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Residual risk in Automatic Train Protection systems: evaluation and management

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Abstract

The paper on typical rail operation hazards, such as Signal Passed at Danger (SPAD) and Failed Braking Application by Driver (FBAD). The protection against these hazards is normally by Automatic Train Protection (ATP) systems and emergency braking activation, operated by the onboard systems over a certain Minimum Release Speed (MRS). The determination of such speed is a key design parameter related with the achievable performances in terms of safety and capacity. The present research deal with a systematic analysis of the operational conditions potentially affecting the determination of such speed values by modelling the dynamics of the problem taking into account the features of the infrastructures (tracks layout, gradients, etc.), the vehicles (mass, braking performances, etc.) and the geography of signalling and ATP systems themselves. In fact, the position of main signals protecting the dangerous points (switches, level crossings, etc.) emerges as key player, affecting both the design and the operation of the systems.

Keywords: Railway, Signalling, Operation, Safety, ATP systems

1. Introduction

A complex transport system, such as the railway, requires a continuous and effective action of risk management and mitigation, to maintain its top safety performances. The translation into practice of this requirement includes the actuation of the actions defined in the safety plans and the continuous monitoring of its effectiveness. Nevertheless,

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the economic relevance of such actions and the need to maintain undisturbed the operational performances and the capacity of the system, suggest to use Decision Support Systems (DSS) to identify the priority actions.

In this context, the present work focuses on typical safety critical events (hazards), such as the Signal Passed at Danger (SPAD) and the Failed Braking Application by Driver (FBAD). The Automatic Train Protection (ATP) systems are normally protecting these situations by emergency braking activation, operated by the onboard systems over a certain Minimum Release Speed (MRS) threshold. Therefore, the determination of such speed in the various operational context represents the key design parameter related with the achievable performances in terms of both safety and capacity.

2. State-of-the-art

The several operational conditions potentially affecting the determination of the MRS for the ATP concern the features of both infrastructures (tracks layout, gradients, etc.) and vehicles (mass, braking performances, etc.). Meanwhile, the position of main signals protecting the dangerous points (switches, level crossings, etc.) is emerging as a key design parameter (Evans, 2007) (Independent Transport Safety Regulator, 2011) (Attou, 2019) (EU Agency for Railways, 2020) (Gawlak, 2023) affecting the effectiveness of the automatic protecting actions by ATP systems, which are progressively migrating towards the automation (Flamm, Scheier, 2019). Therefore, the focus of the present research work is on the wide explication of the correlation between braking distance and MRS in the framework of the risk acceptance requirements (Bepperling, Shaha, Geisler, Beck, 2012). The related potential effects on capacity as anticipated in (Bulkova, Gašparík, Masek, Zitricky, 2022) and highlighted in (Ranjbar, Olsson, Sipilä, 2022) are finally schematized in (Wang, Jeiziner, Luan, De Martinis, Corman, 2022).

3. Methodology

The considered hazard is the event that the train runs beyond a signal at danger protecting a safety relevant point, such as a switch or a level crossing, positioned at a Protection Distance (PD) beyond the signal itself, which is the key design parameter for the automatic protection system to implement. As an example, the Italian Infrastructure Manager RFI applies a MRS of 30 km/h in all conditions, with reduction to 10 km/h when the PD is shorter than 150 m.

The developed methodology is willing to determine the required MRS in typical situations depending on the existing PD, as well as the layout features beyond the protection signal, the rolling stock performances and the amount of traffic. It is potentially useful as a DSS in the ATP design phase, both for new and existing lines, in view of the prioritization of ATP improvements.

The methodological steps are the following:

- Calculation of Braking Distances (BD);
- Comparison between BD and PD;
- Quantification of residual risk according to BD-PD difference and the local conditions.

The *BD* calculation is basing on a 3-phases train trip emergency braking model (Fig. 1), including the trains stops starting from various motions conditions:

- Coasting on a descending slope, with braking effort not yet applied (M):
- Ongoing transition to maximum braking effort (R);
- Maximum braking effort applied (C).

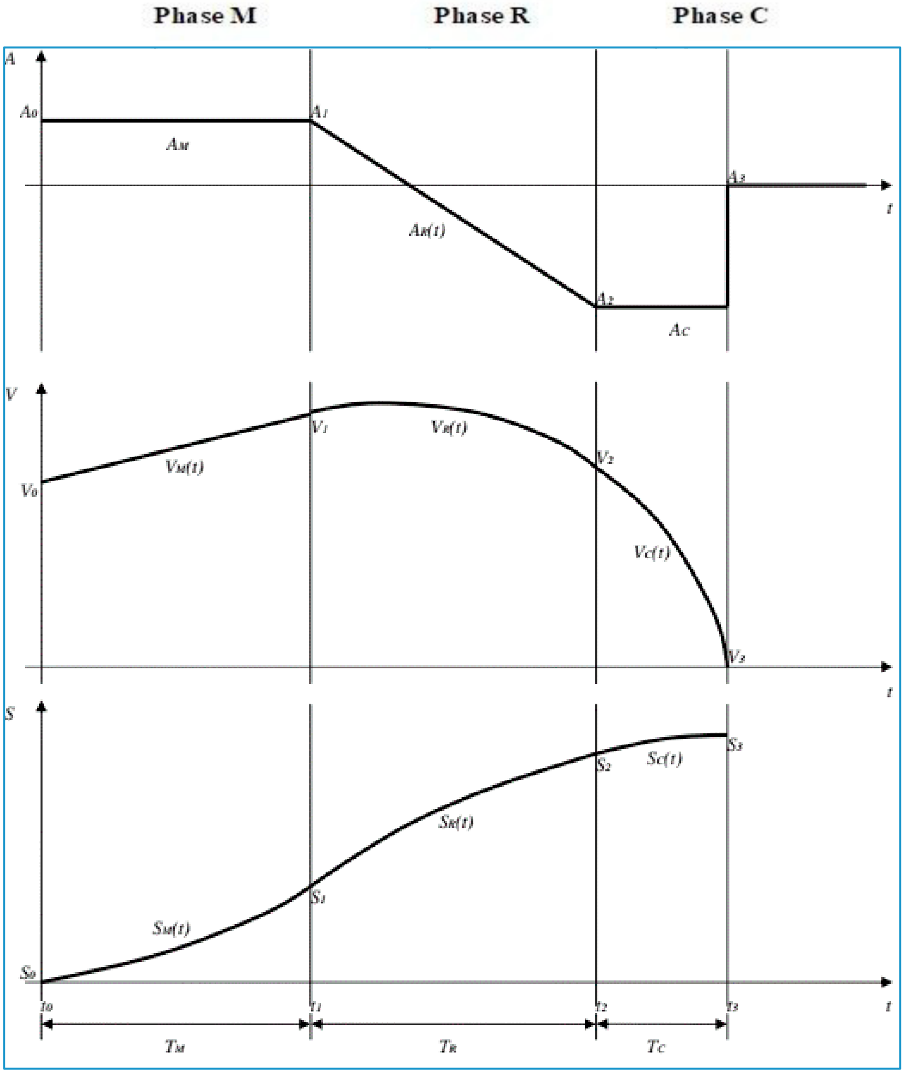

Fig. 1. Acceleration, speed and distance in the 3-phases (M-R-C) emergency braking model for train trip

The model includes the setup of a sequence of algorithms, detailed as an example in the scheme represented in Table 1 for the phase M.

The establishment of the reference parameters is the next key step in the analysis. It includes data fixed by Technical Specification for Interoperability (TSI) (European Commission, 2016) further detailed by National and local specifications and additional specific variable parameters, such as:

- Protection factor (k) basing on the required safety level, e.g. linked to Safety Integrity Level (SIL) (EN 50126, 2017);
- Initial reaction time (dead time) depending on mass, length and braking performances of the concerned trains.

The following methodological step, largely motivated by the relevant variability of the concerned parameters, is a Sensibility Analysis (SA) focused on the effects of:

- Train length and braking mass, differentiated for freight and passengers trains;
- Gradient of the line.

Table 1. Emergency braking calculations (Phase M)

RFI TC.PATC ST CM 01 M11 A

CALCULATION OF d_i

$$d_i = K_{i1} * g * i \quad i > i_1$$

$$d_i = K_{i2} * g * i \quad i_2 < i \le i_1$$

$$d_i = K_{i3} * g * i \quad i \le i_2$$

K_{i1}	0,90	i_1	0,000
K_{i2}	1,00	i_2	-0,021
K_{i3}	1,10		

g	i	K_{ix}	d_i
(m /s²)	(-)	(-)	(m /s²)
9,81	-0,035	1,10	-0,38

CALCULATION OF d_p

$$d_p = k * d_r \qquad d_r = A * \lambda + B$$

A	B	λ	d_r	k	d_p
(m /s²)	(m /s²)	(-)	(m /s²)	(-)	(m /s²)
0,00685	0,094	105,00	0,81	0,90	0,73

CALCULATION OF T_R

$$T_R = 2(t_f - T_M)$$

t_f	T_M	T_R
(s)	(s)	(s)
13,50	3,00	21,00

$$t_f = t_{fV} \quad if \quad TipoFreno = Viaggiatori$$

$$t_f = MAX(t_{fV}, t_{fM}) \quad if \quad TipoFreno = Merci$$

TipoFreno: Viaggiatori = 1 Merci = 0

CALCULATION OF t_{fV} / t_{fM}

$$t_{fV} = a_V + b_V \frac{L(1-EP)}{100} + c_V \left[\frac{L(1-EP)}{100}\right]^2$$

a_v	b_v	c_v	L	EP	t_{fV}
(s)	(s/m)	(s/m²)	(m)	(1/0)	(s)
3,50	0,00	0,15			3,50

$$t_{fM} = a_M + b_M \frac{L}{100} + c_M \left(\frac{L}{100}\right)^2$$

a_M	b_M	c_M	L	t_{fM}
(s)	(s/m)	(s/m²)	(m)	(s)
13,50	0,00	0,04		13,50

PHASE M

TRAIN STOP IN PHASE M

CONDITION A: $t_{MA} = \frac{V_0}{d_i} \le T_M$

$$S_{MA} = \frac{V_0^2}{2d_i}$$

V_0	d_i	t_{MA}	S_{MA}
(km/h)	(m /s²)	(s)	(m)
34,00	-0,38	/	/

CHECK OF CONDITION A

t_{MA}	T_M	CHECK FEEDBACK
(s)	(s)	(YES/NO)
/	3,00	NO

TRAIN STOP IN FOLLOWING PHASES

$$V_1 = V_0 - d_i T_M \qquad S_1 = V_0 T_M - \frac{d_i}{2} T_M^2$$

T_M	V_1	S_1
(s)	(km/h)	(m)
3,00	38,08	28,46

LEGENDA:

- INPUT DATA
- FORMULAS
- REFERENCES TO OTHER CELLS
- GLOBAL FORMULA

An example of the values adopted for the SA (Tab. 2) are those consolidated on Italian railway network.

4. Results

Some interesting results of the SA with reference to the Braking Distance calculated for the shortest (50 m) and the longest (1000 m) train and for the minimum (50 m) and maximum (150%) braking mass, with gradient variable between -6‰ and +6‰ are in Fig. 2, 3, 4 and 5.

Table 2: Set of values of parameters adopted for the Sensitivity Analysis

Length of freight trains [m]	Length of passengers trains [m]	Braking mass [%]	Gradient [‰]
25	70	50	-35
100	100	60	-25
200	150	70	-15
300	200	80	-10
400	250	90	-5
500	300	100	0
600	350	110	5
700	400	120	10
800	500	130	15
900	600	140	25
1,000	660	150	35

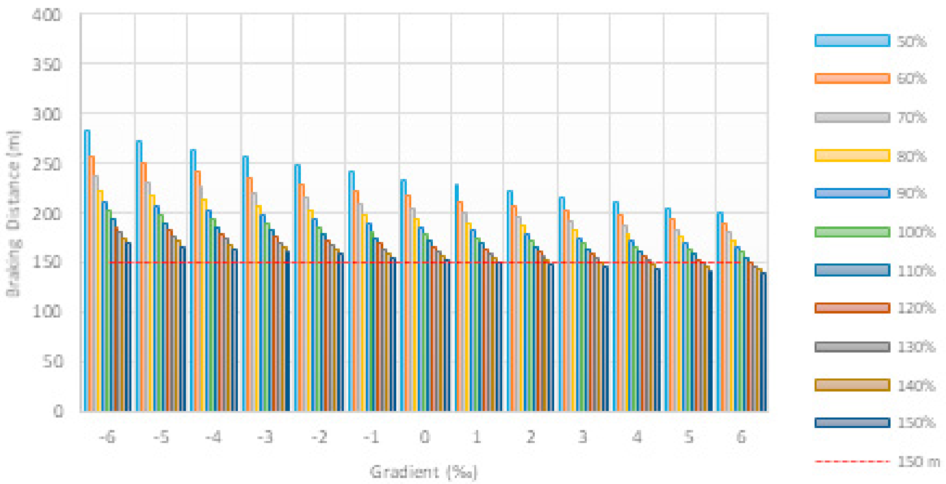

Fig. 2. Braking Distance for the shortest train (25 m) with gradient variable between -6‰ and +6‰

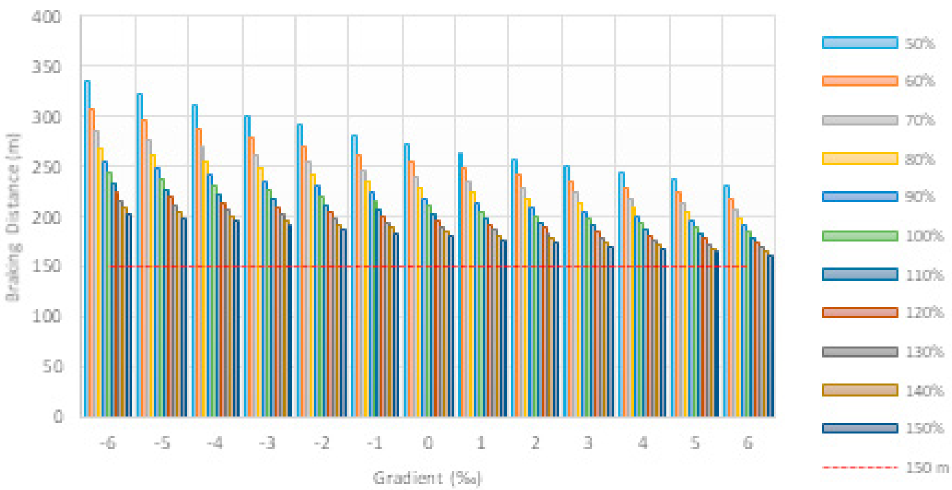

Fig. 3. Braking Distance for the longest train (1000 m) with gradient variable between -6‰ and +6‰

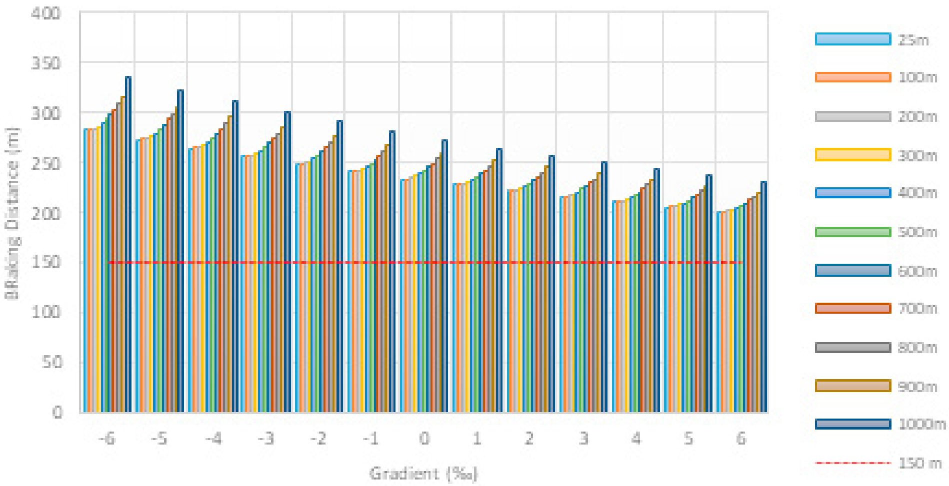

Fig. 4. Braking Distance for the minimum braking mass (50%) with gradient variable between -6‰ and +6‰

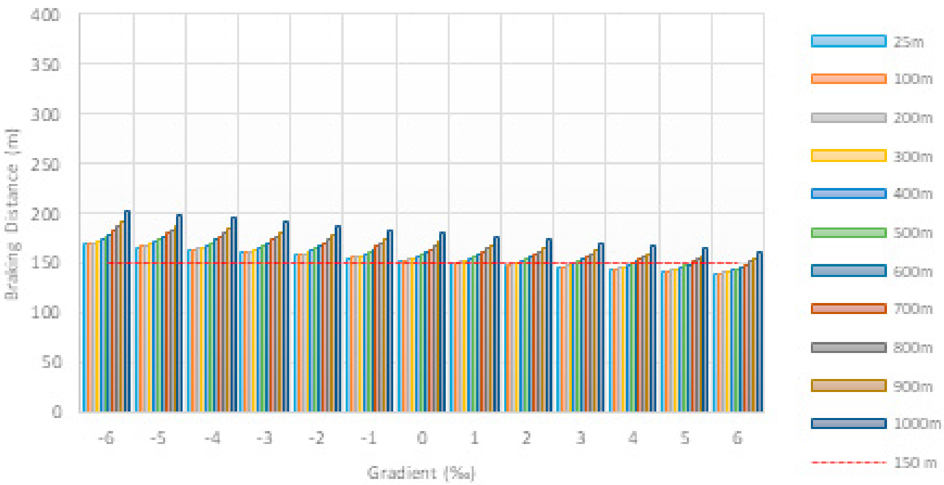

Fig. 5. Braking Distance for the maximum braking mass (150%) with gradient variable between -6‰ and +6‰

5. Conclusions and further research developments

The application of the described methodology confirmed the priority relevance of *PD* and the residual distance run by the train beyond the protected point, if any. Therefore, the first priority index is the difference between *BD* and *PD*, which is able to provide with feedback on:

- Probability to reach the protected point, despite the emergency braking action, which is depending on the intrinsic uncertainty of parameters affecting the calculation of *BD* (friction coefficient, etc.);
- Potential consequences of the hazard, depending on the residual speed in correspondence of the protected point.

Nevertheless, for a complete risk assessment is still necessary to quantify the probability of an ongoing conflicting movement (Kohls et al., 2010). For this purpose, the model includes a second priority index basing on the daily planned traffic of trains (Φ) in correspondence to the protected point.

Therefore, an effective Global Priority index is:

$$GPI = (BD - PD) \ * \Phi \tag{1}$$

In this expression the first term ($BD - PD$) can assume both positive (train running beyond the protected point) and negative (train stopping before the protected point) values. Meanwhile Φ is never negative.

Therefore, the existence of the hazard is for $GPI > 0$ only. Meanwhile the potential severity of its consequences are increasing with the value of GPI.

The main Italian infrastructure manager (RFI) adopted experimentally this methodology for a prioritization of upgrading actions on the ATP systems in operation on its network. This experimental phase will provide relevant feedback in view of a more extended and systematic implementation.

Despite the extended and ongoing test phase, further developments of it on the application of the methodology are necessary to fine tuning the effects of specific parameters, particularly concerning the variability of trains' braking equipment and the combined effects of multiple protected points located in specific areas, such as big stations.

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