1. Abstract

2. Introduction

The purpose of speed control systems is to protect the train and trigger an emergency braking in case of danger. The system takes into account the speed and position of the train relative to the limits allowed for the safety of railway operation. If the allowed limits are exceeded, the driver is first informed and in the absence of appropriate reaction, the emergency brakes are applied automatically.

These systems have been developed on a national basis and the philosophy used to build the control strategy is closely linked to the underlying signalling system, with specific functional concepts. In France for instance the KVB (Speed control by balise) is used for conventional railway whereas the TVM (Track to train transmission) is dedicated to high speed lines. Different solutions exist also for the transmission media (balise, rail, GSM-R…) and for the type of monitoring (piecewise constant speed threshold, parabolic speed threshold…). Speed control systems have been constantly upgraded to increase the performance and to incorporate the latest technological improvements. The development of numeric systems in the 90s has also deeply modified the design of train control systems and opened new perspectives in terms of performance.

As a consequence, a large variety of incompatible speed control systems exists in Europe and represents an obstacle for interoperability and for the development of rail transport at the European level. ETCS is the European Train Control System created to address these incompatibility issues by creating a unique train control system, to replace the existing national speed control systems. The deployment of ERTMS enables the creation of a seamless European railway system.

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. …). On the one hand, some of these curves provide useful information to the driver: the Pre-Indication curve and the Indication curve for instance, inform the driver that he has to initiate a service brake to respect the signals. On the other hand, the safety of the system is based on the Emergency Brake Deceleration curve (EBD). This parabolic shaped curve starts from the Supervised Location (SvL) and is computed with the guaranteed emergency brake deceleration, which incorporates the safety margin. As a result, the statistical dispersion of the emergency braking performance is taken into account, as illustrated in Figure 1 below. Typically, a large safety margin will result in a flat EBD curve, spanning a more important distance range. The Emergency Brake Intervention curve (EBI) which is used to trigger the emergency brake is then directly shifted from the EBD curve with the equivalent emergency brake build up time. To respect ergonomic principles, the curves related to the service brake are positioned upstream compared to the EBI curve: thus a driver who respects the signals will not be impacted by the EBI curve.
3. ERTMS/ETCS framework for safety margins

The management of safety margins is strongly influenced by the existing signalling systems and the speed control systems used. The safety margin can be materialized by a global fixed margin, applied to the overall braking distance and taking into account rolling stock and trackside dispersion. In addition the safety margin is often not ensuring alone the overall safety: it is also supported by operational rules and trackside characteristics. This global value is usually confirmed by operational feedback. However one major inconvenient of this approach is that it doesn’t allow any optimization of the system and that it can be an obstacle to handle the case of cross border trains: the same margin is applied independently from the braking performance.

ETCS has introduced a unified framework to take into account safety margins. This method, described in detail in the latest release of the ERTMS/ETCS System Requirement Specifications (SRS Baseline 3), uses different parameters for safety margins. The main sources of dispersion are separated, making the representation closer to the real apportionment and allowing a more accurate allocation of the safety target. Adhesion, which has a great influence on the performance and which is at the interface between trackside and rolling stock is handled specifically. The approach is based on two multiplicative rolling stock correction factors $K_{dry\_rst}$ and $K_{wet\_rst}$, applied to the nominal emergency brake performance and which depend themselves on two trackside parameters, respectively EBCL and AVADH:

- $K_{dry\_rst}$ takes into account the rolling stock characteristics and represents the statistical dispersion of braking effort on dry rails. It is provided as a table indexed by the confidence level EBCL.
- The Emergency Brake Confidence Level (EBCL) is transmitted by trackside and corresponds to the confidence level on the emergency brake deceleration on dry rails. It is used to select the appropriate $K_{dry\_rst}$ value. It corresponds to the probability of the event “The rolling stock emergency brake subsystem of the train does ensure a deceleration at least equal to $K_{dry\_rst}(EBCL) \times A_{brake\_emergency}$”. Confidence level values are usually between 90% (equivalent to $10^{-1}$) and 99.9999999% (equivalent to $10^{-9}$).
- $K_{wet\_rst}$ is a rolling stock parameter which represents the dispersion due to adhesion degradation. Since adhesion loss depends both on rolling stock and trackside characteristics, the margin is separated from $K_{dry\_rst}$. $K_{wet\_rst}$ corresponds to the deceleration degradation between wet and dry rail conditions as defined in the UIC leaflet 541-05. It is directly modulated by the weighting factor AVADH transmitted by trackside.
- The parameter AVADH (AVailable ADHesion) is transmitted by trackside and is used as a weighting factor for the correction factor $K_{wet\_rst}$. It is used by the Infrastructure Manager to modulate $K_{wet\_rst}$ on the basis of the trackside characteristics (for instance during autumn to handle the case of dead leaves).
Figure 2: Calculation of correction factors
4. Optimization of the safety margin with ETCS

The trackside and the rolling stock characteristics play an important role in the determination of the safe emergency brake deceleration. To take benefit from the new safety margin structure laid down in Baseline 3, the correction factors and the trackside parameters must reflect as much as possible rolling stock and trackside characteristics respectively. The next paragraphs propose methods used by the SNCF Rolling Stock Engineering Center that exploits this new leverage for the safety margin management.

4.1. The safety allocation: first step toward optimization

The confidence level used in the ETCS braking curves concerns the emergency braking performance of the train. It is only a component of the overall safety of train operation. The overall safety target is associated to the probability of the following unwanted event “the train overruns the Danger Point”. The Danger Point (DP) corresponds to the fouling point of a crossing or to beginning of an occupied block. The Supervised Location (SvL) is the point targeted by the EBD curve and is located a distance called overlap before the Danger Point. All the braking events which can lead to overrun the danger point must be considered in the safety study. The safety target is usually expressed as follows:

$$P(\text{Train overruns SVL}) \leq 10^{-x}$$

A first approach consists in allocating directly the overall safety target to the Emergency braking deceleration EBD. Mathematically it corresponds to the equation:

$$P(\text{Train overruns SVL}) \leq 10^{-x}$$

The overall safety target is respected on the Supervised Location and as a consequence on the Danger Point. This means that the whole safety of the system is affected to the emergency braking curve EBD. This is illustrated in Figure 3 where the parameter x is directly used for the EBD curve, thus selecting a relatively low level of deceleration. The Indication curve which is shifted from the EBD curve will be impacted by the selected confidence level and the train A will see it’s braking instruction (materialized by the yellow circle) relatively in advance: as a consequence the driver will apply the brakes early.

It is also possible to take into account the contribution of trackside margins, materialized by the overlap distance. The overlap distance depends on several parameters (speed of the line, traffic density, trackside configuration…) and can vary from few meters to thousand meters. If the probability $10^{-y}$ is associated to the overlap distance, then the confidence level of the EBD curve can be set to the value $10^{-x+y}$ as follows:

$$P(\text{Train overruns SVL}) \leq 10^{-x+y}$$

By selecting the confidence level EBCL = $10^{-x+y}$ for the emergency brake safe deceleration, the overall safety target is still respected, and the margin is then shared between trackside overlap and rolling stock emergency deceleration:

$$P(\text{Train overruns DP}) \leq 10^{-x}$$

Figure 4 shows the shortening of the stopping distance obtained with a steeper EBD curve. Thus the driver observes the braking instruction later and the stopping distance is shorter. The main advantage of the optimized approach is that the allocation of the safety target takes into account each existing margin, and that the performance is increased. The perturbation point is reduced by the distance:

$$d = \text{Indication}[\text{EBCL} = 10^{-x}] - \text{Indication}[\text{EBCL} = 10^{-x+y}]$$
Challenge H: For an even safer and more secure railway

Figure 3: Safety allocation - direct approach

Figure 4: Safety allocation - optimized approach
4.2. Rolling stock correction factors optimization with the Monte Carlo method

4.2.1. Origin and development of the method

The main principles of the method have been established by the UIC Workgroup B126.15C, whose objective was to define a unified algorithm to obtain the safety margins in order to facilitate interoperability. The determination of $K_{dry\_rst}$ is not straightforward since there is no analytical relation between the correction factors and the parameters of the braking architecture. Different options have been investigated and the probabilistic Monte Carlo method was found to be the most suited for the calculation of correction factors to be applied to the emergency brake deceleration. Today Railway Undertakings are still free of choosing their own method for the computation of safety margins; however the European Railway Agency (ERA) encourages the use of this probabilistic method. In the end of 2009, ERA has organized a call for tender for the provision of case studies to compute the correction factor. In the frame of this procedure, the tool developed by the SNCF Rolling Stock Engineering center was submitted and finally selected. A 4 year contract was concluded between ERA and the Rolling Stock Engineering center to deliver correction factor for Railway Undertakings who plan to equip their rolling stock with ERTMS/ETCS.

4.2.2. Description of the methodology

The methodology used to compute the correction factor is composed of following steps:

- Functional description of the braking architecture

This step is very important since the model must be generic, flexible and applicable to every braking architecture. The complexity of braking systems, the large number of components involved and the very different technologies used increase the dimensionality of the problem and the computational burden.

The formula of the correction factor $K_{dry\_rst}$ cannot be obtained directly with the functional description, that’s why the coefficient $k$ corresponding to the ratio actual deceleration $\gamma$ (i.e. including dispersions) by nominal deceleration $\gamma_0$ is first introduced in this procedure. For the functional description, a top down approach is used as illustrated on Figure 5 for a part of the TGV: the architecture is first divided into the different types of braking systems used on the train, and then each type of braking system is split into the different elementary independent braking units implemented. The contribution of each unit to the total braking effort is then expressed with the most influent physical parameters, whose variability impacts the braking performance (cylinder pressure, friction coefficient, failure rate ...).

![Figure 5: Example of functional description](image-url)
The result of this step is the equation of the ratio \( k \), as a function of the most influent physical parameters:

\[
k = \frac{\gamma}{\gamma_0} = f(x_1, x_2, ..., x_q)
\]

- Description of the variability of the physical parameters

The dispersion of the physical parameters is described with the type and the characteristics of their statistical distribution. Uniform and normal laws for the continuous variability and Bernoulli law for the partial/total loss of braking effort are the most commonly used distributions to represent dispersion. The selection of the distribution and the definition of the parameters are important tasks and are based on experimental data or on the braking expert’s knowledge. If necessary, customized distributions can also be introduced to interpolate operational data.

- Numerical simulation with the Monte Carlo Method

The purpose of the simulation is to reproduce the real dispersion of the braking performance, by feeding the mathematical model of the train with the distribution of the physical parameters, as illustrated on Figure 6. This propagation of dispersion through the model is achieved iteratively with the Monte Carlo method. This approach is particularly adapted to complex non-linear systems with a large number of variables. The steps shown on Figure 7 are repeated until the maximum number of iterations is reached:

**Figure 6 : Distribution of physical parameters and distribution of \( k \)**
The maximum number of iterations depends on the confidence level that is requested for the correction factor. The results of the individual evaluations of the model are then aggregated in order to produce the statistical distribution of parameter k. In case of several speed ranges with different deceleration values, the previous method needs to be repeated separately on each speed range.

- Determination of the correction factor K\textsubscript{dry\_rst}

The next step consists in processing the statistical distribution of k in order to extract the correction factor values K\textsubscript{dry\_rst} for each requested confidence level. From a probabilistic point of view, K\textsubscript{dry\_rst} is defined as the value, such as the probability to have a value of k greater or equal is EBCL. Mathematically, this can be expressed by following equations, with probabilities or with the cumulative distribution function F\textsubscript{k}:

\[
\begin{align*}
\left\{ \begin{array}{ll}
  & P(k \geq K_{\text{dry\_rst}}) = EBCL \\
  or \\
  & F_k(K_{\text{dry\_rst}}) = 1 - EBCL
\end{array} \right.
\]

The last equation can be used to determine graphically K\textsubscript{dry\_rst}. On the representation of the cumulative distribution function of Figure 8, the correction factor is directly the value that corresponds to the value 1-EBCL. The results are synthesized in a table, indicating the correction factor values in function of the speed range and the confidence value, according to the template of Figure 9:
### 4.2.3. Implementation of the tool

The software developed by the SNCF Rolling Stock Engineering Center integrates the numerical Monte Carlo method and was specially designed to facilitate the computation of the correction factor. Figure 10 corresponds to the welcome screen of the software and gives an overview of the different functions that are available. A flexible and graphical user interface has been created to simplify the functional description of the train and to guide the user in the definition of the different input parameters. An example of user interface is provided on Figure 11. The possibility of saving input parameters corresponding to a given train has also been added, in order to enrich a rolling stock database containing all the parameters. The core of the software is composed of the numerical algorithm and uses the parameters provided by the user as input. The program was specially written to be able to run in parallel and to increase the performance. In addition, the software has been installed on a scientific workstation with memory space specially dimensioned to manage the large amount of data and with a parallel architecture to accelerate as much as possible the iterations of the algorithm.

**Figure 8 : Graphical determination of Kdry_rst**

![Graphical determination of Kdry_rst](image)

**Figure 9 : Correction factor values versus speed range and confidence level**

<table>
<thead>
<tr>
<th>Speed Range (in km/h)</th>
<th>90</th>
<th>⋯</th>
<th>EBCL</th>
<th>⋯</th>
<th>99,999999</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0;v1]</td>
<td>ki,1</td>
<td>⋯</td>
<td>ki,2</td>
<td>⋯</td>
<td>ki,9</td>
</tr>
<tr>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>[vi;vin]</td>
<td>ki</td>
<td>⋯</td>
<td>Kdry_rst</td>
<td>⋯</td>
<td>ki</td>
</tr>
<tr>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>[vn;vmax]</td>
<td>kn,1</td>
<td>⋯</td>
<td>kn,2</td>
<td>⋯</td>
<td>kn,9</td>
</tr>
</tbody>
</table>

**Figure 10 : Correction factor values versus speed range and confidence level**

<table>
<thead>
<tr>
<th>Confidence level – EBCL (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
</tr>
<tr>
<td>⋯</td>
</tr>
<tr>
<td>⋯</td>
</tr>
<tr>
<td>⋯</td>
</tr>
</tbody>
</table>
4.2.4. Application to safety margin computation and optimization

This method has been applied to multiple existing rolling stock including regional trains and high speed trains. Different European Railway Undertakings have asked for the computation of correction factors with this method in the frame of the contract concluded with the European Railway Agency. It has the advantage of providing safety margins that correspond to the braking architecture of the train, by taking into account the contribution and the specificity of each braking unit implemented. For instance, the contribution of the electro-dynamic brakes, which were often not taken into account in the computation of the emergency braking performance because they were not considered safe enough, can now be incorporated in both the nominal emergency brake deceleration and the correction factor. This offers the possibility to obtain a higher guaranteed deceleration than the one without the contribution of the electro-dynamic brakes, even with a relatively high failure rate of the electro-dynamic brakes.
The relevancy of the model and of the quantification of physical parameters can be checked with a sensitivity analysis: the sources of dispersion are ranked and the variables that need a refinement in the distribution description step are identified. As a consequence, the procedure is not necessarily restricted to a single step but includes several loops until the convergence is guaranteed.

The method is useful also during the design phase of the rolling stock, as a prediction tool to estimate the performance of the braking architecture. It gives indications about the impact of the braking architecture on performance. It can lead for instance to equip the train with additional elements to get time intervals below critical thresholds.

To illustrate this last point, the method is applied to a general 3 cars train architecture, equipped with disc brakes on each axle and a distributor on each car. The option consisting in equipping each bogie with a distributor is investigated. The input parameters used for this simulation correspond to general architectures and are determined according to the expertise of the SNCF Rolling Stock Engineering Center. The characteristics and the performance results are described in Figure 12 and Figure 13 below. Architecture B with one distributor on each bogie allows to achieve a significant increase in performance, as proved by the computed EBI and Indication distances.

<table>
<thead>
<tr>
<th>Architecture A</th>
<th>Architecture B</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Disc brakes”</td>
<td>“Disc brakes”</td>
</tr>
<tr>
<td>“One distributor on each car”</td>
<td>“One distributor on each bogie”</td>
</tr>
<tr>
<td>Nom. Emergency Deceleration</td>
<td>1.2 m/s²</td>
</tr>
<tr>
<td>Max speed</td>
<td>160 km/h</td>
</tr>
</tbody>
</table>

![Figure 12: Characteristics of Architectures A and B](image)

<table>
<thead>
<tr>
<th></th>
<th>Architecture A</th>
<th>Architecture B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{nominal}$</td>
<td>1.2 m/s²</td>
<td>1.2 m/s²</td>
</tr>
<tr>
<td>$\gamma_{safe}(10^{-9})$</td>
<td>0.70 m/s²</td>
<td>0.86 m/s²</td>
</tr>
<tr>
<td>$\gamma_{safe}(10^{-6})$</td>
<td>0.80 m/s²</td>
<td>0.97 m/s²</td>
</tr>
<tr>
<td>EBI($10^{-9}$) at Vmax</td>
<td>1570 m</td>
<td>1310 m</td>
</tr>
<tr>
<td>EBI($10^{-6}$) at Vmax</td>
<td>1390 m</td>
<td>1180 m</td>
</tr>
<tr>
<td>IND($10^{-9}$) at Vmax</td>
<td>1970 m</td>
<td>1710 m</td>
</tr>
<tr>
<td>IND($10^{-6}$) at Vmax</td>
<td>1790 m</td>
<td>1580 m</td>
</tr>
</tbody>
</table>

![Figure 13: Results of Architectures A & B](image)
5. Conclusion

The approach presented in this document, based on the correction factor structure established by the European Railway Agency (ERA), allows to optimize the performance of the signaling system and to respect at the same time the safety target. The first step consists in the allocation of the safety target to the Emergency Brake Deceleration curve (EBD) by taking into account trackside margins. The computation of the rolling stock correction factor with the probabilistic Monte Carlo method which incorporates all the characteristics of the braking architecture is another way to optimize the system. With this method, the constant fixed margins often used for classical signaling can be replaced by a set of correction factors particular to each rolling stock architecture or trackside design. An application of the method to the design phase is also shown to pre-determine the performance of specific braking architectures. Further work has to be done in the statistical modeling, especially for innovative braking systems.

6. Bibliography


7. Authors

- Pierre MEYER (1)
- Richard CHAVAGNAT(1)
- Franck BOURGETEAU(1)

(1): SNCF, CIM/ESF - Safety Equipments and Brake Department, LE MANS - FRANCE