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A statistical study on long freight trains equipped with radio communication within Shift2Rail

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Abstract. Paper reports the main results of a systematic study on longitudinal train dynamics (LTD) of long freight trains equipped with radio communication. It is divided in two parts: the first addresses the global sensitivity analysis aiming to find the most relevant parameters that, with their associated uncertainty, mainly affect the LTD of coupled trains, independently by the train length or train operation. The second part studies the LTD of classic freight trains in Germany (i.e. with one Traction Unit -TU- at the beginning of the train), considering the variation of the parameters identified during the sensitivity analysis. Finally, several train-consists with two up to four TU and having train length up to 1500 m are found to be as safe as the classic trains and therefore can put in service, as long as the LTD is concerned, allowing a relevant increase of efficiency.

1. Introduction

Shift2Rail (S2R) is the first European rail initiative for research and innovation (R&I) and market-driven solutions aiming to accelerate the integration of new and advanced technologies into innovative rail product solutions. This Horizon 2020 R&I initiative develops the necessary technology to complete the Single European Railway Area (SERA).

Research activity described in this paper belongs to S2R Innovative Program 5 (IP5) about freight trains. Within this program, the project Marathon 2 Operation (M2O) has been granted within the Open Calls (OC) framework. The problem addressed by M2O is twofold: a) simulate the in-train forces of freight trains having up to four Traction Units (TU), in radio communication, and 1500 m length; b) study the general safety (by means of an hazard analysis) of these new types of freight trains having the TU in constant radio communication.

This industrial problem is particularly relevant, since the increase of train length can lead to a considerable improvement of freight efficiency (depending also on the hauled mass, but up to 30%). Main limit to the increment of train length is given by the in-train compressive forces (or longitudinal compressive forces - LCF) that arise during a pneumatic braking, because of braking forces a-synchronicity. The simple pneumatic brake that equips most freight wagons, at least in Europe, is designed to brake firstly the wagons that are closer to the points of brake pipe discharge (usually located at TU). If the LCF overcomes the permissible (or admissible) LCF, which depends on the wagon type, its mass and track characteristics, a derailment occurs with dangerous consequences for people, environment, goods, and track. Placing several radio communicating TU along the train allows to discharge the brake pipe from several points and to reduce the LCF and arrange longer (and heavier) trains. Addressing this study is the main challenge of M2O.

This problem was already addressed within S2R and OC framework by DYNAFREIGHT consortium in [1] where an integrated numerical framework able to simulate 3D vehicle dynamics, train pneumatics and train longitudinal (1D) dynamics was introduced. Main difference of this paper is that the simulation results here displayed have been computed by TrainDy software [2], which integrates dynamics and pneumatics in a single software, and it is UIC approved for the calculation of the Longitudinal Train Dynamics (LTD) of freight trains.

In general, the problem of computing the in-train forces has been extensively reviewed in [3], where there are references according to numerical solvers used, the connection models of rail vehicles, the traction and dynamic brake models and other relevant aspects of LTD codes along with several application fields of LTD codes. In [4], several worldwide codes are benchmarked with differences among them depending on the simulation scenario, however such a benchmark neglects the pneumatic issue because of the relevant differences among the LTD codes.

Indeed, the in-train forces that arise during a pneumatic brake are of major concern for Railway Undertakings, when they want to put in service a new train consist or a new technology for regular operation. In these circumstances, the UIC Leaflet 421 [5] envisages the implementation of the relative approach: a new (potentially un-safe) system (i.e. type of train or a train with a new technology and so on) is compared against an already existing (potentially safe) system. This approach fulfils the Common Safety Methods (CSM) adopted by the European rules (Commission Implementing Regulation (EU) 2015/1136 of 13 July 2015).

Several results reported in this paper can be found also in M2O deliverables [6] and [7]; however, this paper adds further insights to those results, highlights and systematizes the main assumptions and conclusions of these deliverables.

2. Sensitivity analysis

2.1. Scope

When a new train consist has to be admitted into traffic, the UIC Leaflet 421 suggests performing a sensitivity analysis in order to understand if there are new parameters that can affect its LTD. For this reason, in M2O, a sensitivity analysis has been performed to address this issue.

In general, two types of parameters affect the LTD, following the UIC Leaflet 421 terminology: the technical and the operational ones. Technical Parameters are usually intrinsic train characteristics (e.g. the brake pipe diameter, or the initial pressure in brake pipe). On average, they present "physical" small uncertainties (e.g. due to tolerances in the manufacturing process or measure errors or aging of equipment) on which Railway Undertakings have not (or very low) control. Operational Parameters, instead, are factors on which Railway Undertakings have full or partial control (e.g. concerning track characteristic, train operations, train system setting). They can usually experience significant variations and contribute to set completely different braking simulation scenarios. The line dividing technical from operating parameters is blurred and ultimately depends on the analysis context. For instance, the "emergency braking starting speed" can be considered both a technical parameter when the object of the analysis is to investigate the importance of uncertainty due to the tachymeter specifics, or an operating one, when the analysis focus is to investigate what happens when the speed shifts from 30km/h to 60km/h.

Moreover, since the freight trains are characterized by a large variety of wagons in terms of: number of axles, braking equipment, couplings, carried load and other parameters and this large variety will continue when the long trains, with radio communication, will be put in service, it is necessary to compare not just two trains, but two train families. A train family is a set of trains having similar characteristics in terms of hauled mass, train length and "technology" (e.g. without or with radio communication). It is appropriate to distinguish between the following train families:

- A *basic* train family is defined by trains having specific wagons, with the hauled mass and train length varying in a specific interval and characterized by a specific "technology".
- A *reference* trains family is derived by a basic train family and a train operation or another operational parameter. In other words, it represents a basic family that has been set in a particular operative scenario.

- A *target* train family is a reference family in which one or more technical parameters are changed. Comparing the behaviour of these families with their reference, it is possible to quantify the effect of the technical parameters that were varied on the LTD.

The basic train families are generated by means of an algorithm compliant with UIC Leaflet 421 [8] and taking as reference the DB AG train database. Each train family is made of 1000 trains: this is a number often used for this type of calculations by Railway Undertakings. The sensitivity analysis reported here refers to three basic train families:

- **H_740** – Trains in G with almost all wagons loaded at the same level; hauled mass is between 2500t and 5500t and the train length is below 740m.
- **T2_740** – 2 trains coupled; first train has an average length 400m and hauled mass between 1200t and 1600t, second train has an average length of 300m and hauled mass between 800t and 1200t. Coupled train is in G braking regime.
- **T4_1500** – 4 trains coupled together having each one a hauled mass between 800t and 1200t. The overall train length is 1500m. Coupled train is in G braking regime.

Two train operations are performed, since considered more relevant for LTD: a) an emergency braking from cruising at 30 km/h; b) an emergency braking from full acceleration, commanded when the speed is 30 km/h. The track considered here is flat; up/down-hill tracks are not taken into consideration, since track topography is an operational parameter and it directly affects the reference family (even if the uncertainty on the slope is a technical parameter): anyway, the effect of uncertainty on track slope is addressed.

The parameters monitored are the in-train forces both compressive (LCF) and tensile (LTF); for the LCF, the 10m LCF are logged (i.e. minimum LCF value -in module- registered for each couple of buffers of a single train at every time step in the preceding 10 meters) and for the LTF, the 2m LTF (i.e. minimum LTF value -in module- registered for each draw gear of a single train at every time step in the preceding 2 meters) are logged.

2.2. Methodology

Every sensitivity analysis requires one or more scalar output(s) to measure the effect of the uncertainty assigned to input parameters on the uncertainty resulting from the simulations outcomes and to build a sensitivity ranking of parameters. Since each train family is characterized by a cumulative distribution function (CDF) and not by just a single value (i.e. for each family there will be 1000 outputs, one for each train in it), the scalar used to quantify the effect of a parameter variation is proportional to the difference between the areas subtended by the reference and target family resulting CDFs, as it is usually done in mechanical reliability to compute the probability of overlapping of stress and strength distributions [9].

Figure 1 gives an example of these areas: comparing the cumulative probabilities of the reference family against the target family (i.e. reference family + technical parameters variation), it is possible to determine negative areas, which is where the target family is more dangerous than the reference family (since the LCF are higher) and the positive areas, which is where the target family is less dangerous than the reference family (since the LCF are lower). If two trains are extracted respectively from the target and reference family, it is possible to compute the probability that the target train will present lower longitudinal forces than the reference one. This probability has been called the Lower Force Probability (LFP). Since comparing two trains sampled from the same distribution, the probability of one train having lower forces than the other one is always (independently from the starting statistical distribution) 50%, another indicator is introduced: The Lower Force Probability Differential (LFPD) as LFPD = LFP - 0.5. A positive value of LFPD means that the technical parameter variation has generated a target train family that is safer than its reference family. It is important to notice that LFPD averages the behaviour of the (target) family (with respect to the reference one) on the whole force spectrum. However, since only the high LCF are interesting for the derailment risk, this parameter is not used to compare the two train families (reference VS target) in terms of safety but only in terms of the effect of a technical parameters variation.

The technical parameters considered for this study are taken from [10]: these parameters proved to influence the wagon stopping distance in a way similar to experimental measurements. Typical variation of these parameters has been given by suppliers or by ECM (Entity in Charge of Maintenance).

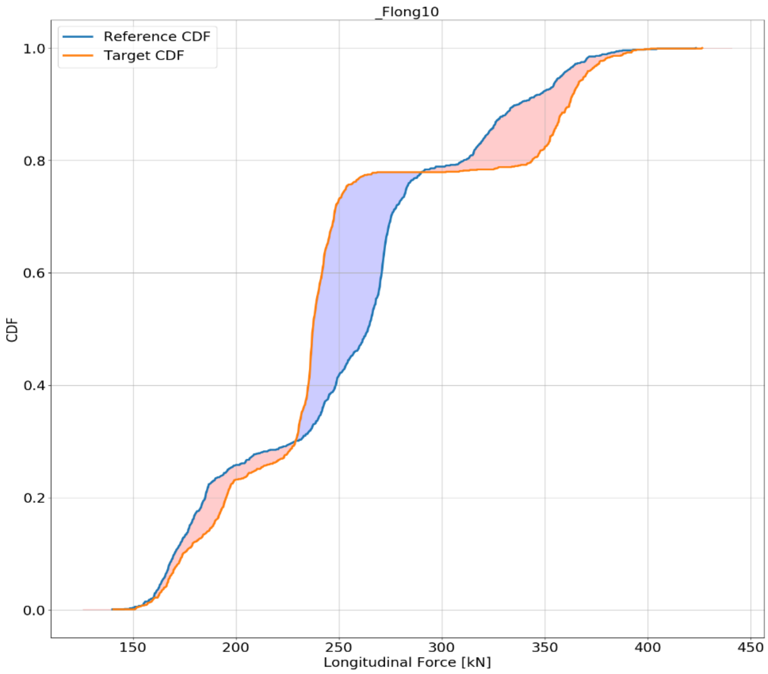

Figure 1. Differential Areas. In red the “negative” area while in blue the “positive” one.

The “Finite change” approach is adopted to perform the sensitivity analysis: this non-parametric approach allows the apportionment of the model output change into the contributions due to the individual and simultaneous changes of the input variables, as described in [11], [12] and [13]. Specifically, the “First Order Finite Change Sensitivity Index” and the “Total Order Finite Change Sensitivity Indices” are calculated for each parameter.

Defining $\boldsymbol{x} = (x_1, \dots, x_i, \dots, x_n)$ as the vector of parameters of interest and y as the model output, a general model can be written as $y = G(\boldsymbol{x})$. A positive difference vector $\Delta\boldsymbol{x}^+ = (\Delta x_1^+, \dots, \Delta x_i^+, \dots, \Delta x_n^+)$ and a negative one $\Delta\boldsymbol{x}^- = (\Delta x_1^-, \dots, \Delta x_i^-, \dots, \Delta x_n^-)$ need to be defined where Δx_i^+ and Δx_i^- are, respectively, the maximum increment and decrement for the i-th parameter that have been established for the sensitivity study.

The first order sensitivity indicator D_i^1 for the parameter i is:

$$D_i^1 = G(x_1, \dots, x_i + \Delta x_i, \dots, x_n) - G(\boldsymbol{x}) \tag{1}$$

Whereas the total order sensitivity indicator D_i^{tot} is:

$$D_i^{tot} = G(\boldsymbol{x} + \Delta\boldsymbol{x}) - G(x_1 + \Delta x_1, \dots, x_i, \dots, x_n + \Delta x_n) \tag{2}$$

D_i^1 measures how much varying the i-th parameter alone affects the model outcome, while D_i^{tot} quantifies the total contribute (including those deriving from interactions with other parameters) of the i-th parameter to the global outcome variation obtained when all parameters together are incremented or decremented.

Assuming the LFP as the model output and introducing it in equations (2) and (3), one obtains:

$$D_i^1 = LFP_i - 0{,}5 = \mathrm{LFPD} \tag{3}$$

$$\begin{gathered} D_i^{tot} = \mathrm{LFP_{all}} - \mathrm{LFP_{all\_but\_i}} = \\ (\mathrm{LFP_{all}} - 0{,}5) - (\mathrm{LFP_{all\_but\_i}} - 0{,}5) = \\ \mathrm{LFPD_{all}} - \mathrm{LFPD_{all\_but\_i}} \end{gathered} \tag{4}$$

This procedure has been conducted both increasing and decreasing the parameters, for a total of 4N+2 simulations (for each family), where N is the number of parameters to analyze. Since each train family has 1000 trains and N is around 20, more than 200k simulations have been performed by TrainDy to finalize the study.

2.3. Results

The results of this large number of simulations have been summarized in Tornado Plots, where the names of TrainDy variables are directly displayed. For the basic train families and train operations (or manoeuvres) reported in §2.1, Figure 2, Figure 3 and Figure 4 report the effect of each technical parameter uncertainty on the train family LTD in terms of LFPD. In particular, the 1st order effect, the total order effect, and the interaction effect (given by the subtraction of total order and 1st order) due both for the increment and decrement of the different parameters are reported.

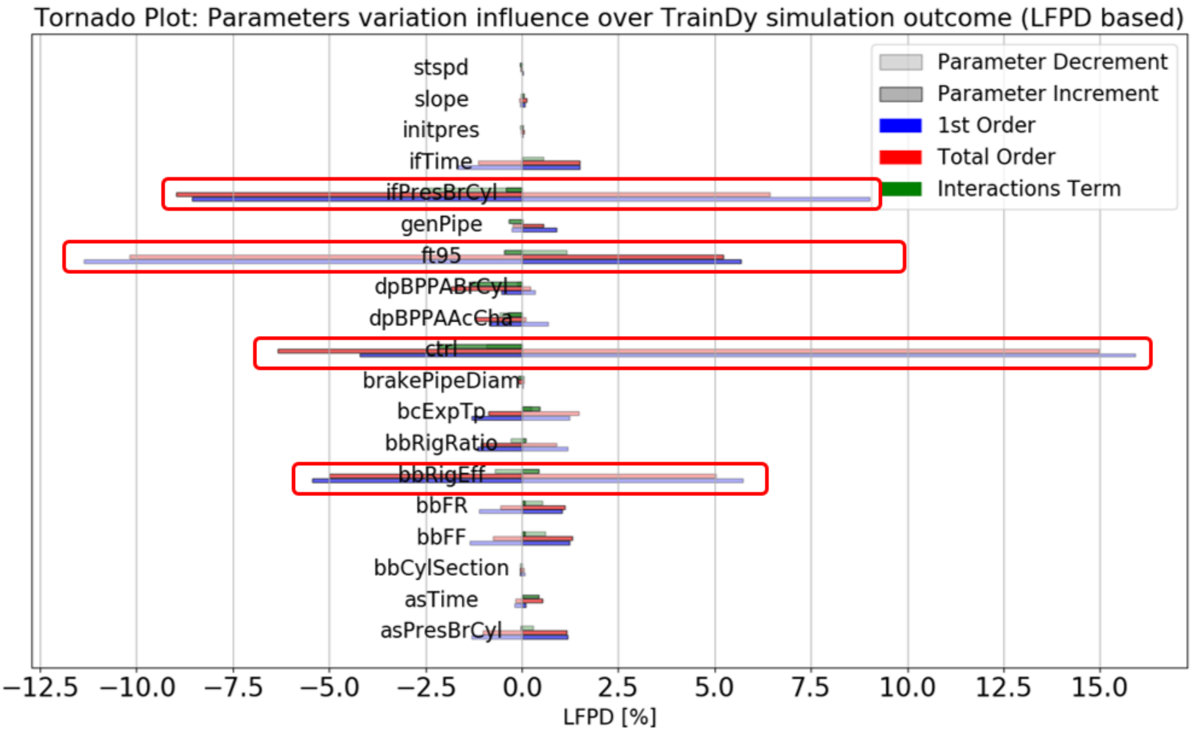

Figure 2. Tornado plot comparing first, and total order technical parameter uncertainties influence on in-train compressive forces for the 2T_740 basic family performing an emergency braking.

From these results, the technical uncertainties associated to the following parameters appear to have a considerable effect on train LTD (variation bigger than 5%):

- ft95: time needed to fill the braking cylinder at 95% [+/- 25%];
- ifPresBrCyl: Pressure in brake cylinder for "in-shot function" phase [+/- 10%];
- bbRigEff: Mean efficiency of the rigging [+/- 8%];
- ctrl: delay scatter in radio communication [+/- 30%] (GSM-R or LTE);

The importance of above parameters (with their associated uncertainty) is the same for the coupled trains, independently from the train operation. Finally, conducting an extensive study on the subject, it has been proved that considering 1000 trains, as statistically representative for each train family, provides accurate results (see [6]).

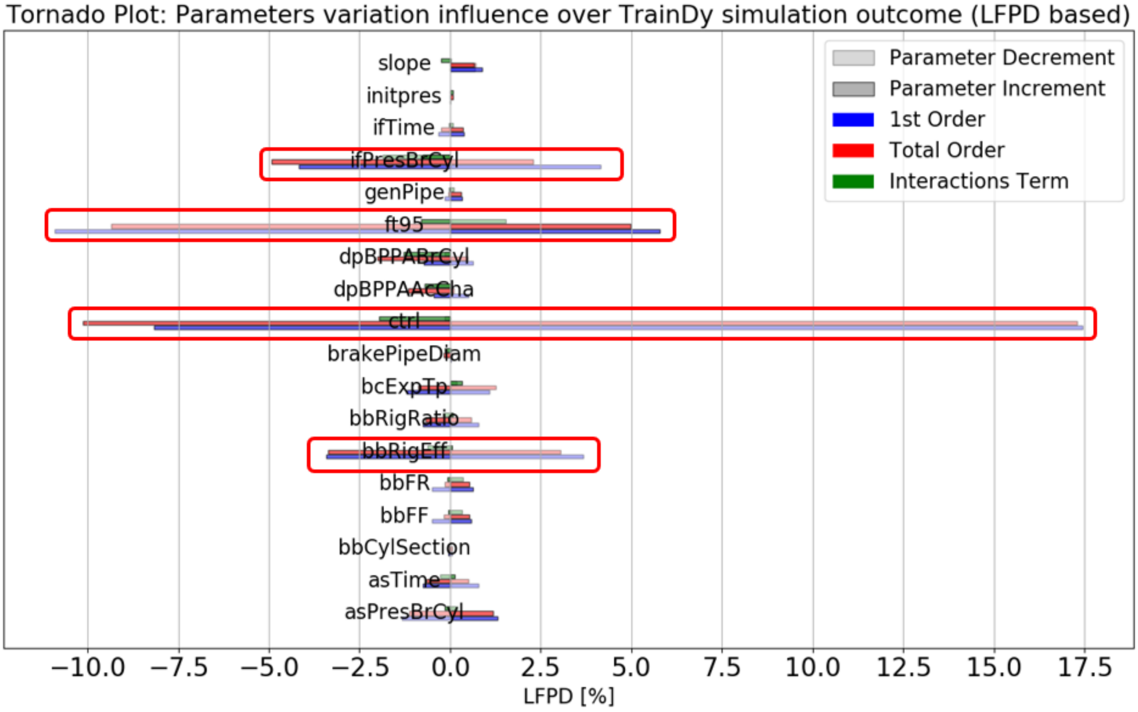

Figure 3. Tornado plot comparing first, and total order technical parameter uncertainties influence on in-train compressive forces for the 2T_740 basic family performing an emergency braking after a full acceleration.

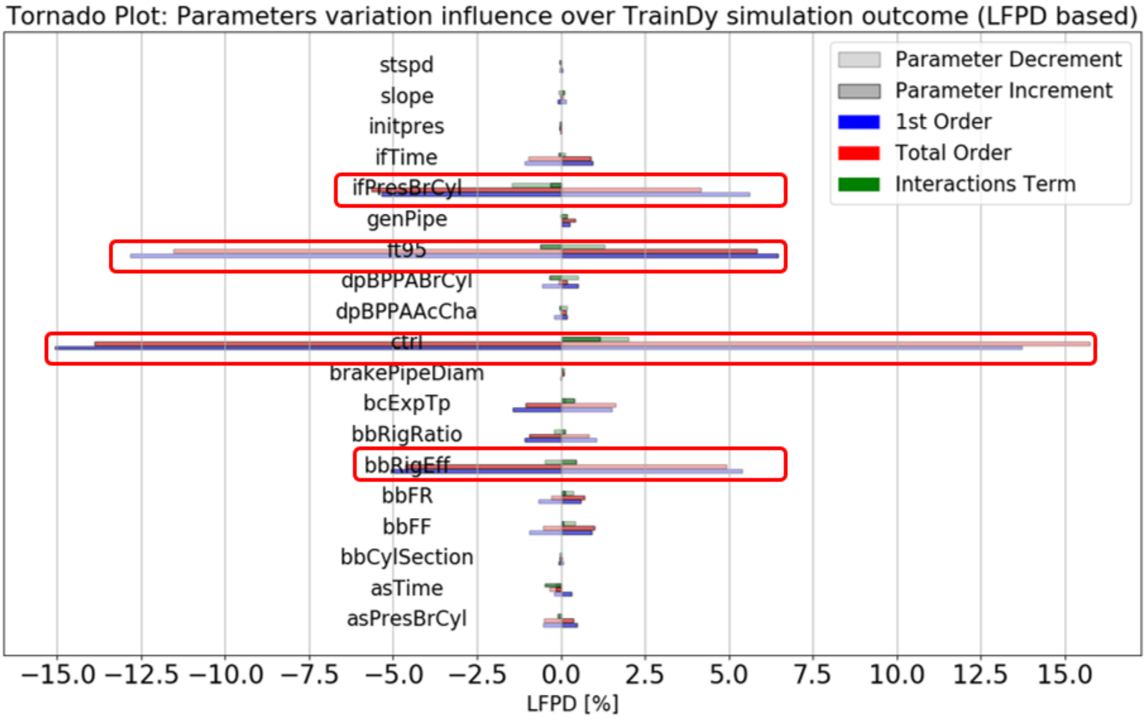

Figure 4. Tornado plot comparing first, and total order technical parameter uncertainties influence on in-train compressive forces for the 4T_1500 basic family performing an emergency braking.

3. Possible train consists in radio communication

It is well-known that the intrinsic features of UIC brake and the limitations of the Railway Infrastructure, it is not possible to increase indefinitely the train length and the hauled mass. It is also known that increasing the points from which the brake pipe is vented, it is possible to reduce the dangerous LCF that arise during a braking and that can lead to a derailment.

In this section, several train-consists are shown that employing a distributed power and braking radio control can increase both hauled mass and train length with respect to standard trains. At this aim, it is necessary to compute the LTD performances of standard trains, preliminary. Standard trains have just one TU; these trains are simulated by TrainDy, generating virtual trains according to UIC Leaflet 421 and taking as reference the DB AG train database. According to the hauled mass and the braking regime, the standard trains are grouped in the following way:

- 0-800 ton, in brake regime P, i.e. all vehicles in P (Passenger) brake regime.
- 801-1200 ton, in brake position GP, i.e. the TU in G (Goods) brake regime and the wagons in P.
- 1201-1600 ton, in brake position LL, i.e. the TU and the first 5 wagons in G, the remaining wagons in P.
- 1601-2500 ton, in brake position G, i.e. all vehicles in G.
- 2501-4000 ton, in brake position G: the wagons are almost homogeneously loaded.

For each group, 1k trains are simulated both in emergency braking (EB) and in full traction followed by an emergency braking (T-EB). As a result, from each simulation, it is computed the maximum ratio (in absolute sense) LCF/LCF_P (where LCF_P is the permissible LCF according to UIC Leaflet 421) and the maximum ratio LTF/LTF_P (where LTF_P is the permissible LTF, fixed equal to 550 kN). Therefore, the probability to experience a (virtual) train derailment (if $LCF/LCF_P > 1$) and a (virtual) train disruption (if $LTF/LTF_P > 1$) are computed.

Considering the different occurrence of these trains (within the general set of standard trains, again considering the DB AG database), it is possible to compute the virtual probabilities reported in Table 1. It is worthwhile to note that the train operations here considered are the most dangerous, but have a low occurrence in practice; moreover, for the virtual derailment probability, it is assumed that the maximum LCF occurs on a track area where the radius of curvature is minimum; for these reasons the values of this table are particularly high and do not represent the occurrence of derailment and disruption experienced by the Railway Undertakings. Nevertheless, they can be considered as a reference for the trains with radio technology since these trains are simulated in the same conditions.

Table 1. Virtual derailment and disruption of standard trains.

Train Operation	Derailment [%]	Disruption [%]
EB	1.94	0.38
T-EB	5.80	1.70

Since the most dangerous manoeuvre is the T-EB, results here reported on trains with radio technology refer just to this train operation. First results refer to trains having one TU in front and another in the end and where the wagons are almost homogeneously loaded. Figure 5 displays the probability to overcome the LCF_P and the LTF_P for these trains: the first number in the left list is the train length (±20 m) and the second is the hauled mass (±250 ton). With GSM-R radio technology, it is possible to employ trains having length up to 1000 m (TU included) and hauled mass of 6500 ton. This figure, but also the next similar figures, show two vertical dashed lines indicating the performance of standard trains: new trains between the dashed lines are safer than the standard trains (in average).

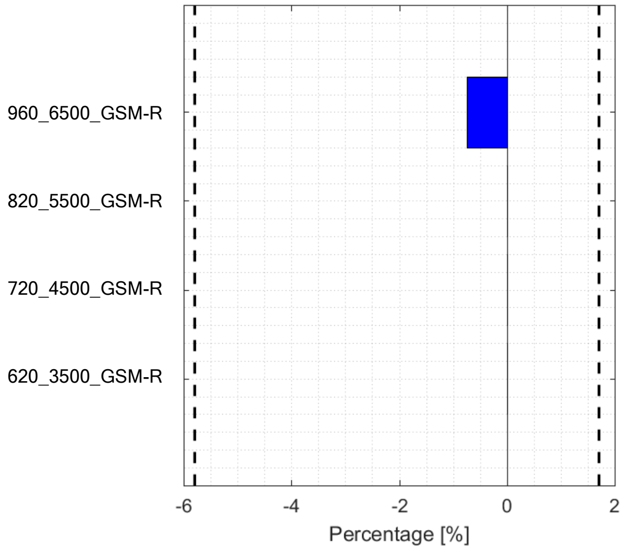

Figure 5. Tornado plot for trains with one TU in front and another at the end, wagons with “same” loaded.

Coupling two trains, according to: a) the radio technology employed (GSM-R or LTE); b) the way the braking is activated -first the leading TU and then the others or the leading TU “synchronously” with the others (Lab “S”)-; c) the length and hauled mass of the two trains, it is possible to reach 1200 m of overall train length. Figure 6 shows some of the possible train configurations having overall length lower than 740 m (typical maximum commercial length of European trains); whereas Figure 7 refers to trains with overall length of 1200 m. It is important to note that the coupled trains operate in G regime. In these figures, the numbers are the average (sub)train length and the letters represent the hauled mass interval (in ton): P = 0-800; GP=801-1200; LL=1201-1600; G=1601-2500. It must be emphasized that the trains of these last figures have wagons heterogeneously loaded: wagon load has been taken by DB AG database.

These two figures clearly show the benefits of LTE radio over GSM-R radio, because of the low latency and the benefits of synchronous braking, realized by braking the leading TU with some delay.

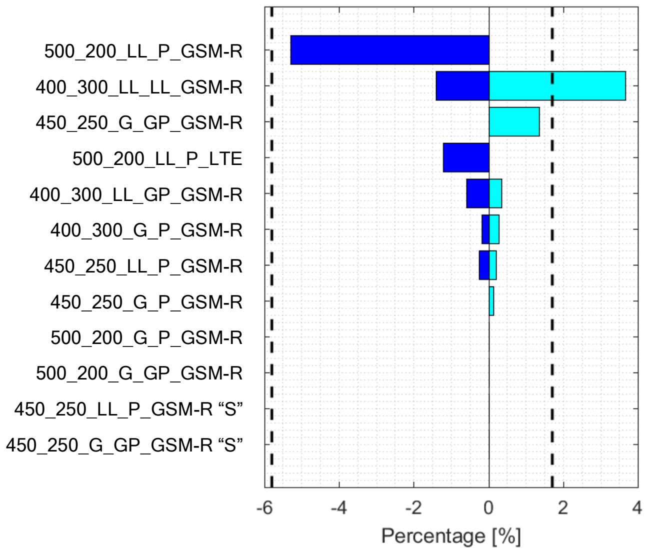

Figure 6. Tornado plot for two coupled trains (740 m, maximum) and different technologies, wagons heterogeneously loaded.

If it would be necessary, it is possible to couple three short trains to realize a train with up to 1200 m of overall length, as displayed by Figure 8. This figure shows how much the LTD depends not only by the overall length and hauled mass, but also by the length and the hauled mass of the (sub)trains.

The complexity of LTD is confirmed by the following figures where possible train consists with four TU are considered: Figure 9 refers to three (sub)trains coupled having another TU at the end, whereas Figure 10 refers to four (sub)trains coupled. In these figures, GH indicates a (sub)train having mass between 2500 and 4000 ton with wagons almost homogeneously loaded. Moreover, with 5G it is indicated the future Railways radio standard that should provide an almost instantaneous communication among the TU.

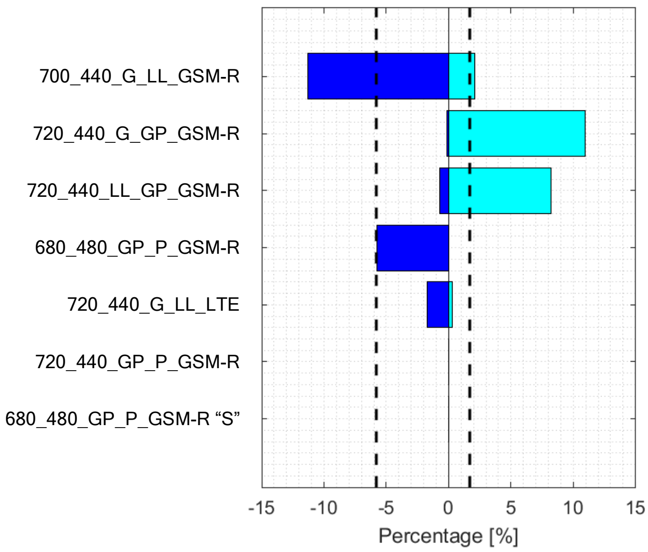

Figure 7. Tornado plot for two coupled trains (1200m, maximum) and different technologies, wagons heterogeneously loaded.

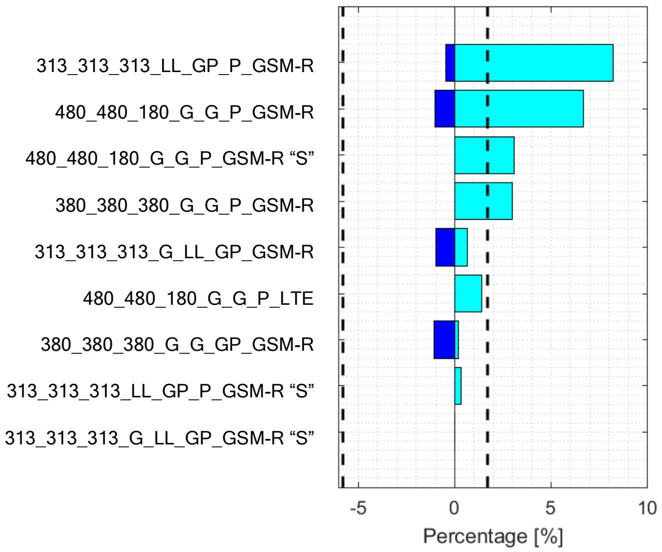

Figure 8. Tornado plot for three coupled trains (1000 m and 1200 m, maximum) and different technologies, wagons heterogeneously loaded.

These figures suggest the need for a more targeted LTD study to address specific needs, since is it easier to find “spot” solutions rather than “general” solutions, as it is possible when just two trains are coupled.

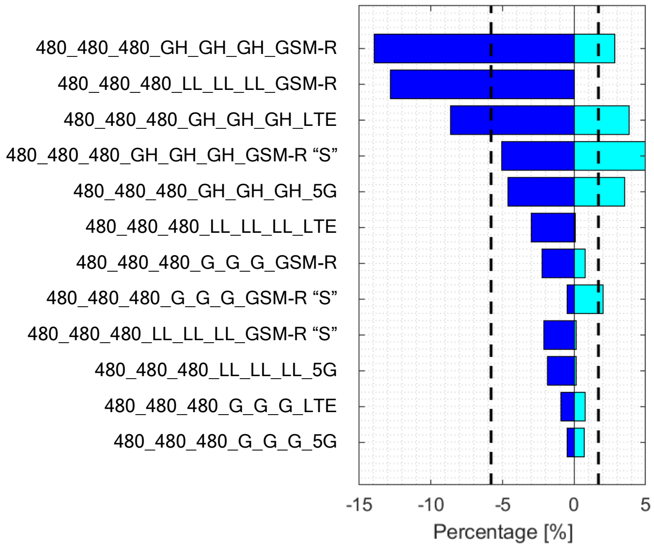

Figure 9. Tornado plot for three coupled trains (1500 m, maximum) and different technologies, wagons heterogeneously loaded.

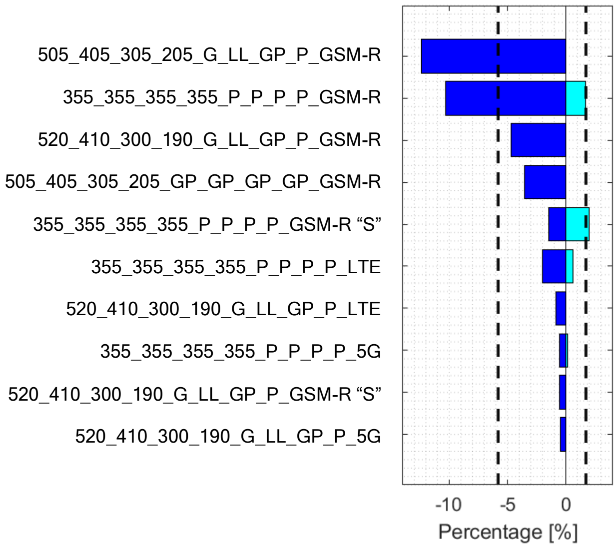

Figure 10. Tornado plot for four coupled trains (1500 m, maximum) and different technologies, wagons heterogeneously loaded.

4. Conclusions

Paper has shown a way to carry out a sensitivity analysis on some families of freight trains, equipped by a distributed power (and braking) system, radio commanded. The Lower Force Probability Differential index has been introduced to effectively manage this situation, in which the comparison is among two train families and not two trains. Sensitivity analysis has found out the parameters that with their associated uncertainty are the most relevant for the Longitudinal Train Dynamics (LTD) independently by the train and by the manoeuvre considered. The results of the sensitivity analysis have been applied to the simulations of train consists having up to four Traction Units (TU) and train length up to 1500 m. Several train-consists, with 2 or more radio-controlled TU, have been proved to be as safe as the classic trains. Simulations results have proved that when four trains are coupled together to form a 1500 m train, it is not the best solution to couple four similar trains (both in terms of mass and length) but it is better to couple trains having a descended train length and hauled mass.

Acknowledgments

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