DEVELOPMENT OF A BRAKING MODEL
FOR SPEED SUPERVISION SYSTEMS

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Summary

The monitoring curves of a speed control system are generally implemented through a model describing the braking performances of trains in terms of initial delay and braking deceleration. The paper presents a braking model developed to be employed in a new ATP system for the Italian railways. Such model, based on the braked weight percentage, was derived from the UIC regulation so as to be applicable to all kind of trains and braking systems. Taking also into account the variability of the major parameters affecting the braking performances of trains, a probabilistic analysis is presented with the purpose of determining the proper safety margins to be applied to the basic braking model.

Abstract

To improve safety and efficiency in the management of railway traffic, a new speed control system named SCMT is currently being carried out at the Italian Railways. Other innovative speed supervision systems are being developed in Europe, such as the ETCS/ERTMS, which will be also installed on the new high speed line Roma-Napoli.

All traffic management systems are generally based on a set of supervision curves relating the permitted velocity of the train to the running distance, in order to ensure the respect of speed restrictions on the line by intervention of an emergency braking in case of train velocity exceeding the permitted one.

These supervision systems must apply to all trains: passenger and freight trains of different lengths, with various braking equipment, for all ranges of velocity. To elaborate this set of supervision curves, the on-board unit needs train deceleration depending on time and speed, as basic information about the braking behaviour of the train.

For high speed trains the knowledge of a deceleration profile is currently available, because modern UIC regulation requires the experimental assessment of this parameter. But the braking performances of conventional trains are usually expressed by the braked weight percentage, calculated through the weights and the braked weights of the vehicles which make up the train. The braked weights are usually determined on the basis of stopping distances obtained in tests, according to UIC leaflet 544-1. The braked weight percentage is therefore an effective way of
expressing the capacity of the train to stop over a certain distance, when running at a definite initial speed. However, this parameter does not provide any information about the actual deceleration characteristics, which can widely vary depending on the brake equipment.

Therefore the implementation of a speed supervision system requires the preliminary definition of braking models which allow to convert the general parameters affecting the braking performances of trains (such as braked weight percentage, goods/passenger brake position, brake equipment, train length etc.) into a basic deceleration profile as function of time, during the deceleration rise phase, and of speed, during fully developed braking.

But this basic deceleration profile is not yet sufficient to build the emergency brake intervention curve, because this one needs a guaranteed deceleration profile, which can be obtained from the basic profile using appropriate safety coefficients.

The paper presents the braking model developed for the SCMT system, based on the UIC evaluation method and applying to all trains, which enables to transform the available information concerning train and brake features into the essential input data for a speed supervision system. This model takes also into account the scattering of the deceleration due to the main factors involved in the braking, in order to obtain the required safety level of the emergency brake intervention curve.

To evaluate the safety margins, a complete analysis of parameters affecting the braking performance was carried out. For the major parameters, the probability distribution was determined on the basis of technical knowledge and experimental results, in order to establish the combined probability distribution for different types of trains, thus enabling the assessment of the safety degree as function of a reduction factor applied to the basic deceleration.

Keywords
Braking model; speed supervision system; braked weight percentage; safety margins; probabilistic analysis.

1. DEVELOPMENT OF THE BRAKING MODEL

1.1 Introduction

For all the conventional rolling stock and for speed until 200 km/h the basic parameter currently used for national and international traffic in order to determine the braking performance of a train is the braked weight percentage as defined by the UIC regulation. For this reason the braking model developed for SCMT is based on this regulation.

Nevertheless, the information about the deceleration during a fully developed braking cannot be directly derived from the UIC braked weight percentage.

The braked weight of vehicles is usually pre-determined by calculations and verified by tests in line carried out either on a single vehicle or on a train-set, using the evaluation diagrams of the UIC leaflet 544-1. Such diagrams establish a relationship, for different initial speeds, between the braked weight percentage and the average stopping distance obtained in emergency braking on level track, with a train having a nominal length and a braking equipment in normal operating conditions. Incidentally it is also important to consider the tolerance of the friction coefficient of the braking components. Therefore, the braked weight percentage only gives information about the average performance of the train in emergency braking and it does not include any safety margin.

This fundamental consideration has to be taken into account for the definition of a braking model applicable to speed control systems. In addition, a braking model that is developed for this purpose has to be applicable both to stop braking and to speed reduction braking.
1.2 Definition of the braking model for SCMT

In general a braking model can be represented as follows (fig. 1):

- an initial delay,
- a linear or step transient,
- a series of constant deceleration steps within established speed ranges.

![General braking model](image1)

As a particular case of that general representation, a braking model with a step transient and one level of deceleration was defined for SCMT (fig. 2), for the speed range until 220 km/h.

![Basic braking model for SCMT](image2)

The basic parameters of this model are the following:

- $t_e$ braking equivalent time,
- $d$ deceleration of fully developed braking.

The step transient variant, even if less accurate than the linear transient variant, is widely and effectively used for braking models because it allows simpler calculations.

For reasons of simplicity this representation refers to the situation on level track. The complete model must obviously take into account the effect of the gradient on the deceleration.

As a consequence of the different brake systems used on the vehicles (disc brake; cast iron block brake with one pressure level; cast iron block brake with two pressure levels etc.), also considering
the possibility of mixed train-sets, the typical curves of the instantaneous deceleration may be different for the same braked weight percentage, as shown in figure 3.

![Figure 3 – Instantaneous deceleration of various types of brakes](image)

Possible evolutions in braking systems must be considered, such as the replacement of cast iron brake blocks with composite brake blocks on freight wagons for noise reduction.

A braking model that will be used for a speed control system must also be applicable in intermediate ranges of speed. For that reason the constant deceleration profile chosen for SCMT has to prevent that real deceleration profiles are overestimated in significant speed areas.

The equivalent time depends on the goods/passenger brake position and on the length of the train. The deceleration depends on the type of brake equipment (disc brake, block brake etc.) and on the brake force. For this parameter it is necessary to determine a relation with the braked weight percentage.

### 1.3 Braking equivalent time

The braking equivalent time $t_e$ is obtained by adding the absolute delay and a half of the deceleration build up time.

The absolute delay represents the delay with which the deceleration due to pneumatic braking appears, from the moment in which the braking is activated. The time necessary in emergency braking to reach the maximum deceleration due to the pneumatic brake has been obtained from diagrams of the ERRI report B126 RP25, providing the braking time at the end of the train depending on the train length.

The following formulas adopted for the present braking model give the braking equivalent time as function of the train length $L$ (m), in emergency braking:

<table>
<thead>
<tr>
<th>Position</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>$t_e = 3.5 + 0.15 \times (L / 100)^2$</td>
</tr>
<tr>
<td>Goods</td>
<td>$t_e = 13.5 + 0.04 \times (L / 100)^2$</td>
</tr>
</tbody>
</table>

Over a certain train length the equivalent time calculated by means of the passenger position formula exceeds the value calculated by means of the goods position formula: in this case even for the goods position the first formula is to be used.

The diagrams relating to these formulas are shown in fig. 4.
1.4 Relation between the braked weight percentage and the deceleration during fully developed braking

1.4.1 General considerations

The purpose of the procedure described in this section is to establish a relation between the braked weight percentage and the deceleration during fully developed braking, based on the UIC evaluation method (UIC leaflet 544-1) and applicable to all kind of trains and braking systems.

Therefore such relation does not supply an average deceleration value linked to a certain braked weight percentage, but the minimum common value among those potentially linked to the same braked weight percentage, for different braking systems and different initial speeds.

The main criteria on which the evaluation curves of the UIC leaflet 544-1 are based were taken into account:

− the evaluation curve for 100 km/h is especially applicable to freight trains with braking in passenger position;
− the evaluation curves for speed between 120 and 160 km/h are based on the braking performance of trains with cast iron block brake, but they have general application for all passenger trains;
− the evaluation curves for 180 and 200 km/h are specifically applicable to passenger trains with disc brake.

The knowledge of such characteristics prevents from following the UIC increasing deceleration at speed lower than 120 km/h for trains with disc brake or composite block brake, to avoid an overestimation of their braking performances.

1.4.2 Deceleration related to the UIC brake weight percentage

The general formula of the UIC evaluation curves is the following:
where $S$ is the stopping distance, $\lambda$ the braked weight percentage, $C$ and $D$ the coefficients depending on the initial speed.

For practical reasons in this procedure such formula was expressed in the following way:

$$S = \frac{C'}{\lambda + D}$$

(3)

where $V$ is the initial speed of braking and $C'$ a new coefficient having a trend that is easier to interpolate for initial speeds different from the nominal ones.

The corresponding deceleration values during steady braking were calculated by the formula:

$$d = \frac{\left(\frac{V}{3.6}\right)^2}{2\left(S - t_e \frac{V}{3.6}\right)}$$

(4)

where the total stopping distance $S$, given by the basic UIC formula, is reduced by the distance covered during the braking equivalent time $t_e$. An example of the results obtained from the evaluation curves of the UIC leaflet 544-1 and of the ERRI report B 126 RP 17 is shown in fig. 5.

Considering the basic criteria established for this procedure, the minimum value of equivalent time related to a train of nominal length is to be used for the calculation. In this way, a shorter distance being covered during the equivalent time and a longer distance being covered during constant braking, the calculation produces a deceleration value that is minimum within the possible range.
1.4.3 Basic relation between deceleration and braked weight percentage

Since different deceleration values depending on the initial speed of braking correspond to the same UIC braked weight percentage, it is important to choose the most suitable nominal condition for which the two parameters must be related to each other.

Among all the possible solutions, the following two were taken into particular consideration:

- the evaluation speed of 120 km/h, according to the latest UIC directives that are valid in particular for disc brakes;
- the stopping distance of 1000 m, according to the current UIC regulation.

In case of high braking performances the first solution has the disadvantage of producing higher deceleration values on shorter braking distance; passenger trains equipped with cast iron block brake are not able to produce such decelerations in the speed range between 120 and 160 km/h.

The second solution has the following advantages:

- it corresponds to the UIC directive officially applicable until now, according to which most of the vehicles that are in service have been evaluated;
- it is generally applicable to different braking systems such as disc brakes and block brakes;
- it allows to determine a relationship between deceleration and braked weight percentage valid for initial speeds increasing in a coherent way with the braking performances.

Due to these significant advantages the second solution has been adopted for the following procedure. This procedure consists of four steps:

- evaluation of the braked weight percentage values producing a stopping distance of 1000 m for initial speeds between 100 and 160 km/h, through the UIC formula and diagrams;
- calculation of the constant values of maximum deceleration from the above mentioned initial speeds, using the minimum braking equivalent time, as explained in the previous paragraph; these deceleration values are associated to the previously determined braked weight percentages,
- determination of the linear regression representing the deceleration as function of the braked weight percentage;
- development of a further study to calculate the reduction of such basic deceleration above a speed threshold for the constant value.

As concerns the braking equivalent time two different hypotheses have been made:

- \( t_e = 3.5 \text{ s} \), as minimum absolute value;
- \( t_e = 4.35 \text{ s} \), as minimum value for a train having a nominal length of 300 m.

The linear relations which link the deceleration to the braked weight percentage in these two hypotheses are:

\[
\begin{align*}
\text{I hyp.} & \quad d_b = 0.00647 \lambda + 0.103 \\
\text{II hyp.} & \quad d_b = 0.00685 \lambda + 0.094
\end{align*}
\]  

(5.1) (5.2)

that are characterized by a good correlation coefficient.

The couples of values "initial speed - braked weight percentage" for which these relations have been determined are shown in table 1 (approximate values).
Table 1 – Relation between the nominal speed and the braked weight percentage

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>50</th>
<th>65</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>165</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in}$</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>140</td>
<td>150</td>
<td>160</td>
<td>km/h</td>
</tr>
</tbody>
</table>

The diagrams of the linear regressions (5.1) and (5.2) are shown in fig. 6 and 7.

Figure 6 – Linear regression for $t_e = 3.5$ s

Figure 7 – Linear regression for $t_e = 4.35$ s
1.4.4  Deceleration as function of the initial speed of braking

To take into account the behaviour of disc brake and composite block brake, in this braking model the basic deceleration determined by the procedure indicated above is applied as a constant value from initial speeds lower than the speed threshold.

For initial speeds higher than the speed threshold it is necessary to apply a gradual reduction of the deceleration during fully developed braking; this reduction can be assumed as linear with a good approximation, in coherence with the UIC evaluation curves.

Even in case of a braking carried out from a speed higher than the threshold, the new value of deceleration is considered as constant over instantaneous speed.

This characteristic behaviour is shown in fig. 8.

\[
\text{Figure 8 – Deceleration for initial speed higher than the speed threshold}
\]

The relations between the deceleration and the braked weight percentage for initial braking speeds exceeding the speed threshold, in the two previous hypotheses, become respectively:

\[
\begin{align*}
\text{I hyp.} & \quad d = (0.00647 \lambda + 0.103) \times (1 - 0.0021(V - V_{\text{thr}})) \\
\text{II hyp.} & \quad d = (0.00685 \lambda + 0.094) \times (1 - 0.0021(V - V_{\text{thr}})) \\
\end{align*}
\]

where such speed threshold is obtained from the formula:

\[
V_{\text{thr}} = 16.17 \lambda^{0.443}
\]

Compared to the decelerations calculated from the UIC / ERRI evaluation curves, the formulas of this braking model present the tendency shown in fig. 9.
As an alternative to the constant deceleration model, the possibility has been considered of replacing the constant deceleration during the fully developed braking with an instantaneous deceleration profile decreasing in a linear way. The total decrease should be equal to a fixed percentage (e.g. 10%) of the deceleration value calculated by the basic formula, being equivalent to this one from the point of view of the total braking distance (example in fig. 10). This behaviour can be more appropriate in case of a speed reduction, for braking systems having a lower performance in a higher speed range.

1.5 Remarks

With the basic deceleration and the braking equivalent time determined by the procedure described above the basic braking model is achieved. Moreover, in order to reduce the possibility of interference in the normal behaviour of the driver, a dynamic reduction of the braking transient was included in the complete model for SCMT, taking into account the deceleration already developed by the safe brakes of the train.
However the basic deceleration values do not include any estimation about the necessary safety margins, so they cannot be directly used to calculate the braking curves of a speed control system. The assessment of such safety margins, to be carried out on the basis of an appropriate probabilistic analysis, is the subject of the next section.

2. PROBABILISTIC ANALYSIS APPLIED TO THE BRAKING MODEL

2.1 Braking model
The braking model used in this analysis is the basic model described in section 1.2 and represented in fig. 11:

- $t_0$ represents the initial delay time;
- $t_d$ is the time necessary to obtain the maximum deceleration;
- $d_0$ is the nominal deceleration value;
- $d'$ is the deceleration value obtained applying a safety coefficient.

In this analysis, $t_0$ and $t_d$ variability is neglected and the dispersion of the braking performance is exclusively related to the variability of deceleration, that is considered the fundamental parameter and is consequently reduced using a proper safety coefficient.

In this paper the analysis was carried out using information relative to a passenger train equipped with disc brake. Similar considerations can be made for different types of trains (e.g. freight trains equipped with cast iron or composite block brakes).

2.2 Model used to calculate the deceleration
During a braking, the train deceleration can be approximately calculated applying the first dynamic equation to the train (projected on the horizontal direction of motion) and the second dynamic equation to each axle. From these equations the following expression can be obtained:
\[
d = \frac{\sum_{i=1}^{n} F_{bi} \frac{r}{R} + R_m}{M + \sum_{i=1}^{n} \left( \frac{J_i}{R^2} \right)} \tag{8}
\]

where:
- \( d \) is the train deceleration;
- \( F_{bi} \) is the braking force applied on the i-th axle;
- \( n \) is the number of axles;
- \( r \) is the distance between the rotation axes and the point where the braking force is applied;
- \( R \) is the wheel radius;
- \( R_m \) is the motion resistance (aerodynamics and internal resistance);
- \( M \) is the mass of the train;
- \( J_i \) is the moment of inertia of the i-th axles.

The braking force applied to each axle is given by:
\[
F_{bi} = (p_i S_i - F_{mi}) \tau \eta \mu \rho \tag{9}
\]

where:
- \( p_i \) is the pressure in the brake cylinder;
- \( S_i \) is the cylinder surface;
- \( F_{mi} \) is the brake cylinder spring force;
- \( \tau \) is the brake rig ratio;
- \( \eta \) is the brake efficiency;
- \( \mu \) is the brake friction coefficient;
- \( \rho \) is wheel-rail adhesion coefficient.

Neglecting the following terms:
- \( R_m \);
- \( F_{mi} \);
- \( \sum_{i=1}^{n} \left( \frac{J_i}{R^2} \right) \);

the deceleration can be expressed using the following simplified expression:
\[
d = \frac{p S \tau \eta \mu \rho \frac{r}{R}}{M} \tag{10}
\]

In this study, besides the surface \( S \) and the ratio \( \tau \), also the ratio \( \frac{r}{R} \) was considered constant, while the variability of pressure \( p \), efficiency \( \eta \), friction coefficient \( \mu \), mass \( M \) and adhesion coefficient \( \rho \) were taken into account.

When each parameter assumes its nominal value \( p_0 \), \( \eta_0 \), \( \mu_0 \), \( \rho_0 \), \( M_0 \), the deceleration is given by:
\[
d_0 = \frac{p_0 S \tau \eta_0 \mu_0 \rho_0 r}{M_0}.
\]

To guarantee the required safety level of the system, the deceleration value to be used in the braking model for the calculation of the monitoring curves is given by:

\[
d' = k \ d_0
\]

where \( k \) is a safety coefficient (\( k < 1 \)).

The objective of this analysis is the evaluation of the probability that the real deceleration \( d \) is smaller than \( d' \), i.e. the ratio \( \frac{d}{d_0} \) is smaller than a given \( k \).

The ratio between real and nominal deceleration can be expressed as:

\[
\frac{d}{d_0} = \frac{p \ \eta \ \mu \ \rho}{p_0 \ \eta_0 \ \mu_0 \ \rho_0} \frac{M}{M_0}
\]

The probability distribution of the ratio can be calculated as a combination of the probability of each parameter.

### 2.3 Probability distribution of the parameters

A probability density function was supposed for each of the ratios in the preceding formula. For the major parameters, the probability distribution was determined on the basis of technical knowledge. The probability density of the ratios \( \frac{p}{p_0} \) and \( \frac{\eta}{\eta_0} \) is not known exactly, only the extremes of the dispersion fields are known with good approximation. In these cases, normal probability distributions were supposed, with mean \( m=1 \) and extremes given by the mean value \( \pm 3\sigma \), in particular \( \pm 5\% \) both for pressure and efficiency.

The ratio \( \frac{\mu}{\mu_0} \) can be expressed as:

\[
\frac{\mu}{\mu_0} = \frac{\mu}{\mu_{\text{med}}} = \frac{\mu_{\text{med}}}{\mu_0}
\]

where \( \mu \), \( \mu_{\text{med}} \) and \( \mu_0 \) represent respectively the real, mean (for a given friction material) and nominal value of the friction coefficient.

The probability distribution of the ratio \( \frac{\mu}{\mu_{\text{med}}} \) was defined using a wide set of experimental data: from the experimental results, a probability distribution was evaluated, then the experimental distribution was approximated by a normal distribution. The mean and the variance of the normal distribution were tuned to minimize the difference between the experimental and the approximated cumulative curve (fig. 12).
For the ratios $\frac{\mu_{med}}{\mu_0}$ and $\frac{M}{M_0}$ only the extremes of the variability fields were known with good approximation. Also in this case normal probability distributions were supposed, with mean $m = 1$ and extremes given by the mean value $\pm 3\sigma$, in particular $\pm 15\%$ for $\frac{\mu_{med}}{\mu_0}$ and $\pm 8\%$ for $\frac{M}{M_0}$.

To take into account the ratio $\frac{\rho}{\rho_0}$, two cases were separately analyzed. The first one is relative to “normal” adhesion condition; in this case the ratio $\frac{\rho}{\rho_0}$ is equal to 1 and its variability was not taken into account. The second case is relative to “degraded” adhesion condition; in this case the ratio $\frac{\rho}{\rho_0}$ was supposed to belong to a normal distribution with mean $m = 0.95$ and $3\sigma = 0.05$. The two cases were combined together, supposing that in the 95% of the cases the adhesion conditions are “normal”, while in the remaining 5% are “degraded”.

2.4 Distribution of the ratio between the real and the nominal deceleration

The distributions of the parameters were then combined to find the distribution of the ratio $\frac{d}{d_0}$. Since the terms $\sigma$ of each distribution were “small”, the calculation was quite simplified. The fraction between the real and the nominal deceleration can be expressed as the ratio between two terms: the numerator of the fraction represents the ratio between the real and the nominal braking force:

$$\frac{F_b}{F_{b0}} = \frac{p}{p_0} \frac{\eta}{\eta_0} \frac{\mu}{\mu_0} \frac{\rho}{\rho_0}$$

while the denominator is the ratio between the real and the nominal mass: $\frac{M}{M_0}$. 

Fig. 12 – Distribution of the ratio $\frac{\mu}{\mu_{med}}$, a) distribution obtained from experimental data, b) comparison between the experimental and the approximated normal distribution.
The numerator is the product of four random variables; each of them is characterized by a normal probability distribution, with given mean and variance values.

Given a series of random variables \((x_1, x_2, \ldots, x_n)\), belonging to normal distributions with mean \(m_1, m_2, \ldots, m_n\) and variance \(\sigma_1^2, \sigma_2^2, \ldots, \sigma_n^2\), the distribution of their product can be approximated with a normal distribution whose mean is the product of the means of each parameter and whose variance is given by:

\[
\sigma^2 = \sum_{i=1}^{4} \left[ \prod_{j=1, j\neq i}^{4} \frac{1}{m_j} \sigma_j^2 \right].
\]  

(16)

The distribution of the ratio between the braking force and the mass can be evaluated using the Taylor series expansion arrested at the first order term. In particular, given two random variables \(x_{num}\) and \(x_{den}\), which belong to two normal distributions \(N(m_{num}, \sigma_{num}^2)\) and \(N(m_{den}, \sigma_{den}^2)\), the distribution of the ratio \(\frac{x_{num}}{x_{den}}\) can be approximated with a normal distribution characterized by mean

\[
m = \frac{m_{num}}{m_{den}}
\]  

(17)

and variance:

\[
\sigma^2 = \left\{ \frac{1}{m_{den}^2} \sigma_{num}^2 + \left( \frac{m_{num}}{m_{den}} \right)^2 \sigma_{den}^2 \right\}.
\]  

(18)

The distribution of the numerator depends also on the number of vehicles in the train: in particular, if \(n\) is the number of vehicles and \(m_1\) and \(\sigma_1\) are the parameters relative to the distribution of the ratio \(\frac{F_b}{F_{b0}}\), evaluated considering only one vehicle, the resulting distribution has mean \(m_n = m_1\) and variance

\[
\sigma_n^2 = \frac{\sigma_1^2}{n}.
\]  

(19)

It was supposed moreover that the distribution of the denominator \(\frac{M}{M_0}\) is not influenced by the number of vehicles.

2.5 Results

In table 2 cumulative probability distribution values corresponding to various safety coefficients and various numbers of vehicles are shown. The results are a combination between the distribution obtained neglecting the variability of the wheel-rail adhesion coefficient and the one obtained taking into account the variability of adhesion.

In fig. 13 the distribution of the ratio \(\frac{d}{d_{b0}}\) obtained neglecting the variance of the adhesion coefficient is shown, while in fig. 14 the results are obtained considering the distribution of the parameter \(\frac{\rho}{\rho_0}\).
In fig. 15 the effect of the number of vehicles on the distribution of the parameter $\frac{d}{d_0}$ is shown.

Table 2 - Cumulative distribution values for various safety coefficients and various numbers of vehicles.

<table>
<thead>
<tr>
<th>$k$</th>
<th>1 vehicle</th>
<th>2 vehicles</th>
<th>4 vehicles</th>
<th>8 vehicles</th>
<th>16 vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>2.05E-09</td>
<td>6.26E-15</td>
<td>2.83E-22</td>
<td>3.23E-30</td>
<td>4.58E-37</td>
</tr>
<tr>
<td>0.65</td>
<td>1.28E-07</td>
<td>7.04E-12</td>
<td>1.53E-17</td>
<td>1.18E-23</td>
<td>6.32E-29</td>
</tr>
<tr>
<td>0.7</td>
<td>8.36E-06</td>
<td>8.28E-09</td>
<td>8.71E-13</td>
<td>4.48E-17</td>
<td>9.14E-21</td>
</tr>
<tr>
<td>0.75</td>
<td>1.73E-04</td>
<td>1.36E-06</td>
<td>2.28E-09</td>
<td>2.38E-12</td>
<td>6.51E-15</td>
</tr>
<tr>
<td>0.8</td>
<td>2.18E-03</td>
<td>9.30E-05</td>
<td>1.50E-06</td>
<td>1.82E-08</td>
<td>4.15E-10</td>
</tr>
<tr>
<td>0.85</td>
<td>1.69E-02</td>
<td>2.69E-03</td>
<td>2.52E-04</td>
<td>2.05E-05</td>
<td>2.41E-06</td>
</tr>
<tr>
<td>0.9</td>
<td>1.01E-01</td>
<td>4.73E-02</td>
<td>1.84E-02</td>
<td>6.89E-03</td>
<td>3.02E-03</td>
</tr>
<tr>
<td>0.95</td>
<td>2.92E-01</td>
<td>2.36E-01</td>
<td>1.85E-01</td>
<td>1.45E-01</td>
<td>1.19E-01</td>
</tr>
</tbody>
</table>

Figure 13 – Distribution of the ratio $\frac{d}{d_0}$ obtained without the parameter $\rho$,

a) probability density function, b) cumulative distribution function.

Figure 14 – Distribution of the ratio $\frac{d}{d_0}$ obtained considering the distribution of the parameter $\rho$,

a) probability density function, b) cumulative distribution function.
Besides the probability analysis relative to the passenger train equipped with disc brakes, other probability analysis were undertaken for freight trains equipped with cast iron block brakes or with composite block brakes, in empty and in loaded conditions.

### 3 CONCLUSIONS

The development of the new speed control system SCMT for the Italian railways required the implementation of a braking model that was able to describe with sufficient precision and proper safety margins the braking performances of passenger and freight trains. With this purpose a braking model having a general validity has been derived from the UIC evaluation method; such model allows to convert the general input parameters (braked weight percentage, goods/passenger brake position, train length etc.) into a basic deceleration profile as function of time and speed.

In addition a complete analysis of parameters affecting the braking performance was carried out. For the major parameters, the probability distribution was determined on the basis of technical knowledge and experimental results, in order to establish the combined probability distribution, thus enabling the assessment of the safety degree as function of a reduction factor applied to the basic deceleration.

Following the same procedure, further analysis could be undertaken in order to choose the proper safety factors on the basis of a complete evaluation of the risks, also taking into account external factors.

### BIBLIOGRAPHY


