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AN OVERVIEW OF THE ETCS BRAKING CURVES

Introduction

Since the second half of the 20th century, there has been a steady increase in the maximum speed of trains in industrialized countries. The first high speed railway (HSR) with a maximum operational speed of 210 km/h was built between Tokyo and Osaka (Japan) in 1964 and named Shinkansen (that means new trunk line) [1]. After the big success of the Shinkansen operation, the new technologies and innovations aimed to establish the basis for HSR has been developed in several European countries, particularly France, Germany, Italy and UK. The French national railway company SNCF started the operation of the first high speed line between Paris to Lyons on 27 September 1981, at a maximum speed in operation of 260 km/h. Then other HSR lines have been built in some European and Asian countries. At present time the average train movement speed in operation in industry countries amount to 200 km/h and above, and on certain lines the trains move with speed 300 km/h (fig. 1). In Great Britain the new project High Speed Two (HS2) line from London to Birmingham will planned to be operated in 2026 with speed 330 km/h (maximum line speed is 360 km/h) [2].

A single standard definition of high-speed rail and even the standard use of terms ("high speed" or "very high speed") don't exist. Therefore, two explanations of the term high speed railway are considered below in accordance with European normative documents [1, 3].

EU Directive 96/48/EC (application 1) defines the main features of high speed railway (HSR) in such terms.

– Infrastructure. Track are built specially for high speed movement or specially upgraded for high speed travel.

– Minimum speed of 250 km/h on lines specially built for high speed and about 200 km/h on existing lines which have been specially upgraded. This condition must be applied to at least one site on the line.

– Rolling stock must be able to reach a speed of at least 200 km/h to be considered high speed.

According to the International Union of Railways (UIC) norms [1] high speed railways shall comprise:

– specially high speed lines built for speeds generally equal to or greater than 250 km/h;

– specially upgraded high speed lines equipped for speeds of the order of 200 km/h;

– specially upgraded high speed lines which have special features as a result of topographical, relief or town-planning constraints, on which speed must be adopted to each case.

The appearance of high-speed train movement necessitated the upgrading of the entire railway infrastructure, including signaling and communication systems to ensure the required level of movement safety.

Other important factor resulted in developing and unification train control systems, was caused by demands of interoperability.

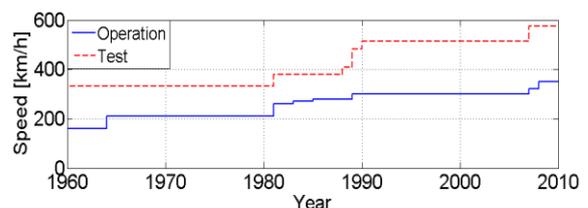


Fig. 1. Increase in maximum speeds in the operation of HSRs [1]

European railways were operated simultaneously with large variety of incompatible railway system types and procedures (more than 6 electric supply systems, 27 different signaling systems, etc.), which restricted competition of supplied companies and put obstacles in free train moving across frontiers. To greatly enhance safety, increase efficiency of trains and enhance cross-border interoperability of rail transport in Europe European Council issued a number of Interoperability Directives for high speed rail and for conventional rail [1, 3-8] and a series of Technical Specifications for Interoperability (TSI) for Rail Command, Control and Signalling (CCS) and European Rail Traffic Management System (ERTMS) [9].

ERTMS was defined by the first European Commission (2001/260/EC) decision as the combination of the European Train Control System (ETCS) and the Global System for Mobile Communication - Rail (GSM-R). The ETCS as element of ERTMS provides two principal functions: Automatic Train Protection (ATP) and Cab Signalling [10].

Automatic Train Protection is the system that automatically applies the train brakes if a driver does not keep the train's speed below the specific trackside safe limits for the train's current location and operating conditions.

Cab Signalling is the system that displays information inside a train cab about the current status of the track ahead. To do so the ETCS onboard computer must predict the decrease of the train speed in the future, from a mathematical model of the train braking dynamics and of the track characteristics ahead. This prediction of the speed decrease versus distance is called a braking curve.

The ETCS on-board computer calculates in real time braking distances, which will also be used to assist the driver and to allow him to drive comfortably, by maintaining the speed of the train within the appropriate limits [11, 12].

ETCS is based on an a set of braking curves, computed in real time and depending on different physical parameters (estimated

speed of the train, track profile, train acceleration, etc.).

Today the ETCS specifications lay down the basic principles for the braking curves and the associated information displayed to the driver, but there is still no harmonized method to compute them [13, 14]. In the absence of any requirement, the algorithms of the ETCS on-board suppliers lead to different braking distances for a given type of rolling stock. This makes the engineering of the ETCS trackside not only dependent on the pure performance of the rolling stock braking system, but also on the ETCS on-board supplier. For cross border trains, the differences through national rules require the implementation in the ETCS on-board of several national braking curves [16]. It can obviously induce increased costs (software design, cross acceptance tests, software upgrade necessary whenever a national parameter is amended).

The purpose of this article is to present an overview of the ETCS braking curves according to the European specifications, including the following main aspects: basic principle to ensure of the train movement safety, the main types of ETCS braking curves, the input parameters for braking curve calculation, construction of the emergency brake deceleration, and guaranteed emergency brake deceleration.

Train movement safety

The basic principle to ensure the train movement safety for a conventional signalling system is based on trains' separation in fixed block distance. The block-section can be occupied by only one train at a time and the train in rear needs under all conditions to be able to stop just before the border of an occupied block section in front of it. The distance between two following trains must be more than the maximum braking distance plus the length of the block section, plus an additional safety factor. The block-sections are equipped by train location sensors (rail circuits, axels counters, balises, etc.).

Another method for ensuring train movement control (so called moving block-sections method) is based on principle that distance between two trains moving in the same direction on the same route must be not lower the maximal available on this section braking distance plus additional safety factor. This method can be used to increase rail line capacity. The method with fixed block-sections is used in conventional train control systems and in EPTMC/ETCC levels 1, 2, the method with moving block-sections is developed for EPTMC/ETCC level 3.

The minimum interval between trains under automatic train protection (ATP) system is defined by minimum movement authority that comprises odometer tolerance, driver allowance, ATP reaction times, brake application time. Minimum train separation for an ERTMS Level 2 system is illustrated in fig. 2 [16].

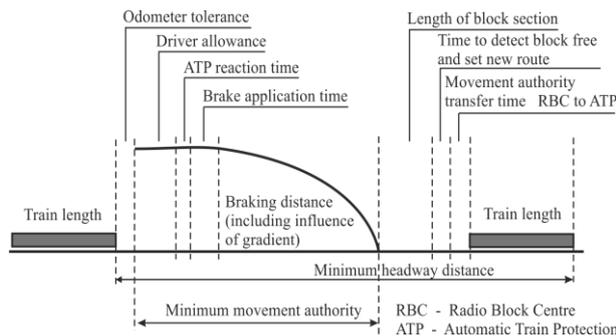


Fig. 2. Principle for determining the minimum interval between trains under ATP

ETCS braking curves

Braking curve predict of the train speed decrease versus distance by the ERTMS/ETCS on-board equipment, from a mathematical model of the train braking dynamics and the track characteristics ahead. ETCS supervises both the position and speed of the train to ensure they continuously remain within the allowed speed and distance limits, and if necessary it will command the intervention of the braking system to avoid any risk of the train exceeding those limits [14, 15].

To do so the ETCS onboard computer must predict the decrease of the train speed in

the future, from a mathematical model of the train braking dynamics and of the track characteristics ahead. This prediction of the speed decrease versus distance is called a braking curve. The purpose of braking curves is to assure that the train remains within the given speed and distance limits.

From this prediction the ETCS on-board computer calculates in real time braking distances, which will also be used to assist the driver and to allow him to drive comfortably, by maintaining the speed of the train within the appropriate limits [14, 15].

The following main ETCS braking curves are defined [17]:

- emergency brake deceleration (EBD);
- service brake deceleration (SBD);
- emergency brake intervention (EBI);
- service brake intervention (SBI).

Emergency braking means the application of a predefined brake force in the shortest time in order to stop the train with a defined level of brake performance. The braking curve related to the speed decrease due to the emergency brake is called EBD (Emergency Brake Deceleration) curve. The braking distance is determined by the performance of the service brake. Each specific target location given by the ETCS trackside is used by the ETCS on-board to compute a fully deterministic EBD curve, which depends on both train and track characteristics. The shape of the EBD curve, for a given piece of track, will therefore vary according to the type of rolling stock.

From the EBD and the measured train speed, the ETCS computer calculates in real time, several times per second, the distance necessary to stop the train from the time the ETCS on-board would command the intervention of the emergency brake.

The purpose of the emergency brake intervention curve is to assure that the train will remain within the limits of the Movement Authority (MA) and the most restrictive speed profile (MRSP) (fig. 3).

The movement authority related to permission for a train to run to a specific location

within the constraints of the infrastructure. End of Authority (EOA) is location to which the train is permitted to proceed and where target speed is equal zero.

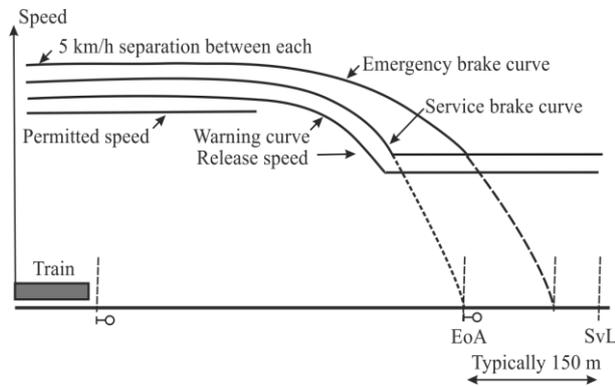


Fig. 3. Headway components for open line [2]

The speed limit is defined by the MRSP that takes into account all speed restrictions imposed by trackside and the train itself.

The MRSP defines the maximum operational speed for the train.

That means the estimated speed of the train will be a certain margin higher than the MRSP before the speed supervision function will intervene. Danger point is the location beyond the EOA that can be reached by the front of the train without creating a hazardous situation (fig. 4) [15].

The Supervised Location (SvL) shall be defined onboard as [15, 17]:

- the end of the overlap, if an overlap is implemented and if it has not timed out;
- if no overlap is implemented or if it has timed out, then the Danger Point;
- if no Danger Point is implemented, then the End of Authority.

The End of Authority and the Supervised Location are related to the Movement Authority and are the references for the different braking curves under different circumstances.

Service braking means the application of an adjustable brake force in order to control the speed of the train, including stop and temporary immobilization. The emergency brake is available in the event that the service brake does not provide sufficient retardation to stop the train safely within the movement authority

but the emergency brake will be requested by the ATP further in advance, only when and if the service brake does not perform adequately.

The EBD curve and the resulting EBI supervision limit are the elements of the ETCS speed and distance monitoring function, which materialize the so called ETCS parachute.

Therefore the ETCS on-board calculates in real time other supervision limits: Indication (I), Permitted speed (P), Warning (W) and Service Brake Intervention (SBI). They consist of locations that, when crossed by the train, will trigger some information to be given to the driver through appropriate graphics, colors and sounds on the Driver Machine Interface.

These locations are defined in order to:

- for the “I” supervision limit: leave the driver enough time to act on the service brake so that the train does not overpass the Permitted speed, when this latter will start to decrease. Without the indication it would not be possible for the driver to perform a transition from ceiling speed supervision to the target speed supervision without overpassing the Permitted speed;

- for the “P” supervision limit: in case of over speed, to leave the driver an additional time to act on the service brake so that the train will not overpass the point beyond which ETCS will trigger the command of the brakes;

- for the “W” supervision limit, to give an additional audible warning after the permitted speed has been overpassed;

- for the “SBI” supervision limit, to take into account the service brake build up time so that the EBI supervision limit is not reached after the command by ETCS of the full service brake effort. The SBI supervision limit is facultative and can be implemented on-board the train in order to avoid too frequent emergency braking, which can be damaging for both the rolling stock and the track.

The main purpose of the ETCS display is to invite the driver to keep the train speed as close as possible to the permitted speed (fig. 4). However the driver might eventually fail to do it and should be the case, ETCS of-

fers him (her) a second chance to brake the train before it takes over the responsibility to command the brakes. This is materialized by a more visible and audible warning and an additional time left to act on the service brake in order to avoid the ETCS intervention, i.e. to avoid that the EBI or the SBI supervision limit (depending on whether the ETCS command on the service brake is implemented) is reached.

Input parameters for breaking curve

Numerous input parameters are necessary to feed the ETCS braking curve algorithms and to allow the ETCS on-board computer to perform in real time its supervision and advisory functions; they can be classified in four categories [15]:

- physical parameters, which results from the real time measurements by the ETCS on-board equipment: instantaneous position, speed and acceleration;
- ETCS fixed values, which are invariant within a given ETCS baseline. They mostly relate to the ergonomics of the braking curve model itself (e.g. driver reaction times, see fig. 1);
- ETCS trackside data. It consists of signalling data (target speed/locations), infrastructure data (downhill/uphill slopes) and also some of the so called ETCS national values, which can affect the ETCS braking curve model. These parameters are under the strict

control of the infrastructure manager and are transmitted through the relevant ETCS transmission medium (balise, loop or radio);

- on-board parameters, which are captured before the start of mission as part of the so called ETCS train data. They mostly relate to the rolling stock braking system itself.

Amongst the two last categories of input parameters, a particular care must be paid to the ones contributing to the computation of the EBD curve. Indeed, the responsibility of the ETCS being solely to command the emergency brake in due time, the overall safety of a railway system highly relies on the fact that the trains will be effectively braked according to the predicted EBD.

Therefore the EBD curve must fulfil the relevant safety, which is required for the operation of ETCS trains on a given infrastructure. This is materialized in the ETCS braking curve model by the so called “correction factors”.

The purpose of the emergency brake intervention curve is to assure that the train will remain within the limits of the Movement Authority and the MRSP.

High speed trains are not capable of braking at the same rate throughout their speed range since the power dissipation in the brakes would be too high at maximum speed. The deceleration due to braking shall be given as a step function of the estimated speed of the train.

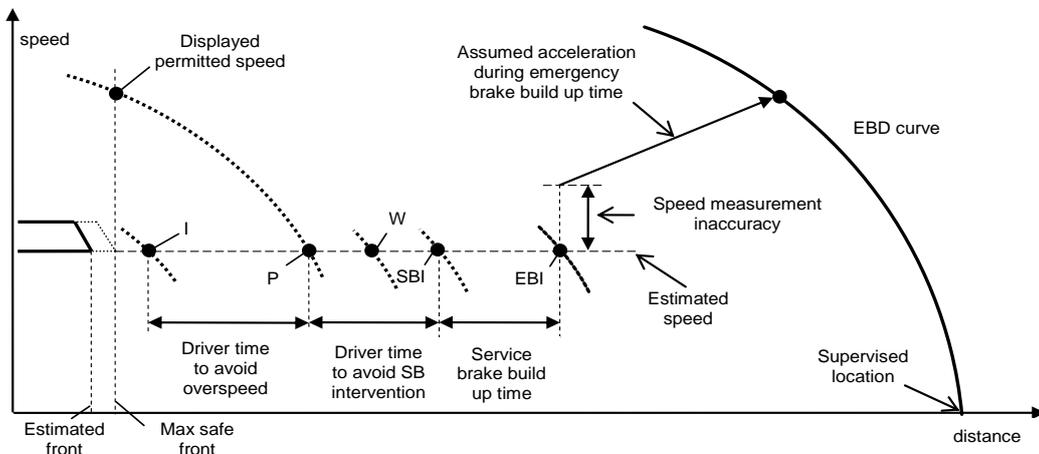


Fig. 4. Overview of the EBD braking curve and its related supervision limits

As an example fig. 5 [15] depicts braking force A_{brake} vs. estimated speed V . with 4 steps:

The dependence A_{brake} vs. speed V has 4 steps:

- $A_{brake} = AD_0$ when $0 \leq V \leq V1$;
- $A_{brake} = AD_1$ when $V1 < V \leq V2$;
- $A_{brake} = AD_2$ when $V2 < V \leq V3$;
- $A_{brake} = AD_3$ when $V3 < V$.

The European High Speed Interoperability legislation [7] defines a minimum braking capability for level track as shown below:

- 350-300km/h – 0.30 m/s²;
- 300-230km/h – 0.35 m/s²;
- 230-0km/h – 0.60 m/s².

Construction of the EBD

The EBD is a parabolic shaped curve that starts from the target location and is computed with the deceleration resulting from [15,17,18]:

- the guaranteed deceleration due to the emergency brake system itself (A_{brake_safe});

- the deceleration/acceleration due to the uphill/downhill slopes ($A_{gradient}$).

To that effect, the emergency brake deceleration is modelled through a step function of deceleration against speed (“emergency brake deceleration profile”), while the track slopes are sent by the ETCS trackside as a step function of constant slopes against distance (“gradient profile”). The combination of both gives a set of interconnected parabolic arcs, each of them corresponding to a speed and distance “region” with a constant (fig. 6).

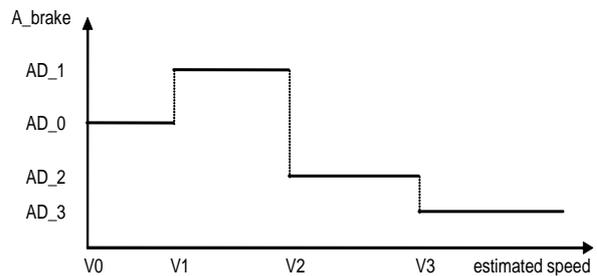
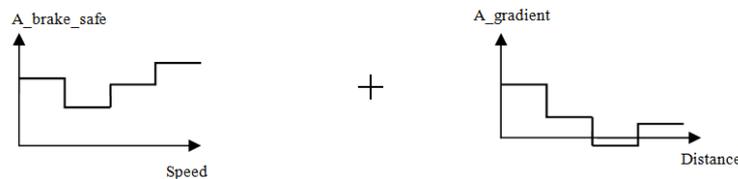


Fig. 5. The braking force A_{brake} vs. estimated speed V



$$A_{safe}(v, d) = A_{brake_safe}(v) + A_{gradient}(d)$$

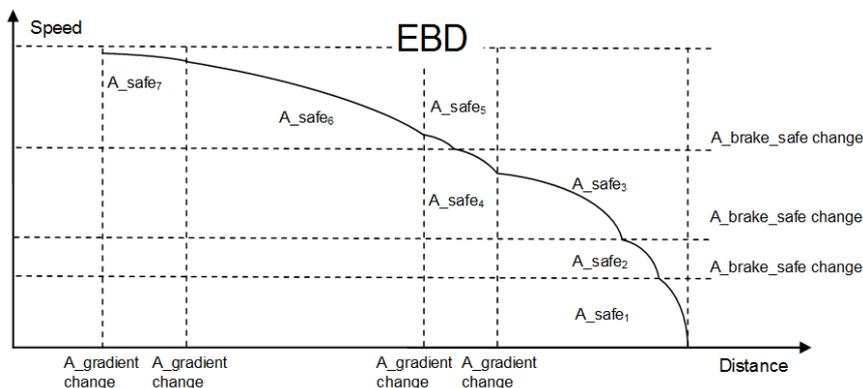


Fig. 6. Construction of the EBD [15]

Guaranteed emergency brake deceleration

Even though the current ETCS baseline 2 specification introduces the concept of EBD curve, they do not tell how reliable must be the EBD curve, or in other terms what do represent the margins that are taken in order to obtain the guaranteed emergency brake deceleration [14,15].

With the ETCS braking curve model, the margin between the nominal emergency brake performance ($A_{\text{brake_emergency}}$) and the guaranteed one is quantified by the so called correction factors. This margin is essentially related to characteristics of the rolling stock itself and depends on:

- the dispersion of the performance of some braking elements (pads, cylinders, etc.);
- the reliability of the braking system components;
- the architecture of the braking system;
- the efficiency of the Wheel Slide protection system in case of wet rail etc.

Since there can be a natural tendency in some countries to already include hidden margins when establishing the nominal braking performance of a rolling stock, first of all ETCS sets the reference conditions under which the nominal emergency deceleration must be established: environmental conditions, friction elements, track profile, wear of the wheels, all braking systems considered for the emergency braking up and running.

While it is relatively easy to represent through a statistical model the dispersion of the braking performance on dry rails (fig. 7), the physical phenomenon that occur when braking on wet rails are still today extremely difficult to model.

In order to overcome this difficulty, two distinct rolling stock correction factors have been created in order to get the guaranteed emergency brake deceleration:

- $K_{\text{dry_rst}}$, to quantify the dispersion of the emergency braking performance on dry rails. This factor is relevant for confidence levels, which represent the probability that one

emergency braking will effectively ensure a necessary deceleration;

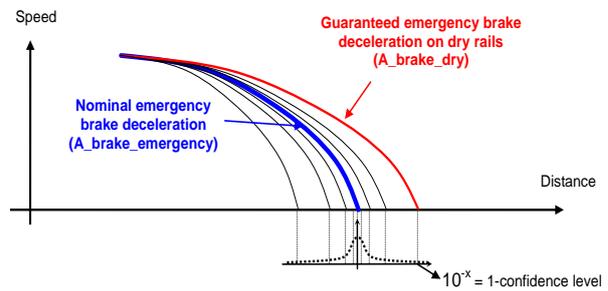


Fig. 5. Dispersion of emergency braking performance on dry rails [15]

- $K_{\text{wet_rst}}$, to quantify the loss of emergency braking performance on a reference reduced wheel/track adhesion, with regards to dry rails. It can be retrieved from the field tests prescribed to qualify the WSP system, as per standard EN15595 [20].

On the one hand, these two correction factors offer the advantage to be strictly under the responsibility of the railway undertaking, because only related to the rolling stock characteristics. On the other hand, the ETCS braking curve model offers the infrastructure manager two levers in order to interact on the computation of the EBD curve:

- the selection of the confidence level with which the guaranteed emergency braking on dry rails will be considered;
- a weighting factor that can mitigate $K_{\text{wet_rst}}$, in case the available wheel/rail adhesion is higher than the reference one defined in the standard EN15595.

As a matter of fact, these two parameters (sent by ETCS trackside as national values) are under the sole infrastructure manager responsibility and can be used to derive the overall safety target applicable to a given infrastructure.

Conclusion

The main features of the braking curves have been reviewed in the article, including the following main aspects: basic principle to ensure of the train movement safety, the purpose and main types of ETCS braking curves,

the input parameters for braking curve calculation, construction of the emergency brake deceleration curve, and guaranteed emergency brake deceleration.

Though the ETCS specifications lay down the basic principles for the braking curves and the associated information displayed to the driver, but there is still no harmonized method to compute them. In the absence of any requirement, the algorithms of the ETCS on-board suppliers lead to different braking distances for a given type of rolling stock. For cross border trains, the differences through national rules require the implementation in the ETCS on-board of several national braking curves. The basic principle to ensure the train movement safety is based on their separation in fixed block distance (for a conventional signalling system) or in moving block-sections (for ERTMS/ETCS level 3). To ensure these principles the ETCS onboard computer must predict the decrease of the train speed in the future, from a mathematical model of the train braking dynamics and of the track characteristics ahead. This prediction of the speed decrease versus distance is called a braking curve. The minimum interval between trains under automatic train protection system is defined by minimum movement authority that comprises odometer tolerance, driver allowance, ATP reaction times, brake application time. Braking curve predict of the train speed decrease versus distance by the ERTMS/ETCS on-board equipment, from a mathematical model of the train braking dynamics and the track characteristics ahead. ETCS supervises both the position and speed of the train to ensure they continuously remain within the allowed speed and distance limits, and if necessary it will command the intervention of the braking system to avoid any risk of the train exceeding those limits.

There have been considered in the work the main ETCS braking curves and the supervision limits of the EBD braking curves, the movement authority, the end of authority, the most restrictive speed profile, the supervised location and others. Differences in braking on

dry and wet rails are considered. The braking on dry rails is relatively easy to represent through a statistical model that take into account the dispersion of the braking performance. But on wet rails the physical phenomenon that occur when braking are still today extremely difficult to model. In order to overcome this difficulty, two distinct rolling stock correction factors have been considered in order to get the guaranteed emergency brake deceleration.

The braking on dry rails is relatively easy to represent through a statistical model that take into account the dispersion of the braking performance. But on wet rails the physical phenomenon that occur when braking are still today extremely difficult to model. In order to overcome this difficulty, two distinct rolling stock correction factors have been created in order to get the guaranteed emergency brake deceleration.

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