Headways on High Speed Lines

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Abstract

Some parts of the European high speed line network are near saturation. ETCS-L2, the so called Level 2 of the European train control system, standard for providing signalling and automatic train protection (ATP) on new high speed lines (HSL), offers a pretty good level of capacity. However, even with the mobile block system provided by ETCS-Level 3, it seems quite impossible for the practical capacity to reach 20 trains per hour per HSL track as soon as maximal speed is at 300 km/h or higher.

At very high speed, headway between trains is mainly determined by the braking performance of the trains.

The paper presents a new running mode using relative braking distances on one hand, and keeping absolute emergency distances in any case on the other hand. The devised running mode is here described within the classical ETCS_L2 context, where signalling still uses track circuits or axle counters.

This secure mode of operation could offer a practical capacity more than 20% higher than the today ETCS_L2 Full Supervision mode.

Keywords: *Braking curves, Capacity, ERTMS, ETCS, headway, HSL, ATO*

1. Introduction: Minimum technical headway at high speed

The European Train Control System (ETCS) was firstly developed to offer to the European Rail community a common Automatic Train Protection system in replacement of the existing ones. In theory, this is needed urgently as more than 15 different and incompatible ATP systems equip the European main rail networks, which obviously preclude interoperability.

The level 2 of ETCS (ETCS_L2) provides *in cab* signalling and allows braking distances over numerous block sections.

Strong impact on headway of the service braking absolute distance

Equation (1) gives a general formula to calculate the minimum technical headway h_{min}.

$$h_{\min} = t_{ind} + \frac{\left(1+\frac{1}{n}\right)\cdot v}{2\cdot d} + \frac{L_o + L_t}{v} + t_{IXL} \;\; [\mathrm{sec}] \qquad (1)$$

With: t_{ind}=indication/watching time [sec], n=number of block sections needed by a train to stop from cruising speed, d=safe average service deceleration [m/s^2], v=speed [m/s], L_o=overlap length [m], L_t=train length [m] and t_{IXL}=interlocking time [sec]

Comprehensive explanations for equation (1) can be found in [Emery, 2008] and many other documents. As soon as *v* is high and n higher than 4 or 5, h_{min} comes close to the minimum technical headway obtained by moving block systems.

$$h_{\min} = \frac{0.6\cdot v}{d} + \frac{500}{v} + 10 \;\; [\mathrm{sec}] \qquad (2)$$

With: d=safe average deceleration [m/s2], v=speed [m/s], n=5,
Lo=100m,Lt=train length=400 m, and tw+ti=10 sec

Considering equation (2) deduced from equation (1), and with v=300/3.6 m/s and d=1.0 m/s^2, the part 0.6 v/d is 75% of h_{min}. However, significant increasing of the service deceleration is very challenging. A new way has to be searched for keeping the technical headway low at very high speed.

2. Twin Full Supervision: Relative service braking distance coupled with absolute emergency braking distance

Dealing with two main objections about relative service braking distance

Absolute service brake distance seems to be an irremovable concept of modern railways, as two main relevant objections are systematically made regarding relative brake distances: *"When points are to be moved between two trains the second one has to have full braking distance to the points until the points are locked in the new position. Another problem is that in case of an accident of the first train the second train has no chance to stop and is going to collide with the first train. Because of these problems, train separation in relative braking distance is only a theoretical idea with no realistic chance to be adopted in railway transportation."* [Pachl, 2004]

When we talk about relative braking distances, we generally do no distinguish between service braking and emergency braking. Two reasons, valid during the whole 20th century, have confirmed this shortcut. The first is the relatively low difference in distance between a full braking application and an emergency braking application for relatively high speed trains in poor adhesion conditions, as the stronger and faster depletion along the brake pipe in emergency conditions brings only a better deceleration during the very first seconds of the braking, and almost nothing for modern passenger trains whose braking system is equipped with electric driven valves. The second is that the speed of a preceding train was unknown and could not be used to consider relative braking distances.

Nowadays, both those reasons can be challenged. The couple ETCS/GSM-R allows information about train speed to be transmitted to the ground and then to other trains - if necessary. Furthermore, Eddy-Current Brakes, independent of adhesion conditions, are in service on some high speed trains and let consider powerful emergency braking, in particular at very high speed.

Relative service braking distance without a safety-net leads to an unacceptable risk

Already in 2004, Alstom asserted the potentiality of capacity enhancement through the use of relative braking distances [Lacôte, 2004]. However the risk of consecutive accidents due to derailment of a preceding train was mistakenly minimised. It is indeed psychologically hard to accept an increase of the risk due to a new operation design. How would have react people if the recent disaster in Eschede[1] was worsened by the subsequent collision of another train running normally behind?

More recently, RFF, in charge of the saturated HSL Paris-Lyon, took up the relative distance idea again: *"A significant increase in the capacity of the lines will only be possible by taking into account, at least partially, the relative distance from braking of the trains, rather than the absolute distance as it is used in the railway system"* [Castan, 2006]. The purpose is then qualified.

Relative braking distances offer more capacity but must induce no additional risk in any case.

Absolute emergency braking distance is the safety-net we need to increase capacity

Already for conventional rail, a lot of ATP systems (KVB, ZUB, ...) use the absolute emergency braking curve as safety-net. Even ERTMS/ETCS uses the emergency braking curve as a last resort to avoid reaching the Supervised Location (SvL) beyond the End of Authority (EOA).

So, a new mode of operation, mixing absolute and relative braking distances, seems to be one promising way to reduce the technical headway and thus increase capacity without reducing safety.

Service Brake Maximal Deceleration Curve and Emergency Brake Minimal Deceleration Curve

The proposed mode of operation was described recently [Emery, 2008 & 2009]. Its main requirements, translated here in the ETCS_L2 context, is to have at one's disposal three new braking curves in addition to the whole family of ETCS_L2 braking curves. The first one, the so-called Service Brake Maximum Deceleration Curve (SBMD) of the preceding train, determines the shift ahead of the

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[1] Eschede: Accident of an ICE which derailed and collided with a bridge pillar and thus brought within a couple of meters from 200 km/h to still.

End of Authority (EOA) with the recalculation of the associated braking curves. The second one, the so-called Emergency Brake minimum Deceleration curve (EBmD), protects the Emergency Supervision Location (SvL_E), which always stays behind the preceding train. The last one, the Emergency Brake Intervention curve (EBmI), can be easily deduced from its associated EBmD curve.

The Emergency Supervised Location (SvL_E) could jump from one block section to another or follow a more frequent update of the safe rear-end position of the preceding train.

In this paper, it is admitted that all braking curves are updated only after each track section release. When the P/GUI curve intervenes long before the EBmD curve (cf. **figure 1** - case #2), this new mode is compatible with the classical manual driving of trains. Nevertheless, Automatic Train Operation (ATO) is highly recommended in both #1 and #2 cases.

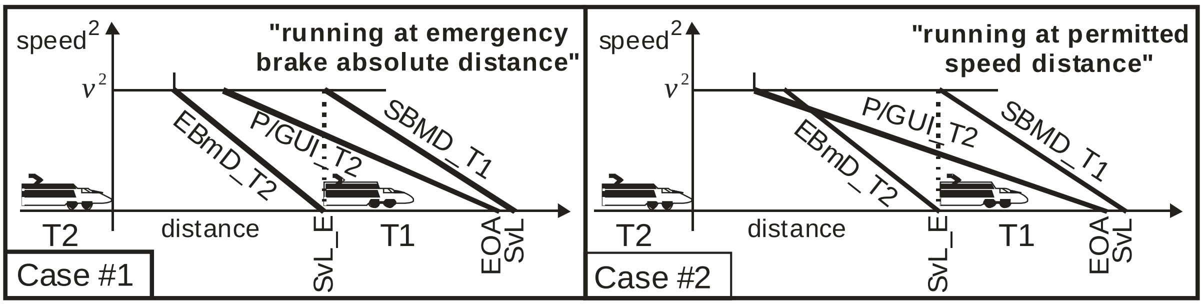

Figure 1: The Emergency Supervised Location SvL_E and the two possible cases

Twin Full Supervision and Automatic Train Operation

Such a new mode of operation can be called "Twin Full Supervision" (TFS) as two locations are simultaneously supervised. Depending namely on the Service Brake Maximum Deceleration Curve (SBMD) of the first train, on the Permitted/Guidance Deceleration Curve (P/GUI), and on the Emergency Brake minimum Deceleration Curve (EBmD) of the second train, the first braking curve encountered by the following train could be either the P/GUI curve or the EBmD curve (cf. **figure 1**).

This TFS mode is generally useful only above 200 km/h. In fact, only high speed provides a Service Brake minimal distance (SBmd) for the first train long enough to allow a jump of the EOA, over the first train, one or many block sections ahead. ATO is not compulsory as long as speeds are higher than 200 km/h and emergency braking performance is significantly higher than the P/GUI one. However, ATO is strongly recommended, as it can not only deal with both cases (cf. **figure 1**) but can also be coupled with complex driving algorithms to offer a smooth control and an optimal anticipation. Such algorithms can minimise time losses due to merging or splitting routes and reduce energy consumption before a stiff down-slope.

3. Study case: Hypothesis

Strong emergency deceleration thanks to Eddy-Current Brakes

Given service braking performances of the preceding train, maximal reductions of technical headway are obtained by Case #2. Such case is reached for very good emergency deceleration and conservative P/GUI values. Above 200 km/h, Eddy-Current Brakes (ECB) are convenient for hard braking. In fact, at high speed, Eddy-current brake forces can be high without unmanageable attraction forces (cf. **figure 2**). Furthermore, Eddy-current brake forces are independent of adhesion, which is low at very high speed (cf. **figure 3**).

EIM, the association of the European Rail Infrastructure Managers, reminds that Eddy-current brakes must have a total compatibility with the line side equipment (tracks circuits and axle counters in particular) [EIM, 2009]. This has to be verified for the strong magnetic fields Eddy-current brakes could produce.

One other point to consider is the elevation of the temperature in the rail head, which has not to lead to track buckling. Critical elevation of the temperature in the rail can be avoided if Eddy-current brakes are not used in normal service but only in case of emergency.

Strong enough service brake decelerations can be obtained by electro-dynamic braking coming from numerous three-phase motors distributed along the whole train set, and from reasonable use of friction brakes.

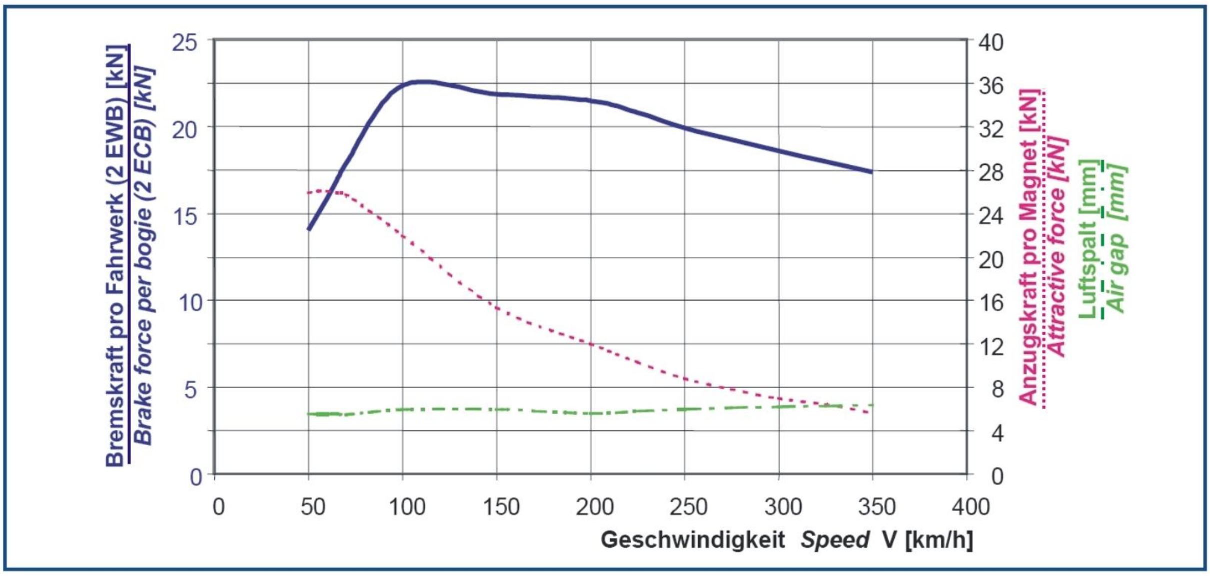

Figure 2: Main characteristics of Eddy-current brakes (ECB) at high speed [Knorr, 2004]

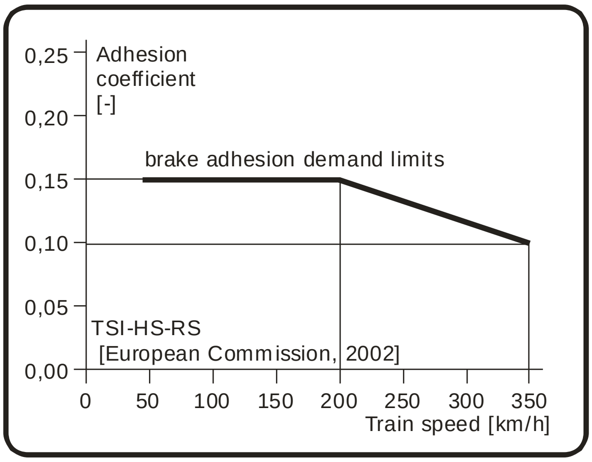

Figure 3: Brake adhesion demand limits according to TSI-HS-RS [European Commission, 2002]

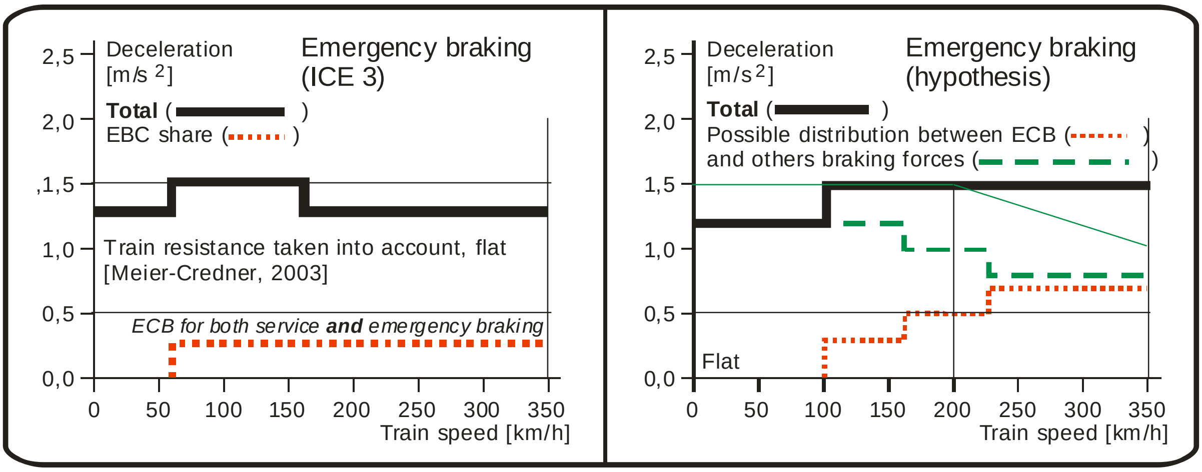

Figure 4: Emergency deceleration hypothesis

For demonstration purpose, the minimal emergency deceleration accepted is 1.5 m/s^2 between 300 km/h and 100 km/h. It is not significantly different of the actual emergency deceleration of an ICE 3 set (cf. **figure 4**). For speeds higher than 300 km/h distribution of the braking forces could also take into account the natural - or mechanically increased - aerodynamic drag.

The Service Brake Maximum Deceleration (SBMD) is considered as very high under 160 km/h. At speed higher than 160km/h, the maximum service deceleration permitted is fixed at a minimum of two times the deceleration of the permitted/guidance curve. So, the minimum stop distance along the Service Brake Maximum Deceleration curve should always be longer than the effective stop distance in case of the application of 100% of the Service Brake Power. In a practical situation, the adjustment of SBMD values can be done by tests. An undervaluation of practical SBMD could only lead to inopportune emergency brake situations.

	Speed [km/h]				
Curve	0-100	100-160	160-230	230-300	> 300
EBmD (m/s^2)	1.2	1.5			1.2
SBMD (m/s^2)	1.8		1.0	0.8	0.8
P/GUI (m/s^2)	0.6			0.4	0.4

Table 1: Braking deceleration main curves (hypothesis) [m/s^2]

As we can see in **figure 5**, for speeds above 290 km/h for both trains, the P/GUI curve (GUI-3) is reached more than 15 seconds before the EBmD curve. The Emergency Brake Intervention Curve (EBmI) can take place between these curves. So, if the driver of the second train reacts accordingly to the P/GUI curve, the absolute emergency distance safety-net can stay invisible. Nevertheless, ATO is highly recommended to optimise the speed of the second train considering both P/GUI and EBmD curves.

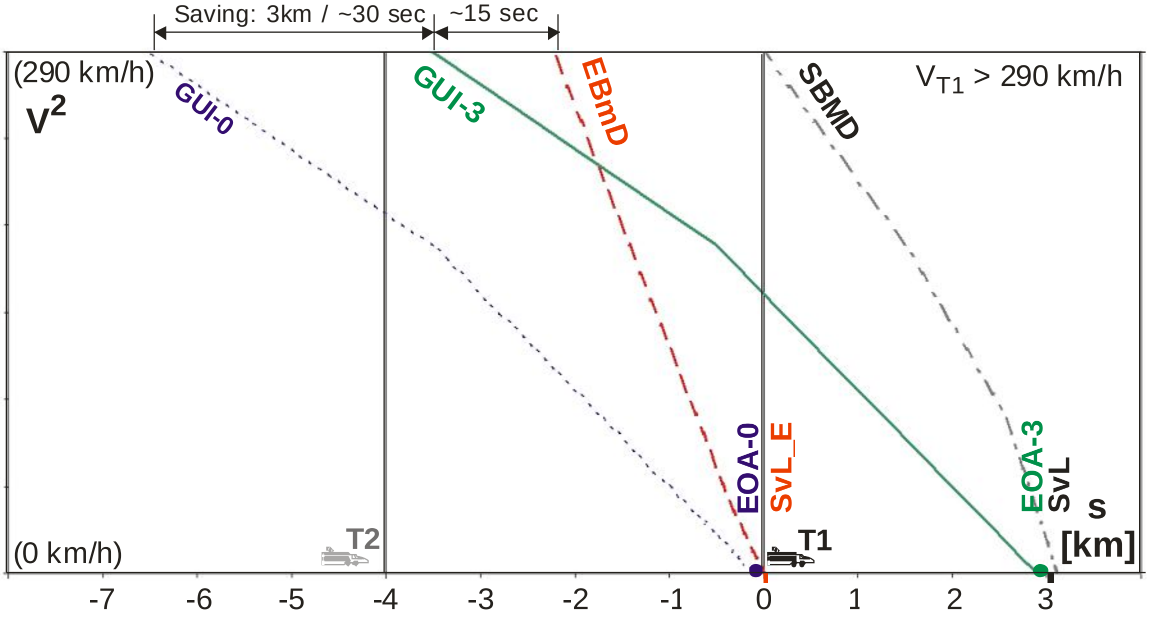

Figure 5: Main braking curves according to Twin Full Supervision (TFS) mode and **table 1** (1 km block section length, flat)

4. Study case: Results

Twin Full Supervision reduces drastically the technical headway at 300 km/h and above

Optimised block section length makes the ETCS_L2 headway very competitive with ETCS_L3, the level using mobile block (cf. [Wendler, 2007]). Indeed, a new EOA occurs each 12 seconds for a block section of 1 km run at 300 km/h. So, the maximum saving brought by ETCS_L3 is roughly 10 seconds.

At the same speed of 300 km/h and with the TFS mode, the shift of the P/GUI and associated curves is 3 km ahead and the saving is approximately half a minute (cf. **figure 5**). Such amount is not negligible compared to the ETCS_L2 technical minimal headway at 300 km/h of approximately two minutes (105 sec to run the guidance distance, plus one block section length, plus the train length, plus the overlap, and additional 15 seconds for the computational, transmission and indication times needed by the IXL, RBC, EVC, DMI and driver).

The twin full supervision can probably lower significantly the increase rate of the technical headway for very high speed (cf. **table 2**).

Cruise speed [km/h]	ETCS_L2	Jump ahead of EOA	ETCS_L2 Twin Full Supervision (TFS)	**Saving with Twin Full Supervision (TFS)**
300	117 sec (~2 min)	3 km	81 sec	36 sec
330	127 sec	4 km	84 sec	44 sec
360	138 sec	5 km	88 sec	50 sec
380	145 sec (~2½ min)	6 km	89 sec (~1½ min)	56 sec
410	156 sec	7 km	95 sec	61 sec

Table 2: Technical headways at cruise speed
(1 km block section length, 400 m train length, 100 m overlap, braking deceleration curves according to **table 1**, time "interlocking+RBC+GSM-R+EVC+indication" of 15 seconds)

Twin Full Supervision and set of points switching

Points switching is time consuming. Most of the practical headways of the lines have to be increased at junctions.

During the switching of the blades of the points, continuity of the track is interrupted. Therefore, with TFS, the SvL_E must stay in front of the set of points as long as the blades are not locked in their new positions. In the cases described below, it is supposed that diverging routes are not occupied by other trains.

As long as the EOA of the second train stays before the set of points, no difficulty arises. At soon as the TFS proposes a new EOA over the set of points, some additional controls have to be made. In case the second train follows the same route as the first one, the set of points remains locked; thus, it has no impact on the headway. If the second train will follow another route than the first one, we are in a diverging situation. If two trains, coming from different lines will follow each other, we are in a converging situation.

Table 3 shows five cases in which the second train can follow the first one according to the TFS mode. Only nominal speeds are considered here.

Case	Junction Type	V1 - First train	V2 - Second Train
D300	Diverging	300 km/h	300 km/h
D230			230 km/h
D160			160 km/h
Dfree		V1 < V2	300 km/h
Cfree	Converging	300 km/h	V2 ≤ 300 km/h

Table 3: Succession sequence and speeds on the set of points - (free: free flow procedure)

In the diverging cases D300, D230 and D160, a new EOA is given to the second train every 12 seconds (V1 = 300 km/h - 1 km block section).

In the D300 diverging case, when the rear of the first train reaches the set of points (cf. **figure 6**), it is convenient that the EOA stays at the end of the GUI-2 curve, because extra times (run over the set of points of the first train and switching and locking of the set of points) could have led to cross the EBmI curve at its intersection with the GUI-3 curve. After completion of these operations, the EBmD curve is removed and the GUI curve changes from GUI-2 to a new GUI-0 curve normally situated far ahead on the new route. The increase of the TFS technical headway is about 12 seconds. The transition from TFS to FS mode is natural.

In the D230 diverging case, when the rear of the first train reaches the set of points (cf. **figure 6**), for the same reasons as explained in the D300 case, the change from GUI-2 to GUI-LOA-230 is only performed after the set of points is locked in its new position. The increase of the TFS technical headway is about 12 seconds. The transition from TFS to FS mode is natural.

In the diverging case D160, when the rear of the first train is 1 km in front of the set of points, the GUI-1 curve does not change to the GUI-2 curve but to the GUI-LOA-160 curve (cf. **figure 6**). The TFS technical headway stays unchanged. The transition from TFS to FS mode is natural.

In the diverging case Dfree, the first train begins its braking sequence in order to respect the LOA on the set of points. In order to realize the shortest possible headway on the set of points, the following train has to anticipate and to brake even before the first train does. According to time forecasting concerning the clearing of the set of points by the first train and acceleration potential of the second train, the ATO of the second train brakes, coasts and re-accelerates it with a suitable rate. Accordingly, the second train runs again at 300 km/h about 1 km before the EBmD curve just at the time this curve is removed, the new route being set. The TFS-ATO technical headway on the set of points stays unchanged. The increase of the TFS technical headway is the sum of the time lost by the first train due to its braking sequence and the time to switch the sets of points. The added time can be about 30 seconds for a diverging speed of 230 km/h and about 1 minute for a diverging speed of 160 km/h. The transition from TFS to FS mode is natural.

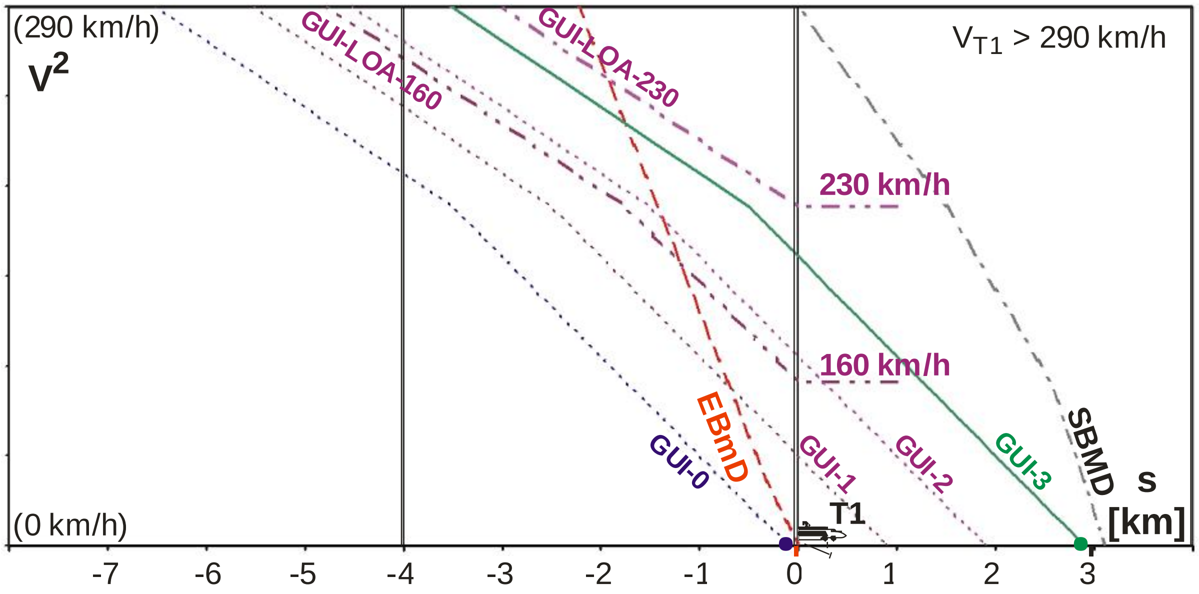

Figure 6: Guidance curves for diverging routes

In converging cases, the value of the saving is mainly depending on the speed of the first train. In the Cfree case, the following train has to adapt its speed according to the forecasted time for clearing the set of points by the first train, and according to its own LOA on the sets of points. Alike the Dfree case, the second train has to run at an appropriate speed at a certain distance before the EBmD curve just at the time this curve is removed, its route beyond the sets of points being set.

5. Headway and Capacity

For High Speed Trains at 300 km/h without merging or splitting routes and no intermediate stops, a buffer time of one minute between the position of the head of a train and the position of the indication point, the practical headway is 3 min with ETCS_L2-FS and 2½ min with ETCS_L2-TFS. If we consider a "breathing train path" after each group of four planned train paths with ETSC_L2-FS or after each group of six planned train paths with ETCS_L2-TFS-ATO, the practical capacity of one track is 16 trains an hour with ETCS_L2-FS and 20 trains with ETCS_L2-TFS-ATO.

A train, having an intermediate stop on the HSL, uses more or less the same among of capacity either in FS or in TFS mode.

The impact on capacity of sets of points forcing a relatively low speed for the diverging route is less noticeable by the TFS-ATO mode than with the FS. Firstly, the switching of the set of points in diverging position, after the run of the first train, can be done during the normal braking sequence of the second train. Secondly, the third train can draw near the set of points at ceiling speed thanks to performing algorithms and steep emergency brake curve.

6. Conclusions

With the combination of service brake relative distances and emergency brake absolute distances, the TFS mode provides a performing mode of running. Such a new mode, coupled generally with an ATO module, allows not only schedulers to introduce shorter buffer times during timetable construction, but also offers significant savings of time in case of operational disturbance, in particular on high speed lines. ATO algorithms taking into account the speed and the route of the train running ahead can offer some more savings.

With an ETCS_L2-TFS-ATO mode the dream to build a robust timetable with twenty trains per hour and per track running safely at 400 km/h can become true.

Abbreviations and Acronyms

ATO	Automatic Train Operation
ATP	Automatic Train Protection
DMI	Driver Machine Interface
ECB	Eddy-Current Brakes
EIM	European Rail Infrastructure Managers
EOA	End Of Authority (ETCS)
ERTMS	European Railway Train Management System (= ETCS + GSM-R + ETML)
ETCS	European Train Control System
ETML	European Train Management Layer
EVC	European Vital Computer (on board)
FS	Full Supervision (ETCS_L2 mode)
GSM-R	Global System for Mobile communications - Railways
GUI	Guidance Speed/Deceleration (ETCS braking curve)
HS	High Speed
HSL	High Speed Line
I	Indication Point/Curve
IXL	Interlocking
KVB	Contrôle de Vitesse par Balise
LOA	Limit Of Authority (ETCS)
P	Permitted Speed/Deceleration (ETCS braking curve)
RBC	Radio Block Centre (GSM-R)
RFF	Réseau Ferré de France
RS	Rolling Stock
SATO	Semi-Automatic Train Operation
SvL	Supervised Location (ETCS)
TSI	Technical Specification for Interoperability
ZUB	ZUg Beeinflussung
EBmD	Emergency Brake minimal Deceleration (braking curve)
EBMd	Emergency Brake Maximal distance
EBmI	Emergency Brake Intervention (braking curve)
SBMD	System Brake Maximal Deceleration (braking curve)
SBmd	System Brake minimal distance
SvL_E	Supervised Location in case of Emergency
TFS	Twin Full Supervision (cf. FS)

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