CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013
Guest Editors: Enrico Zio, Piero Baraldi
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ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333126

Prognostic and Simulation Tools for the Preliminary Design and Verifications of Braking Performance of Railway Vehicles

Monica Malvezzi[a], Susanna Papini[b], Luca Pugi*[b], Gregorio Vettori[b], Simone Tesi[c], Andrea Rindi[b], Enrico Meli[b]

[a] University of Siena, Dept. of Information Engineering, Via Roma 26 53100 Siena, Italy
[b] University of Florence, Dept. of Industrial Engineering, Via Santa Marta 3, 50139 Firenze Italy
[c] Ansaldo Breda SPA, Via Ciliegiole 110, 51100 Pistoia, Italy
luca.pugi@unifi.it

Modern railway braking plants are complex mechatronics systems that have to be optimized in the design phase and monitored for all the their remaining life, in order to ensure required levels of safety and integrity. In this work, after some more general considerations, the attention is concentrated on a procedure of validation of a tool aimed to the prediction of train braking performances.

1. Introduction

Reliability of train braking performance is an important issue for railway systems affecting many aspects of interoperability and safety, including the design of signaling and traffic management systems.

The regulations concerning the design of braking components, and, more generally, the interoperability, such as the European TSI (Technical Specifications for Interoperability), prescribe an accurate analysis and verification of braking systems performances, considering some degraded and critical modes and worst operating conditions, whose statistical occurrence should be quantified.

Taking into account the high level of safety required in this type of application and its important impact on both construction and maintenance costs, this system has to be optimized. This work is part of a time-extended cooperation between AnsaldoBreda group with University of Florence and Siena, about the development of an integrated approach providing the harmonized use of different engineering tools, embracing complementary aspects of the problem:

1. *Macroscopic occurrence of braking performance and failures*: assigning a statistical occurrence to each failure source, an extended population of possible configurations (several millions) ican be generated, to give a macroscopic reliability evaluation of the system performance. Due to the complexity of these models the computation resources has to be optimized. An example of this kind of analysis performed by the authors is also available in literature (Malvezzi et al., 2012).
2. *Train braking performances simulation*: this intermediate level model of the whole braking plant is used to simulate train braking performances and identify some plant parameters from a limited population of inline experimental tests. The provided information about statistical occurrence of braking degradations can be used to tune the aforementioned statistical-macroscopic model.
3. *Detailed plant models:* brake plant components can be simulated with specific models, in order to describe in details the effects of each single failure. In the literature it is possible to find some works on this kind of analysis for pneumatic plants and components. In (Pugi et al., 2004) a general approach to the simulation of the pneumatic brake plants is described, while more recent works such as, (Piechowiaka, 2009) and (Cantone, 2011) are more focused on the simulation of the whole system including interactions with train longitudinal dynamics. Also some works about the testing of complex

Please cite this article as: Malvezzi M., Papini S., Pugi L., Vettori G., Tesi S., Rindi A., Meli E., 2013, Prognostic and simulation tools for the preliminary design and verifications of braking performance of railway vehicles, Chemical Engineering Transactions, 33, 751-756
DOI: 10.3303/CET1333126

brake system such as WSP (Pugi et al., 2006) or elementary components such as brake pads (Pugi and Allotta*,* 2012) are available in literature.

In this work a benchmark case study concerning the simulation of train braking performances of AnsaldoBreda EMU V250 is presented. It highlights that an accurate identification of the braking pad friction factor is fundamental for the right prediction of braking performances.
The availability of tools as those described in this paper are useful in prognostics and condition monitoring, since they allow to predict the dynamical behavior of the whole braking system by combining the models of its components. The tool can be adopted, for instance, to analyze how system performance, also in terms of integrity or safety, are affected by the failure of one or more of its components.

2. The TTBS01 braking performance simulator tool

(EN 14531, 2009) provides indications about the preliminary calculation of the braking performances, providing a general workflow adaptable to different vehicle categories such as: freight wagons, mass transit, passenger coaches, locomotors and high speed trains. The authors have developed a Matlab™ tool, called 'TTBS01', which implements the calculation method of braking performances, whose structure and functioning is stated by the (EN 14531, 2009) regulation in forces

3. Ansaldo Breda EMU V250 the proposed benchmark

'TTBS01' tool has been validated and tested on the AnsaldoBreda EMU V250, an High Speed Electrical Multiple Unit for the passenger transport with a maximum operating velocity 250 km/h (maximum test speed 275 km/h), composed of 2 train sets of 8 coaches. Traction is distributed according to alternating motor and trailer vehicles in the MTMTTMTM composition (M stands for motorized coach, T for trailer one), the resulting composition is shown in Figure 2. The motorized coach (wheelset B_0-B_0) traction motors can be used for electro-dynamic braking (both regenerative and dissipative). The 2nd and the 7th coaches are equipped with an electro-magnetic track brake to be used in emergency conditions. The mandatory pneumatic braking system is implemented with the support of both direct and indirect electro-pneumatic operating modes: the braking command can be directly transmitted by wire to the BCU (Braking Control Unit) on each coach, or indirectly, by controlling the pressure of the pneumatic pipe. Braking forces are automatically adjusted using a pneumatic load sensing pressure relay. Finally a backup mode where the brake plant is controlled as a standard pneumatic brake, ensures interoperability with vehicles equipped with a standard UIC Brake. Each axle is equipped with three brake discs for trailing axles and two for the motorized ones, where the electric braking is available, too. Also in this configuration the magnetic track brake (as in Figure 2/c) should be available, since the track lowering is controlled by a pressure switch, commanded using the brake pipe (threshold at 3bar Absolute). The feasible coupled configuration, where two standard compositions of eight coaches are joined together, has to be tested and simulated.

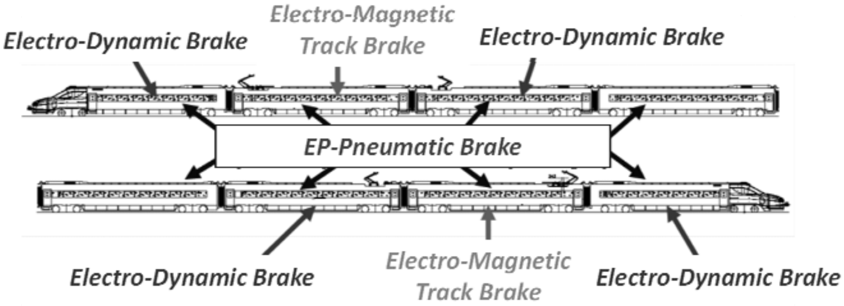


Figure 2: EMU V250 brief description of the braking system

4. Population of test results

In order to validate the tool, the results of the experimental activities performed on EMU V250, on the line between Rotterdam and the Belgium border, were kindly supplied by AnsaldoBreda.
In particular the test train was instrumented with the sensor layout described in Table 1. About 50 braking test runs, where the following testing conditions were parametrically varied, have been performed:

1. launching speed: ranging from 100 to 275 km/h, including different motion sense of the train;
2. loading conditions: ranging from VOM to CE load, as defined by TSI regulations (TSI, 2002);

3. different degradation levels of braking plant: direct electro-pneumatic braking, indirect electro-pneumatic braking, standard UIC brake plant, as defined by the Fiche (UIC 540, 2006);
4. different kind of braking manoeuvres: service, emergency considering different level of availability of the magnetic track brake, as defined by (TSI, 2002), regulation in forces (EN 2009,2010) (UIC, 2006, 2009).

Table 1: Sensor layout for experimental test runs on EMU V250 from test specifications (AnsaldoBreda, 2010a) and report (AnsaldoBreda, 2010b)

Sensor	Aim	Accuracy	Range	Quantity/Layout
Pressure Transducer	indirect measurement of brake cylinder clamping forces	0.5% w.r.t. full range	0-12 bar	8 pressure transducer/ on brake plant
Radar Doppler Sensor	direct speed and travelled distance estimation	±1 km/h	0-500 km/h	1/fixed over a coach frame
Servo-Accelerometer	train acceleration measurements	0.1% w.r.t. full range	1 g	1/on a coach carbody
Thermocouples	monitoring of disc temperatures	K type termocouples with precision according to UIC regulations		4/on monitored discs

5. Validation of TTBS01 Tool: Acceptance Criteria

In order to verify and validate the TTBS01 simulation tool, the relative error e_s, between the simulated stopping distance (s_{simul}) and the experimental one (s_{test}), as defined according to (1), and the corresponding speed and acceleration profiles have been evaluated.

$$e_s = \frac{s_{test} - s_{simul}}{s_{simul}} \tag{1}$$

According to (ERRI, 2004) and (UIC, 2006) the repeatability of braking performances in terms of mean deceleration can be considered, as in Table 2: the relative error on stopping-braking distance s, for an assigned launching speed v_0, is approximately proportional to the deceleration a, as stated by (2).

$$s = \frac{v_0^2}{2a};\Rightarrow \frac{\partial s}{\partial a} = -\frac{v_0^2}{2a^2} \Rightarrow \frac{\partial s}{s} = -\frac{\partial a}{a} \tag{2}$$

Table 2: Statistic distribution of degraded braking performances according to to (ERRI, 2004) and (UIC, 2006) referred to an homogenous population of braking tests

Probability	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
(n. of test)	(10^{1})	(10^{2})	(10^{3})	(10^{4})	(10^{5})
Mean dec.	0.969	0.945	0.926	0.905	0.849
Nominal dec.	(-3.1%)	(-5.5%)	(-7.4%)	(-9.5%)	(-15.1%)

Considering a test population of 50 test runs, a 4% error between simulation and test results can be considered acceptable. The campaign on EMU V250 was referred to a population in which every test was performed with different boundaries and operating variables, so an higher variability of results, compared to expected simulation ones, should be considered. Also some further consideration have been done considering longitudinal train oscillations.

During the tests a 1-2 Hz longitudinal mode was observed by both speed and acceleration sensors, in accordance with the results of a previous modal analysis (Pugi and Conti, 2009). The phenomenon is clearly recognizable on acceleration profiles in Figure 3, and causes a 1-2 km/h variability of the measured speed compared to the mean value (1-1.5 % compared to launching speed); the sensitivity of the braking distance to the correct evaluation of the launching speed, as in (3), produces an additional 2-3% uncertainty on the estimated braking distance..

$$s=\frac{v_0^2}{2a};\Rightarrow\frac{\partial s}{\partial v_0}=\frac{v_0}{a}\Rightarrow\frac{\partial s}{s}=\frac{2\partial v_0}{v_0} \tag{3}$$

As a consequence, the authors finally considered a level of acceptability for the results equal to 5-6%.

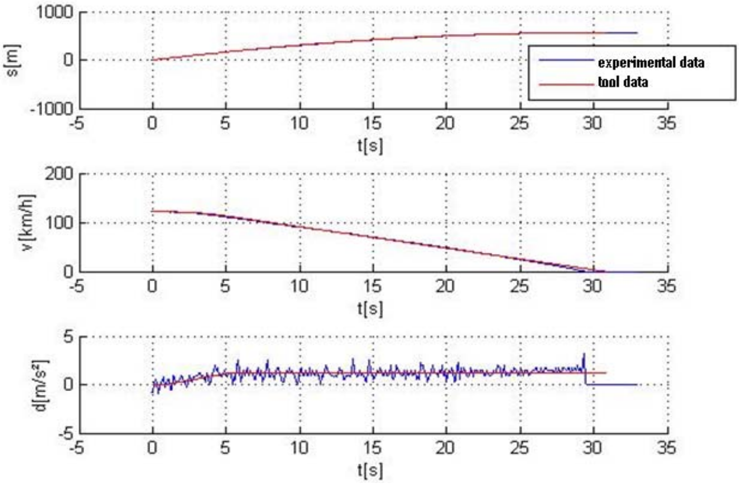


Figure 3: space, speed and deceleration profiles measured and calculated during a braking maneuver

6. Identification of brake pads friction factor and preliminary validation of the tool

Applying on experimental data the TTBS01 procedure with the calculation prescribed by EN14531, leaded to unsatisfactory results in terms of statistical distribution of e_s, as in Figure 4/a: only 60% of the simulated test runs satisfied the requirements, even considering a 5.5 % admissible value for e_s. The real behavior of brake pad friction factor is clearly dependent from three parameters: the speed, the dissipated energy (which mainly depends from clamping forces and starting speed) and the clamping forces to which is subjected the pad. As a consequences, the authors, providing data from the friction builder data and using a narrower population of tests on the train (four braking tests over a population of 50) have identified a feasible behavior of the pad friction factor (Figure 4.b), as a function of the traveling speed v and the loading condition of the train: in fact the clamping forces of the brakes are self-regulated according to the vehicle weight and the traveling speed, once fixed the mean values of the clamping forces with respect to the dissipated power. Implementing the proposed brake pad behavior the software TTBS01, the obtained results, visiblie in figure 5 satisfied the requirements for the software validation, considering a 5.5 % acceptable value of e_s (exactly 5.35%). It is worth to point out that, after the modifications, the number of elements under the threshold of 2%-3% and 4% is more than doubled .

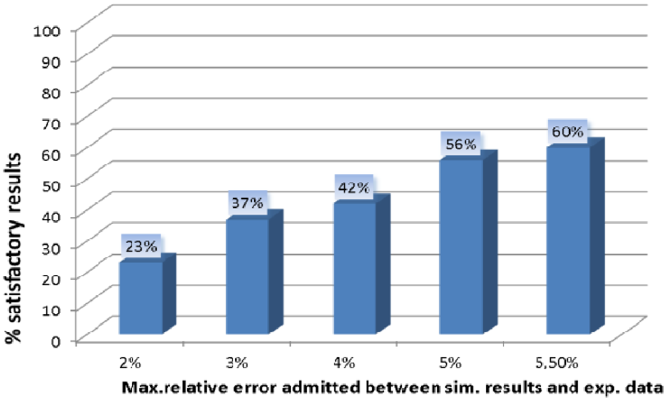


Figure 4/a: number of satisfactory sim. results considering as a function of the admissible value of e_s (constant brake pad friction faction).

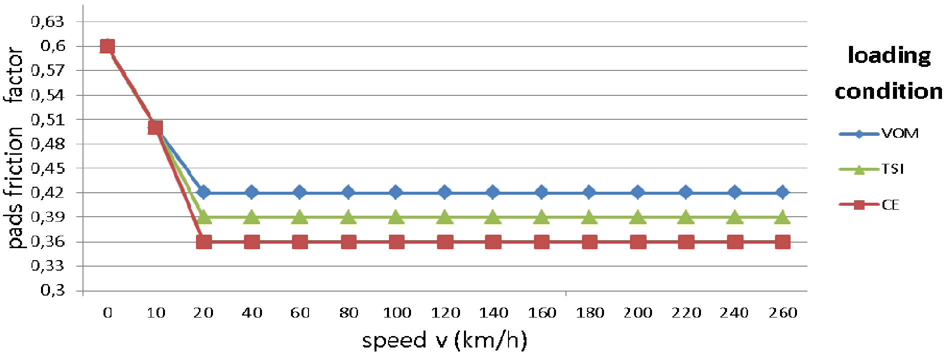


Figure 4/b: variable braking pad friction factor implemented on TTBS01 for the validation on EMU V250.

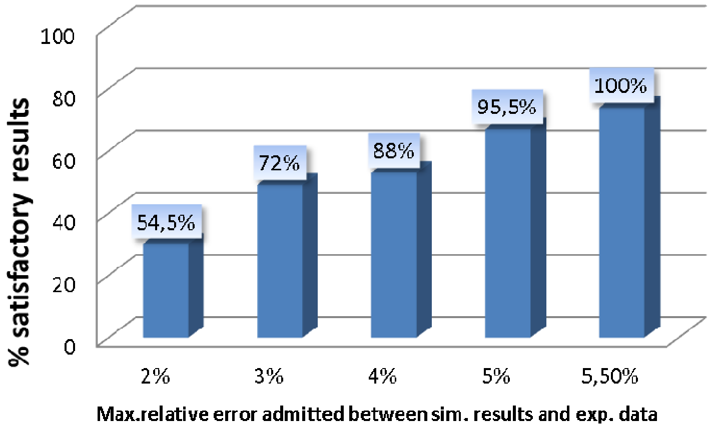
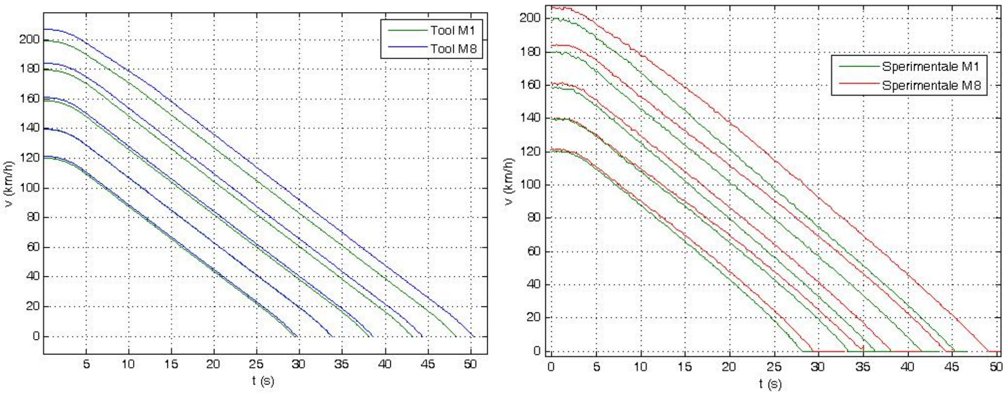


Figure 5: number of satisfactory sim. results considering as a function of the admissible value of es (introducing variable pad friction factor).

Finally, as in Figure 6, where the first ten braking test simulations and experimental results are compared, a general good fitting-agreement in terms of shape and behavior of speed profiles can be noticed. In particular, the results of Figures 6\a and 6\b are referred to emergency braking maneuvers performed in the VOM loading condition (vehicle tare), repeated twice in both the sense of motion over the line.



a) b)

Figure 6: Comparison between the first ten braking test simulations and experimental results a) variable braking pad friction factor implemented on TTBS01 for the validation on EMU V250, variable braking friction factor implemented on TTBS01 for the validation on EMU V250.

7. Conclusions and acknowledgments

Preliminary validation of TTBS01 tool on EMU V250 experimental data has provided an encouraging feedback. As a consequence, TTBS01 can be considered both a good tool for the preliminary simulation of braking plants and a base to build up real-time code for the monitoring of brake plant performances. It is relevant to point out that the calculation suggested by EN regulations in forces should be inadequate, since they do not consider the influence of the braking pad on the braking forces. Considering the wide availability of data about pads, deriving from the requested by regulation in forces (UIC 541-3, 2010) homologation activities and from the continuous research of manufacturers, it is highly recommendable that the implementation of this feature on standard calculation methods is prescribed by regulation in forces, too. Moreover the unconventional use of reliability statistics, proposed by ERRI documents, should be further investigated. Finally the authors wish to thank all the workers of AnsaldoBreda for their competence and their cooperative approach which helped much the positive conclusion of this activity.

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