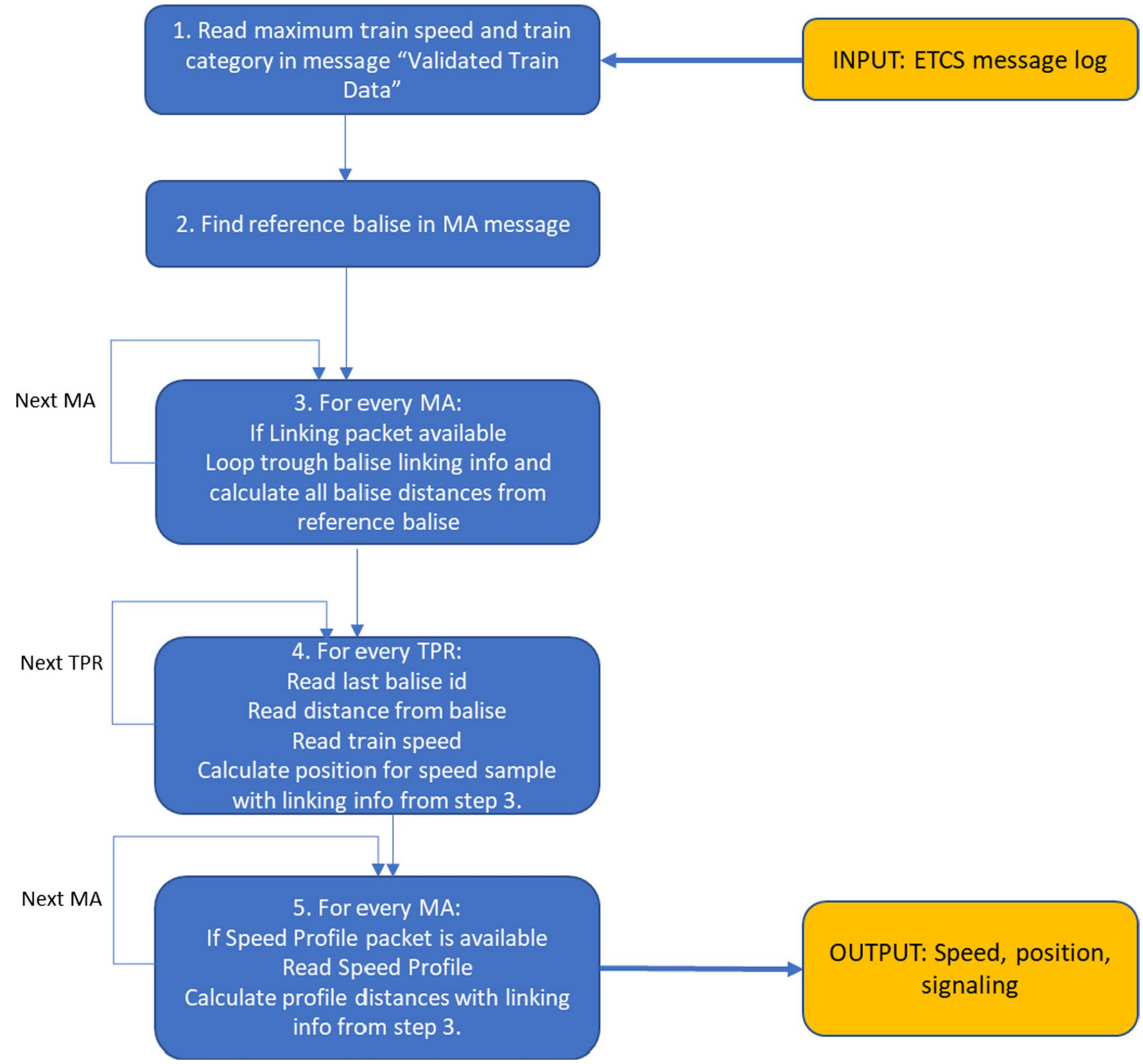

Fig. 3 Flow chart for the ETCS message extraction

3 Methods

The methodology used to reach the aim of the first research question consists of three steps, which are all presented in Sects. 3.1, 3.2, and 3.3. First the approach to the radio-based train data collection is described, including the idea behind the software development and the speed calculations. This is followed by an explanation of the data collection procedure and last, the validation process is described. The methodology used to answer the second research question regarding release speed at signaling points is presented in Sect. 3.4.

3.1 Approach

With the knowledge presented in the background a radio-based method was developed, which is described in this section. To enable comparison between the results from the suggested method and traditional methods, a verification GPS measurement was performed as described in Sect. 3.2.

3.1.1 ETCS message data extraction

A software was developed reading an ETCS message log as input, and generating speed-distance, speed-time, signaling-distance data as output. The software was designed according to Fig. 3. A sample output from the data extraction is displayed in Fig. 4. Note the low-speed resolution on the speed graph (blue line).

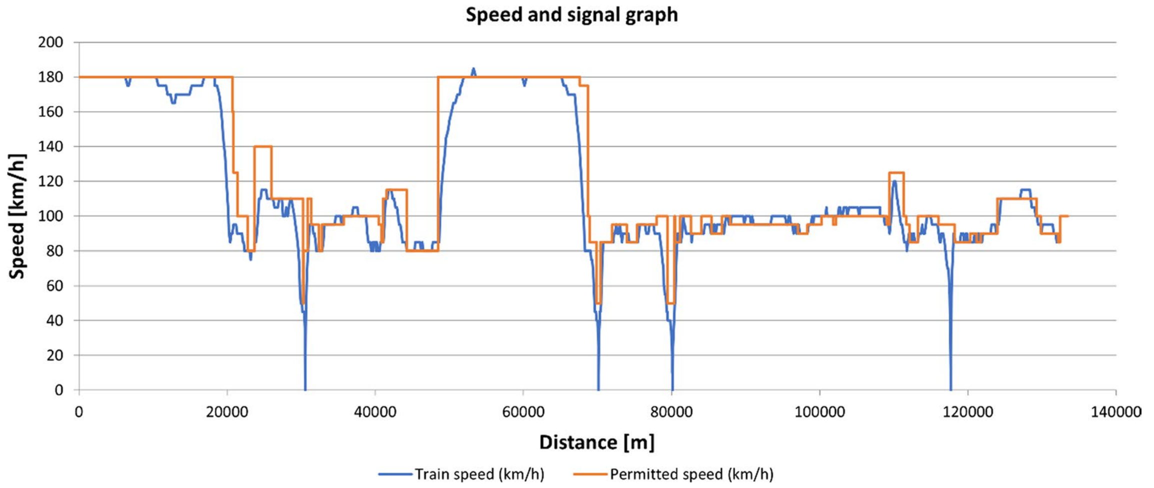

Fig. 4 Result from ETCS message extraction, speed-signal-distance graph

3.1.2 Speed calculation

Three different alternatives of collecting and calculating speed samples from TPR were used and validated, see Fig. 5. The first is based on the protocol raw data TPR speed, V_TRAIN (alternative 1). The second is based on a calculation of average speed from TPR reported train position, D_LRBG, and trainborne clock (alternative 2). The third alternative is based on D_LRBG, train born clock and an algorithm processing the data (alternative 3). The motive for the second and third alternative is the low requirements [26] on resolution for V_TRAIN (5 km/h), and an attempt to refine these.

The basic idea behind alternative 2 is the train average speed between two TPRs, which was calculated as the travelled distance between two TPRs divided by the time difference based on the trainborne clock.

The approach of alternative 3 is an advancement of alternative 2, acknowledging the uncertainty in the reported position. The onboard odometry system and the distance to the last relevant balise group (LRBG) affect the accuracy of the reported position. For the measured distance, the performance requirement is set to $\pm 5\ m + 5\%\ m$ of the measured distance [26]. The under/over-reading values are dependent of the measured distance and are reported in the TPR within the variables L_DOUBTOVER and L_DOUBTUNDER, according to Fig. 6. Balise location accuracy is given by the variable Q_LOCACC in the Linking package ($5\ m$ in this study). With these preconditions, TPRs sent close after passing LRBG, have a high impact from Q_LOCACC, and might be more inaccurate compared to TPRs sent at a longer travelled distance from LRBG, see Fig. 7. This accounts for the relation between the confidence interval and the travelled distance from LRBG. The confidence interval, according to Fig. 6, is increasing with the travelled distance.

To minimize the impact of reported positions with high uncertainty, a distance limit was introduced, d_{min}. If the measured distance between two reports do not exceed d_{min} the measurement is expanded to the next TPR that fulfils the distance limit. With this approach all TPRs will contribute to a speed sample. An alternative could be to ignore all reports with high uncertainty, i.e. high relation between L_DOUBTOVER, L_DOUBTUNDER and the measured distance. However, this has a large impact on the sampling rate in a situation where all sample points are needed. A normal situation with TPRs every 6 s (T_CYCLOC) generates a sampling rate on 0.17 Hz.

The challenge with this way of creating speed samples is in the low-speed area. When the train has stopped, the algorithm will iterate to the TPR that fulfills d_{min}. This point is not reached until the train has started to move and reach the limit, d_{min}, and will thereby form many high fault speed samples, see Fig. 8.

This phenomenon is avoided by setting d_{min} to 0 in the low-speed area. In this study the low speed was defined as < 15 km/h.

3.2 Data collection

The data collection of reference measurements was performed during 5 days in November and December 2019 with a high performing GPS VBOX measurement equipment from Racelogic [16] recording GPS position, speed, and UTC time. In total 19 measurement runs on the same line was conducted. The regional trains from Sundsvall to Västeraspby at Ådalsbanan have an approximate running time of 1:30 h, which yielded approximately 30 h of measurement data. The main operator Vy contributed with

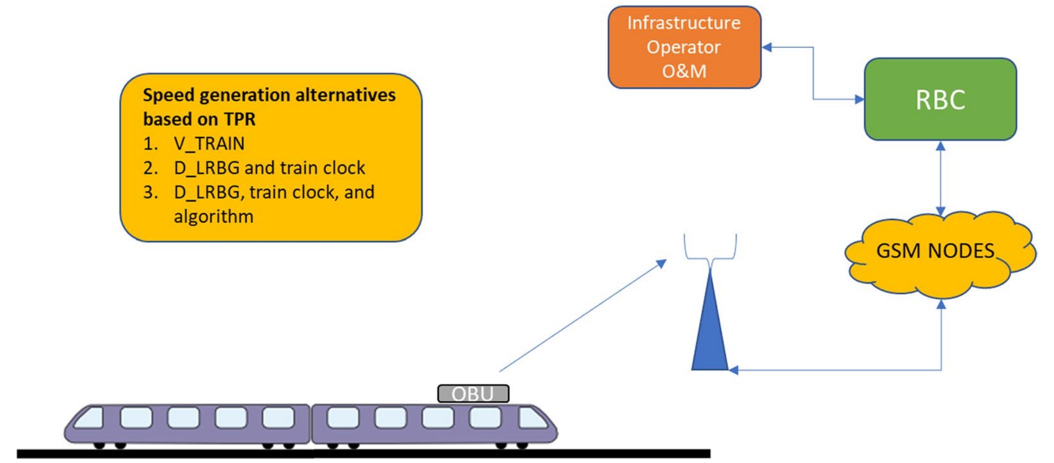

Fig. 5 Three different alternatives based on data in uplink TPRs were tested to generate speed samples: V_TRAIN variable, average speed based on D_LRBG variable, and average speed processed by an algorithm

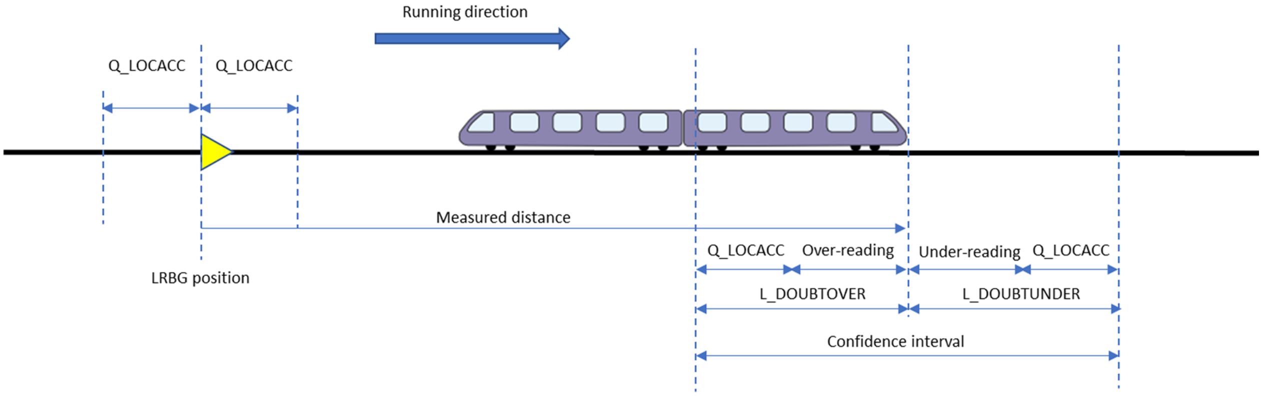

Fig. 6 Principles for ETCS train positioning

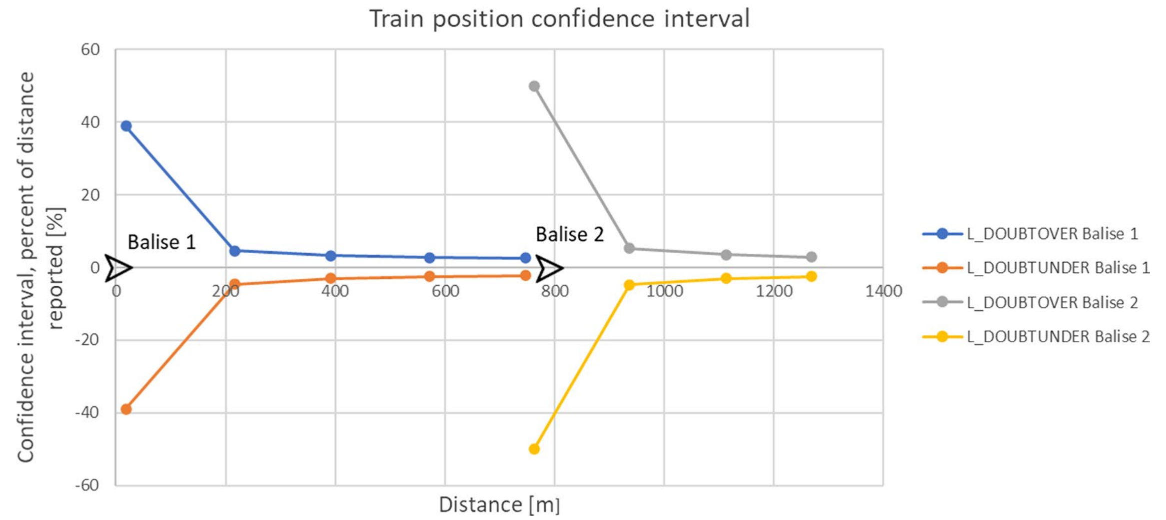

Fig. 7 Example of train position confidence interval. The train passes two balises and sends 9 TPRs during these 1300 m

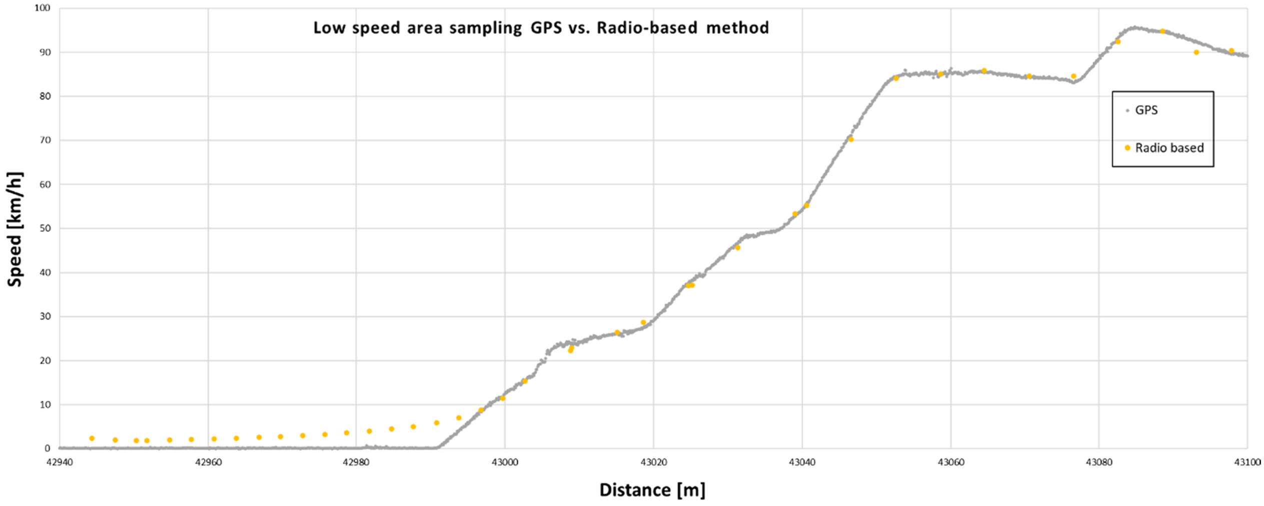

Fig. 8 Speed samples in the low-speed area with GPS measurement as reference

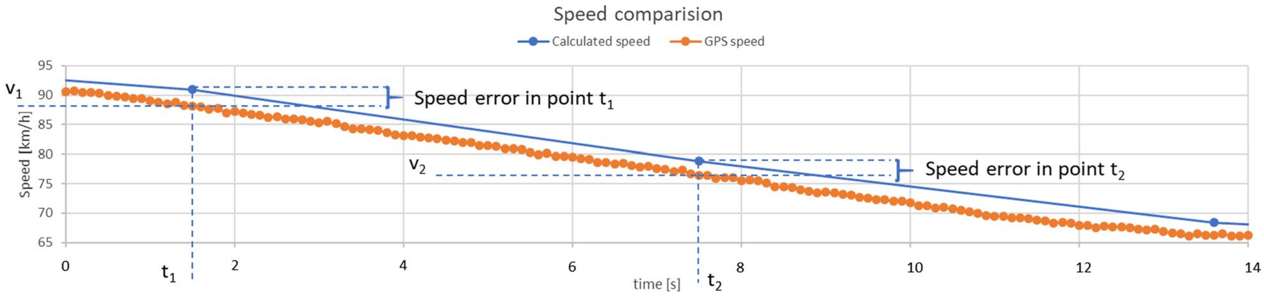

Fig. 9 Speed data from GPS versus speed calculation from suggested method; $v_1 =$ gps train speed at time point t_1 (m/s), $v_2 =$ gps train speed at time point t_2 (m/s)

trains for the validation. This section is operated on daily basis by electrical multiple units (EMU) from Alstom and Bombardier.

3.3 Validation

Speed validation was performed for the speed samples according to the three alternatives presented. The acceleration accuracy is based on the speed uncertainty.

3.3.1 *Speed*

The speed accuracy on the VBOX equipment is specified to 0.1 km/h. To achieve this accuracy, a minimum of 4 satellites have to be locked to the equipment [16]. To maximize the accuracy in the speed validation, only VBOX samples with signal coverage of 12 satellites were used. To validate speed, the average error was calculated as the difference between VBOX speed and the three alternatives of collecting and calculating speed from protocol data. The standard deviation for the average error was also determined.

3.3.2 *Acceleration*

The train acceleration is an important parameter in capacity analytics. In this study, the accuracy of the acceleration is of interest, i.e. how the speed error propagates to the acceleration calculation. In Fig. 9 the speed comparison between VBOX and generated speed samples is illustrated. Under normal traffic conditions the acceleration and braking rate is within ±1 m/s^2. The maximum limit for the method accuracy was set to ±0.05 m/s^2.

To quantify the acceleration uncertainty, the acceleration deviation was calculated (with 95% confidence interval) according to:

$$a_{measured} = a_{train} \pm a_{dev} = \frac{v_1 - v_2}{t_1 - t_2} \pm 2\sigma_a \qquad (1)$$

If the speed error is independent and the time difference constant, the standard deviation can be formulated:

$$\sigma_a = \sqrt{V\left(\frac{v_1 - v_2}{t_1 - t_2}\right)} = \frac{\sqrt{V(v_1) + V(v_2) - 2C(v_1, v_2)}}{t_1 - t_2} = \frac{\sqrt{\sigma_{v1}^2 + \sigma_{v2}^2}}{t_1 - t_2} = \sqrt{2}\frac{\sigma_v}{t_1 - t_2} \tag{2}$$

$$a_{dev} = \pm\frac{2\sqrt{2}\sigma_v}{t_1 - t_2} \tag{3}$$

where $a_{measured}$, measured train acceleration with respect of uncertainties (m/s^2). a_{train}, trains actual acceleration (m/s^2). a_{dev}, acceleration deviation part (m/s^2). σ_a, std of measured acceleration (m/s^2). σ_v, std of measured speed (m/s). t_1, time point for speed measurement 1 (s). t_2, time point for speed measurement 2 (s). v_1, measured train speed at time point 1 (m/s). v_2, measured train speed at time point 2 (m/s).

In addition, time between speed samples affect the accuracy of the calculation. Increasing the delta time gives a lower acceleration fault. However, the delta time is limited by the time span of the train acceleration or retardation. The acceleration deviation in Eq. (3) assumes that there is no uncertainty in the train clock.

3.4 Deceleration towards signaling points with different release speed

81 trains where selected and ETCS protocol logs from the Traffic Administration O&M system were analyzed using alternative 3. 27 of these trains were braking towards a stop signal at Örnsköldsvik station with a release speed of 15 km/h, and 27 trains were braking towards a stop signal at Örnsköldsvik station with a release speed of 40 km/h. The remaining 27 trains were braking towards platform in Nordmaling without any signal restriction, but with a scheduled stop according to the timetable. Both meeting points are stations with platforms and passenger exchange.

The driver is guided by the permitted braking curve in the DMI towards the stopping point. Should he or she fail to do so for any reason (slippery rail, brake inattention, etc.) there is still some distance to allow the train to stop on short notice. In the standard, this distance is referred to as Supervised Location (SvL) [27]. The SvL is supervised by the emergency brake curve which in turn affects the permitted braking curve, depending on the protection distance. To avoid different interference in the guidance from the SvL, stopping points with the same preconditions were chosen (SvL = 50 m).

All signal points in the same category were gathered and an average value of deceleration was calculated. Students T-test (α = 0.05) was performed to examine the difference between signal points.

4 Results

In Sect. 4.1 the result of the speed validation is presented, followed by a calculated speed error propagation to the train acceleration in Sect. 4.2. All results are presented for each speed generation alternative respectively. In Sect. 4.3 the results of the deceleration measurements towards stop are presented.

4.1 Speed validation

The basic speed profile based on protocol raw data, V_TRAIN, was validated for six train runs on Ådalsbanan, see Table 3. In Tables 3–5 the total number of samples is presented together with average error, which is defined as the difference between V_TRAIN and speed measured by GPS equipment, and the pooled standard deviation.

Table 3 Alternative 1: speed validation based on speed samples, V_TRAIN, in message TPR

Date/train run	Train type	No. of validation samples (n)	Average error (km/h)	Standard dev, σ (km/h)
191031/7401	Alstom X62	682	2.53	2.30
191031/7406	Alstom X62	863	2.36	2.17
191031/7409	Alstom X62	593	2.38	1.99
191101/7409	Alstom X62	512	3.15	2.11
191101/7412	Alstom X62	614	2.06	2.00
191112/7406	Alstom X62	671	3.02	2.11
Total	–	**3935**	–	–
Average	**–**	**–**	**2.58**	**–**
Pooled standard deviation	**–**	–	**–**	**2.11**

Table 4 Alternative 2: speed validation based on position D_LRBG and trainborne clock in message TPR

Date/train run	Train type	No. of validation samples (n)	Average error (km/h)	Standard dev, σ (km/h)
191031/7401	Alstom X62	676	− 0.15	1.99
191031/7406	Alstom X62	839	− 0.20	1.78
191031/7409	Alstom X62	593	− 0.50	3.66
191101/7409	Alstom X62	521	− 0.46	2.98
191101/7412	Alstom X62	607	− 0.14	1.58
191112/7406	Alstom X62	638	− 0.21	1.91
Total	–	**3874**	–	–
Average	**–**	**–**	**− 0.28**	**–**
Pooled standard deviation	**–**	–	**–**	**2.32**

Table 5 Alternative 3: speed validation based on D_LRBG and trainborne clock in message TPR

Date/train run	Train type	No. of validation samples (n)	Average error (km/h)	Standard dev, σ (km/h)
191031/7401	Alstom X62	682	0.06	0.70
191031/7406	Alstom X62	862	0.05	0.67
191031/7409	Alstom X62	594	0.13	0.80
191101/7401	Alstom X62	701	0.06	0.65
191101/7406	Alstom X62	839	0.02	0.59
191101/7409	Alstom X62	520	0.13	0.75
191101/7412	Alstom X62	603	0.07	0.85
191112/7401	Alstom X62	844	0.05	0.69
191112/7406	Alstom X62	643	0.05	0.76
191112/7409	Alstom X62	574	0.07	0.71
191112/7412	Alstom X62	546	0.12	0.74
191113/7401	Alstom X62	581	0.06	0.78
191113/7406	Bombar-dierX52	650	0.02	0.99
191113/7409	Alstom X62	449	0.06	1.18
191114/7403	Bombardier X52	710	0.06	1.16
191114/7410	Bombardier X52	479	0.06	0.86
191114/7413	Bombardier X52	532	0.04	1.23
Total	–	**10,809**	–	–
Average	–	–	**0.07**	–
Pooled standard deviation	–	–	–	**0.83**

For speeds over 15 km/h 120 m distance limit was used. For speeds under 15 km/h no distance limit was used

The speed inaccuracy in V_TRAIN is the source to the difference between GPS and train reported speed. For alternative 2, using the balise distance, D_LRBG and trainborne clock for speed calculation, the average fault is significantly reduced. The standard deviation is however increased compared to V_TRAIN, which is shown in Table 4. The high level of speed error and standard deviation makes a more comprehensive validation, that is including several train types and more runs, for these alternatives of limited interest. This is also confirmed by F-test between alternative 1 and 3, and alternative 2 and 3, which revealed $F_{A1A3} = 6.52$ ($p < 0.05$) and $F_{A2A3} = 8.15$ ($p < 0.01$) respectively.

For the alternative 3 the effect of introducing a TPR distance increment limitation is displayed in Table 5. For speeds over 15 km/h a minimum distance increment of 120 m have been used. The correlation between GPS speed and speed based on filtered D_LRBG positions is strong. Pearson's test gives the result r (10,809) = 1.000 ($p < 0.001$).

The numbers in Table 5 and 95% confidence interval reveals the uncertainty in the speed estimation according to:

$$v_{measured} = v_{train} + 0.07 \pm 1.66 \text{ (km/h)} \tag{4}$$

where v_{train}, trains actual speed (km/h). $v_{measured}$, measured train speed (km/h).

4.2 Acceleration validation

The acceleration validation results, including pooled standard deviation and acceleration deviation, are displayed in Tables 6 and 7. Acceleration based on V_TRAIN speed (alternative 1) and acceleration based on balise position D_LRBG processed by algorithm (alternative 3) respectively, was compared. Alternative 2 has a higher speed standard deviation compared to alternative 1 and 3. This alternative was therefore not meaningful to analyze further and thus not included in the comparison.

Acceleration deviation a_{dev} is defined according to Eq. 3. Again, it is not meaningful with a more extensive acceleration validation based on V_TRAIN. The high

Table 6 Train acceleration validation based on V_TRAIN speed (Alternative 1)

Date/train run	Speed standard dev σ_v (km/h) Speed based on V_TRAIN	Acceleration standard dev σ_a (m/s^2) $t = 6$ s	Acceleration standard dev σ_a (m/s^2) $t = 12$ s	Acceleration standard dev σ_a (m/s^2) $t = 18$ s
191031/7401	2.30	0.15	0.08	0.05
191031/7406	2.17	0.14	0.07	0.05
191031/7409	1.99	0.13	0.07	0.04
191101/7409	2.11	0.14	0.07	0.05
191101/7412	2.00	0.13	0.07	0.04
191112/7406	2.11	0.14	0.07	0.05
Pooled standard deviation, σ_a	**2.12**	**0.14**	**0.07**	**0.05**
Acceleration dev, a_{dev}	–	**±0.28**	**±0.14**	**±0.09**

Table 7 Train acceleration validation based on D_LRBG distance, trainborne clock and algorithm (Alternative 3)

Date/train run	Speed standard dev σ_v (km/h) Speed based on D_LRBG, clock, and algorithm	Acceleration standard dev σ_a (m/s^2) t = 6 s	Acceleration standard dev σ_a (m/s^2) t = 12 s	Acceleration standard dev σ_a (m/s^2) t = 18 s
191031/7401	0.70	0.05	0.02	0.02
191031/7406	0.67	0.04	0.02	0.02
191031/7409	0.80	0.05	0.03	0.02
191101/7401	0.65	0.04	0.02	0.01
191101/7406	0.59	0.04	0.02	0.01
191101/7409	0.75	0.05	0.03	0.02
191101/7412	0.85	0.06	0.03	0.02
191112/7401	0.69	0.05	0.02	0.02
191112/7406	0.76	0.05	0.03	0.02
191112/7409	0.71	0.05	0.02	0.02
191112/7412	0.74	0.05	0.02	0.02
191113/7401	0.78	0.05	0.03	0.02
191113/7406	0.99	0.07	0.03	0.02
191113/7409	1.18	0.08	0.04	0.03
191114/7403	1.16	0.08	0.04	0.03
191114/7410	0.86	0.06	0.03	0.02
191114/7413	1.23	0.08	0.04	0.03
Pooled standard deviation, σ_a	**0.83**	**0.05**	**0.03**	**0.02**
Acceleration dev, a_{dev}	–	**±0.11**	**±0.05**	**±0.04**

level of speed standard deviation on V_TRAIN propagates to a high level of acceleration deviation. $F_{A1A3} = 6.72$ ($p < 0.01$), where the F-test accounts for level t = 6 s.

Equation 1 applied on the numbers in Table 7 reveals (95% confidence interval) for timespan 12 s:

$$a_{measurement} = a_{train} \pm a_{dev} = a_{train} \pm 0.05 \left(\mathrm{m/s^2}\right) \quad (5)$$

4.3 Deceleration towards signaling points with different release speed

The braking behavior including 81 deceleration measurements from single track meeting points with passenger exchange is shown in Table 8, together with the total number of measurements and standard deviation. Deceleration towards signaling points with release speed 15 km/h is 43% lower than targets with 40 km/h release speed. This results is significant with $t(28.9) = 7.38$ ($p < 0.001$). The corresponding effect size expressed with Cohen's d = 2.01, which indicates strong power. Deceleration towards stopping point without any restriction is presented as a reference measurement.

5 Discussion and future work

A main motive for this work is the lack of a proper method to compare train driving brake behavior with the ERTMS braking curves [19]. The aim with this study was to design, validate and apply a radio-based train data collection method to enable cost-efficient and avoid time-consuming train data collections. To reach this aim, the following research questions were formulated: (1) How should a radio-based train data collection method be designed to enable efficient train data collections? (2) How is the deceleration effected by the signaling points with different release speeds?

To answer the first research question, three alternatives of collecting and calculating speed samples from TPR were tested. Results revealed that using the standard speed data, V_TRAIN, reported from the train in the TPR message (alternative 1) leads to an acceleration estimation including a large systematic error and deviation. This is due to the low resolution of V_TRAIN reports (steps of 5 km/h). Using TPR signal parameters D_LRBG and trainborne clock (alternative 2), reduces the systematic speed error yet entails a high level of deviation due to uncertainties in reported position. In alternative 3 the speed and acceleration bias are further reduced by using D_LRBG, trainborne clock, and the described algorithm, which in sum limits the effect of position reports with

Table 8 Deceleration measurements for three types of target points

Train type/meeting point	Deceleration release speed 15 km/h (80–0 km/h) (m/s^2)	Deceleration release speed 40 km/h (80–0 km/h) (m/s^2)	Deceleration without any restriction (80–0 km/h) (m/s^2)
Alstom X62/Örnsköldsvik	− 0.22		
Alstom X62/Örnsköldsvik		− 0.38	
Alstom X62/Nordmaling			− 0.45
Total no of measurements	**27**	**27**	**27**
Standard deviation	**0.03**	**0.11**	**0.14**

high uncertainty. This alternative was most promising and therefore more extensively statistically analyzed.

The results from the speed validation measurements with two types of EMUs on Ådalsbanan, show high correlation between speed generation alternative 3 and GPS reference equipment. By using the proposed algorithm, the speed error is drastically decreased and so is the error propagation to the acceleration. As an example, with only samples from V_TRAIN, reaching a proposed accuracy of 0.05 m/s^2 requires a measurement time of more than 30 s. With the algorithm the same accuracy is reached at a 12 s time interval, which gives better possibilities to catch the train dynamics at points of interest even if the sample rate is poor. The disadvantage compared to a GPS measurement equipment is a drop in sampling rate from typically 10 Hz [16] to 0.2 Hz. The sampling rate is directly dependent of how frequent the train sends its position (T_CYCLOC). As expected, the GPS system's high measurement accuracy cannot be reached. The scope is foremost to gain efficiency with an accuracy sufficient for the measurement purpose, in this case to explore how capacity, signal systems, and driving behavior interact. Efficiency is significantly improved compared to traditional methods [18]. Further comparison with other methods is difficult, since there is limited literature on this topic and specifically the focus has not been on describing measurements methods but rather capacity [10], running time [2], and driving style [15]. The lack of data on how trains are driven on ERTMS lines has been highlighted previously [15].

This paper has examined two types of EMUs, where the correlation between GPS measurements and the proposed algorithm shows good results. The parameter setting and tuning of the minimum distance between two TPRs, d_{min}, has an impact of the accuracy. Tuning aspects must be investigated further to be optimized in terms of method accuracy and different types of trains. Both EMU train types included in this study are configured with modern odometer systems. This means that the impact of slip and adhesion is probably lower than for example a freight train with only tachometers. Furthermore, the position uncertainty is likely higher for the latter case, which would decrease the method accuracy. These tunings and parameter settings are subjects for further studies. With the algorithm of alternative 3 a speed and acceleration bias of ± 1.66 km/h and ± 0.05 m/s^2 can be reached. It should be noted that the algorithm assumes that the trainborne clock is reported without uncertainty, and GPS reference speed is regarded as the trains true speed. This is a simplification, and the impact of this uncertainty should be further analyzed.

The second research question was approached by measuring train deceleration at single-track meeting points with passenger exchange, using the proposed measuring method (alternative 3). From a single-track meeting point perspective, the signal layout affects the braking characteristics. Avoiding stopping points with release speed 15 km/h implies higher deceleration rates, which in turn enables shorter meeting point time. This effect is revealed in the study, however needs to be quantified in terms of line capacity and set against the cost for protective points etc. One background variable difficult to control is the actual stopping point location. The driver is guided towards the stopping point situated close to or at the end of the platform. However, the driver of a short train is also affected by where the passenger exchange normally occurs. This is a subject for further studies.

One of the important steps in the signal planning process is the static speed profile, where the suggested method can contribute to the understanding of how the speed variations is used, based on data from lines were ETCS have been implemented. This study contributes to increased knowledge on driveability, as requested in several previous studies [3, 9]. The next step towards understanding how capacity, signal systems, and driving behavior interact, is to deploy this method to study differences between capacity simulations and real train driving for ERTMS as previously performed with Swedish lineside ATP signaling [18].

Another important aspect of these results is the measurement efficiency. Achieving the same result with traditional methods would be a logistical challenge. Measuring 81 trains with the same preconditions (train type, length, timetable etc.), would request several weeks of working time. With the proposed method, data from 81 trains is collected in a couple of hours. In the light of the upcoming broad ERTMS roll-out, this method gives a new opportunity to examine and optimize signal planning and timetable design, based on the traffic history and learnings from ERTMS at earlier stages.

6 Conclusion

With the proposed method, basic dynamics data for all types of trains running on ERTMS (with at least Level 2) can be collected over time in a smooth way.

The general idea to use data in the ETCS protocol, process it and provide a sufficient accuracy in speed and acceleration predictions was successful. The method described presents one approach of dealing with the uncertainty in the train position reports, which is the main cause for bias in speed and acceleration measurements. Comparison with traditional GPS method suggest that the method is valid.

The algorithm is time saving when it comes to train driver behavior studies where several trains and drivers can be followed over time, and act as input to studies concerning acceleration and braking behavior connected to signaling points and ETCS braking curves. For future studies in the ERTMS train driver area, this method implies that the input train dynamic data is not limited to specifically equipped train individuals. Instead, all trains followed by the O&M system can be used as the information base.

The method efficiency highlighted by addressing the braking characteristics from signaling points with different release speeds at single-track meeting points revealed significant results. Braking depends on the signaling point release speed, and the deceleration is 43% lower towards targets with 15 km/h compared to 40 km/h release speed. Consequences connected to this result is a topic for future research.

Acknowledgements

The authors wish to thank Vy for help with the train data collection.

The idea behind the measurement method presented was born at a study visit at Trafikverket telecom department in Örebro during august 2019. The train measurement validation with its technical preparation setup and data post-processing, followed by the method programming, was performed by TR. Pär Johansson at the Swedish Transport Administration, department capacity center, gave valuable input to the method development. The paper has been written in collaboration with associate professor BT. Both authors read and approved the final manuscript.

Funding

This work was funded by the Swedish Transport Administration.

Availability of data and materials

All data and material used in this study is stored at VTI.

Received: 9 November 2021 Accepted: 22 April 2022

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