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Effective ways to compare two families of freight trains

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Abstract. The paper shows several use cases of the "relative approach" method, envisaged by international recommendations, for evaluating the safety of two families of freight trains. This is relevant when a decision is needed about a new technology or a new operating mode of freight trains to keep the same safety as existing trains. The paper discusses the heterogeneity of the database of trains and provides examples of the classic application of the "relative approach", highlighting the effect of train operation. Furthermore, it shows the application to DAC and radio-controlled Traction Units. Finally, it introduces the "Iterative Proportional" algorithm to generate a freight train from an existing one just by changing the hauled mass of each wagon. This algorithm is helpful when the "relative approach" is applied to trainsets having articulated wagons and running with a similar braking regime.

1. Introduction

Unlike typical passenger trains, freight trains have wagons that do not brake simultaneously. The freight trains still predominantly use a braking system derived by George Westinghouse. They usually miss the electrification and the second pipe used in electro-pneumatic (EP) brake or electronically controlled pneumatic (ECP) brake. One of the main benefits of such devices is the possibility of reducing the in-train or the Longitudinal Forces (LFs) during braking [1], [2]. The reduction of LFs is critical for safety and efficiency reasons: high Longitudinal Compressive Forces (LFC) can cause train derailment; high Longitudinal Tensile Forces (LTF) can cause train disruption, i.e., the division of the train into two parts and the need for a recovery train.

The accurate determination of LFs is a difficult task since it requires the contemporary solution of the pneumatic problem (determination of air pressure in the braking system) and mechanical problem (determination of the relative movement of wagons along the track). The reference [3] extensively reviews the problem of computing the in-train forces, considering the numerical solvers, the connection models of rail vehicles, the traction and dynamic brake models and other relevant aspects of Longitudinal Train Dynamics (LTD). [4] benchmarks several worldwide codes, showing results differences depending on the simulation scenario; however, such a benchmark neglects the pneumatic issue because of the relevant differences among the LTD codes.

The LFs penalize the freight train efficiency more than the infrastructure limitation, or, in other words, they do not allow extracting all the capacity from current railway infrastructures. Several European projects have been launched in the past years to overcome such problems. The references [5]-[7] report the LFs of trains equipped with Distributed Power System, i.e. a train in which the Traction Units (TUs) communicate between them by radio and can vent the brake pipe. More recently, within Horizon Europe, the joint undertaking programme Europe's Rail has launched the Digital

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Automatic Coupler (DAC) to overcome all the barriers that prevent the freight trains from using all the network capacity [8][9]

The UIC software TrainDy solves both pneumatic and mechanic problems and satisfactorily matches experimental data as reported in [10]. This software is suggested by the IRS 40421 [11] to compute the LTD of freight trains. The IRS 40421 describes the "relative approach" method, which provides an effective way to compare two families of freight trains and establish relative safety; this method is also recalled by the European Railway Agency (ERA) in [12], which provides acceptable means of compliance for freight trains.

After describing the "relative approach" method in §2, the paper shows several use cases of the "relative approach" method: the classic application, the application to DAC and DPS system. Then it introduces the Iterative Proportional ("IP") algorithm in 3.6. as a way to handle the articulated wagons in new trainsets. Articulated wagons are not explicitly handled by [11], and the paper describes a way to handle them appropriately; §3.6.1. and 3.6.2. provide ways for their usage applying the "relative approach" method.

2. The "relative approach" method

This paper applies the "relative approach" described in the IRS 40421 [11]; the recent document [12], which provides acceptable means of compliance for freight trains, recalls this method. The "relative approach" compares a new train family with an accepted train family in terms of LCF and compares the number of potential derailments of these two families. If this number is lower for the new train family, it can circulate safely. Trainsets respecting the IRS 40421 are examples of accepted train families, e.g., G-braked trains (all vehicles brake in position "G") having a mass up to 4000 T and length up to 700 m (traction unit(s) excluded). An example of a new train family is the one in which a radio-controlled traction unit works at the trainset end. The comparison requires the checking of a series of parameters, noting the value in reference and new train family (or system), describing the (statistical) changes from reference to the new system and commenting on them (optionally). An example of parameters to check is:

- Train composition (arrangement of vehicles) in terms of mass and length.
- Brake equipment of vehicles, e.g., considering empty/load devices and auto-continuous devices.
- The means the braking is controlled: e.g., pneumatically, via radio, by wire.
- Braking regime, P-braked or G-braked trains
- Type of wagons, e.g., the wagons are the same, but the permissible LCF is different, as it is for DAC
- Initial braking speed
- Braking mode: emergency braking or full-service braking, from coasting or acceleration (traction). The most common braking mode is electro-dynamic braking, followed by service braking, full-service braking, emergency braking from coasting (cruising), and emergency braking from acceleration. The train derailment and disruption risks follow
- Wagon load, e.g., positioning of empty wagons at the train end.
- Coupling feature, e.g., the new trainsets have the same wagons but different couplings.

As much as possible, the changes must be limited to the parameters that want to be investigated. In the example of a radio-controlled TU, the reference trains must be generated with a TU at the train end behaving as a wagon; on the contrary, this traction unit in the new system is radio-controlled. In this way, the behaviour of the traction unit is the only difference; see §3.5. for another example of applying the "relative approach" in radio-controlled TUs.

In this paper, the algorithm used to generate a family of trains is that described in [13], except when the algorithm described in §3.6. is employed.

3. Use cases of the “relative approach” method

The following subsections report several use cases of the “relative approach” method. Primary wagon data are listed in Table 1 to ease the recalculation; cast iron is the friction material for block brakes. Figure 1 reports buffers and draw gears data; buffers are “side buffers” if not specified differently.

Table 1. Main wagon data

Name	Length [m]	Tare [T]	Mass [T] vs % of braked weight [%]	Buffer	Draw gear
Bogie1	16.94	18.98	$\begin{bmatrix} 18 & 57 & 69.5 \\ 100 & 100 & 82 \end{bmatrix}$	Buff_L	Draw_L
Bogie2	19.9	24	$\begin{bmatrix} 24 & 58 & 80 \\ 100 & 100 & 72.5 \end{bmatrix}$	Buff_NL	Draw_NL
Art1	34	34.7	$\begin{bmatrix} 34 & 88 & 135 \\ 100 & 100 & 65.1 \end{bmatrix}$	Buff_L	Draw_L
Art2	26.6	28.7	$\begin{bmatrix} 28.7 & 109 & 135 \\ 100 & 100 & 80.7 \end{bmatrix}$	Buff_NL	Draw_NL

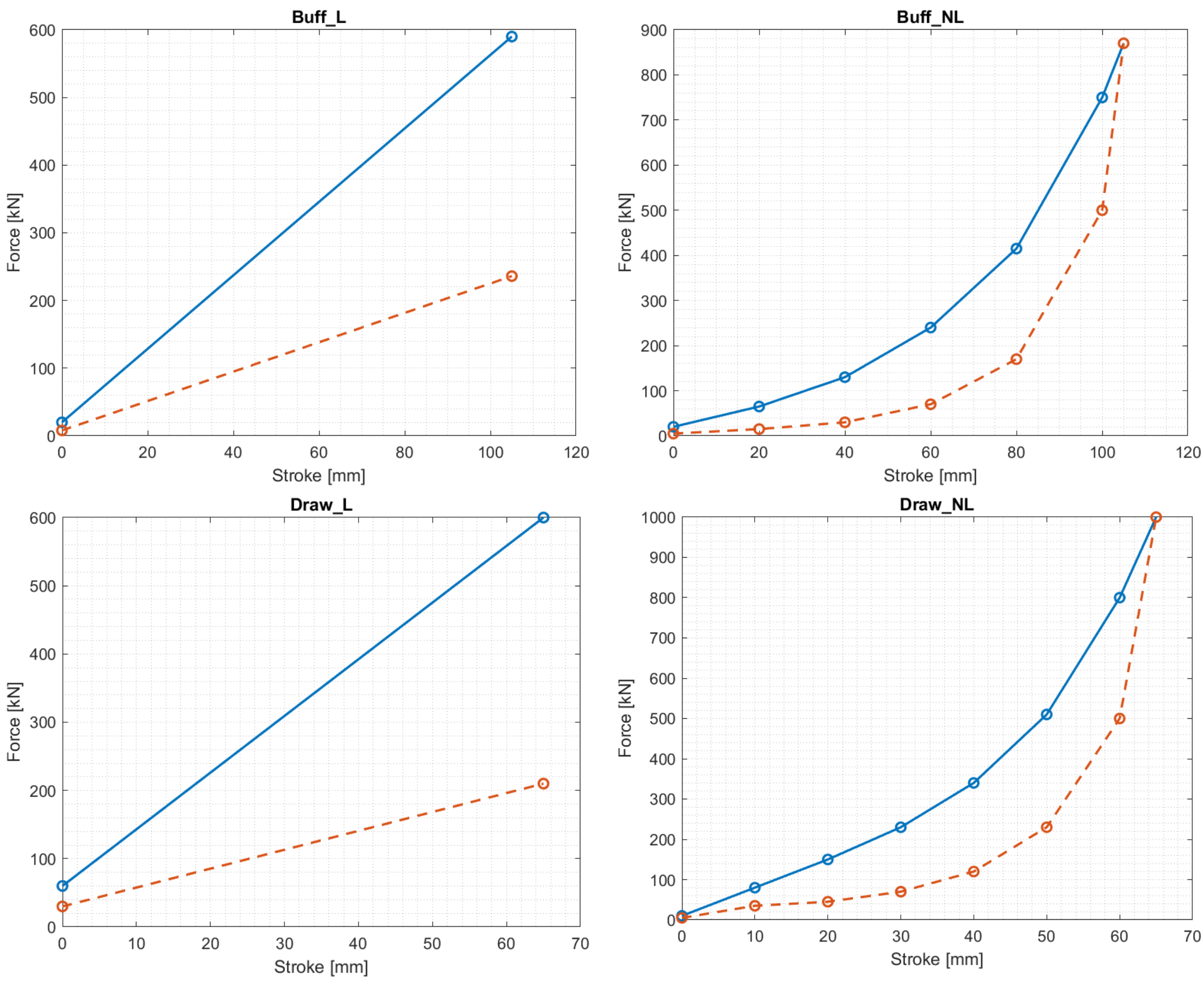

Figure 1. Force/stroke characteristics of the coupling elements used.

The results shown in this paper employ the permissible values for the LCF as in [11]. In contrast, the paper assumes for permissible LTF (PLTF) a fixed value of 550 kN since this value is the threshold for the activation of the fatigue process in typical draw gears.

3.1. *The payload for articulated wagons*

Before explicitly addressing different use cases for the "relative approach" method, it is worthwhile to mention that articulated wagons can be unevenly loaded, affecting the payload used when the PLCF is of concern.

The payload of articulated wagons is divided into two parts, loading at the maximum possible (according to a maximum mass per axle of 22.5 t) one of the two parts and considering as payload, for the IRS 40421 extrapolation, the remaining payload; in this way, the calculation of PLCF is conservative. In formulas:

- $m_{pa} = 22.5$
- $L = L_H + L_L$. The total wagon payload (L) is the sum of the load of the heavy part (L_H) and the load of the light part (L_L).
- n_a is the number of axles of the wagon
- T is the tare of the wagon (wagon mass is $M = L + T$, of course)

$$L_H = \min\left(L, \quad \frac{m_{pa} \cdot n_a - T}{2}\right) \tag{1}$$

$$L_L = L - L_H \tag{2}$$

L_L is used as the wagon payload for the extrapolation rules of IRS 40421. The PLCF for articulated wagons is computed parametrically, considering them as axle wagons (conservatively), as bogie wagons (as an assumption) and with an intermediate value. §3.6.1. and §3.6.2. show the application of this parametrization.

3.2. *Heterogeneity issue of the trains database*

The generation of virtual trains requires a database of trains from which to extract the probability distribution of employed wagons and, for each wagon, the payload distribution. If the original train database is homogeneous (it contains similar trains in terms of mass and length), the generated trains match the real trains in terms of percentages of the train derailment and disruption (breaking of the train in two parts because of a draw gear breakage). Figure 2 reports (in (a) and in blue) the cumulative frequency of the LFs (compressive forces have negative values) for 42407 real trains running in GP mode (i.e., the TU brakes in G and the wagons in P). The trains have a mass in the interval 800-1200 T and perform an emergency braking from 30 km/h after a full acceleration (TEB): each dot represents the maximum LF (in modulus) for each train. This figure also reports the maximum ratio with the permissible force for each train in green: negative values for LCF/PLCF and positive for LTF/PLTF. The label reports the percentages of train derailment and disruption between brackets: they are linked to the number of trains having a ratio with the permissible value bigger than 1 (in an absolute sense). Part (b) refers to 1000 virtual trains generated from the trains database: the probabilities of train derailment and disruption are pretty similar. Moreover, the relatively high probability of potential derailment for the actual trains is the result of a conservative calculation: i) the PLCF values in IRS 40421 are conservative; ii) the LTF/PLTF ratio assumes that the wagon subjected to the highest LCF is also running on a track section with a low radius of curvature; iii) the likelihood of TEB is low (around 10^{-4}).

Part (c) refers to 993 real trains having a length between 10 and 620 m and a mass in the interval [10-2000] T; by repeating the generation of virtual trains, as in (d), the results differ more than before. The reason is the heterogeneity of the actual train database. Extracting a small number of trains from the trains database, as in (e), and generating virtual trains from this reduced but more homogeneous database improves the results regarding train derailment and disruption probability (f).

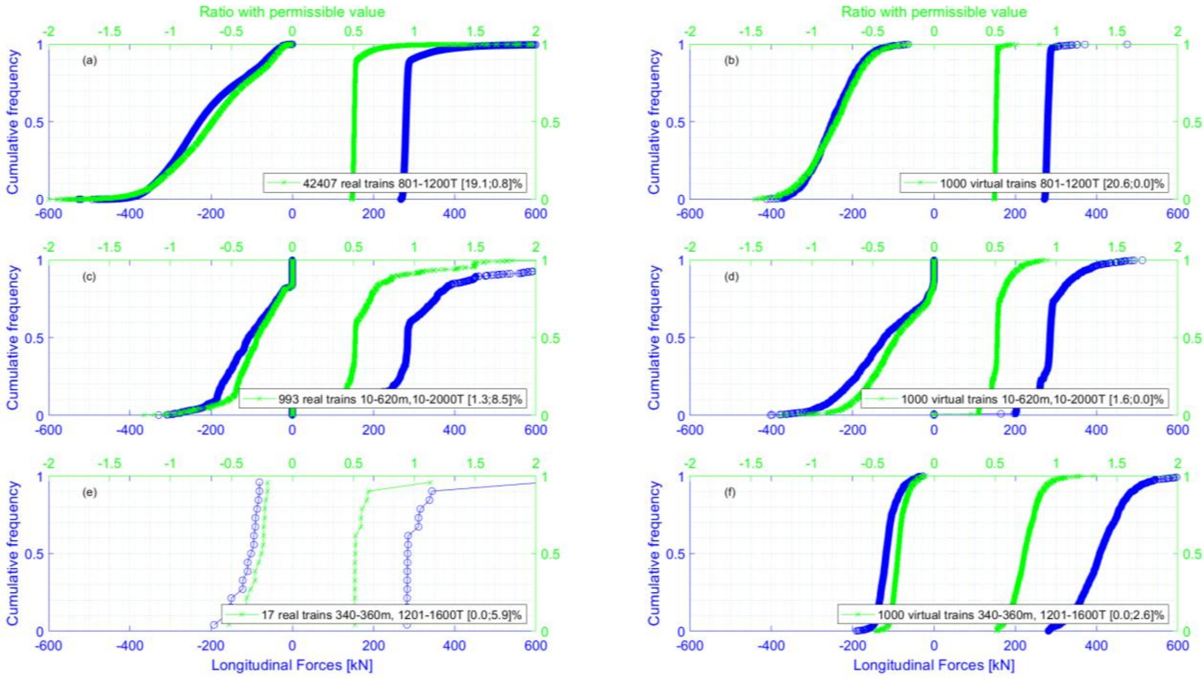

Figure 2. Longitudinal forces and ratio with permissible value for real and generated trains are on the left and right of the figure, respectively.

Consequently, the trains database used to generate the virtual trains must be homogeneous to obtain virtual trains representative of real trains. It is impossible to give general guidance on the heterogeneity of trains; however, trains with the same service (connecting the same places and carrying similar goods) are examples of homogeneous trains.

3.3. A classic application of "relative approach"

This paper considers as reference train families those explicitly allowed by UIC IRS 40421: trains with hauled mass in the range [1200-1600] T with Long Locomotive regime (LL) and trains with hauled mass in the ranges [1600-2500] T and [2500-4000] T in G; all with train lengths in [640-740] m (TU included), but without DAC or EP brake. The first two train families are likely to have empty wagons, which does not happen for the third train family because of the higher hauled mass. Remember that in the LL regime, the first five wagons and the leading TU are in freight position G (G braked); in contrast, the remaining wagons are in passenger position P (P braked). As the results of the following sections show, the higher minimum hauled mass of the last train family is beneficial in terms of safety. Figure 3 part (a) shows the cumulative frequency of LFs, for an emergency braking from 30 km/h in coasting conditions. The number of virtual trains is 1000, which provides a satisfactory evaluation of the mean and standard deviation of LCF (as required by [11]), and the trains contain only bogie wagons. Part (b) shows the ratios of LCF/PLCF and LTF/PLTF, as in Figure 2. Looking at (a) and (b), [2500-4000] T trains have LCF like [1200-1600] T trains in UIC IRS 40421 but have a lower risk of derailment because of higher wagon mass, as also confirmed by the histograms in (c) and (e).

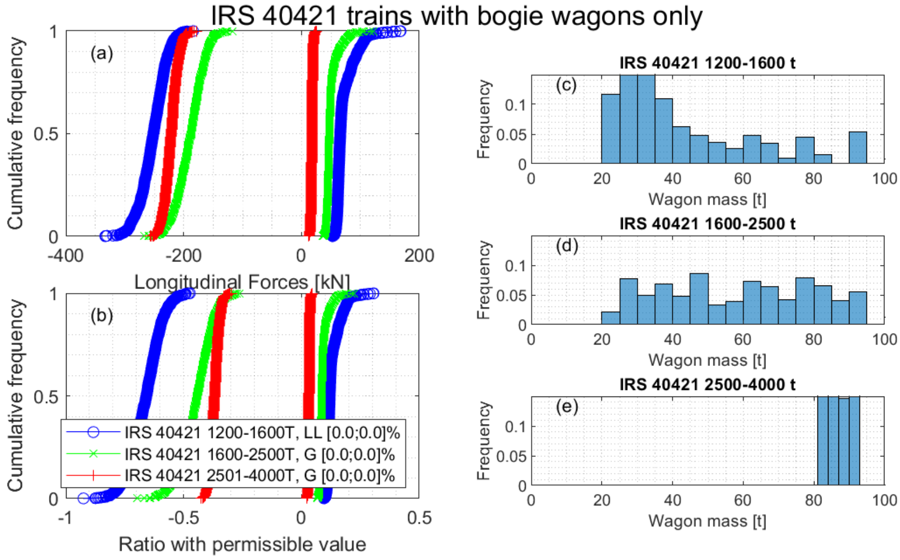

Figure 3. Trains explicitly allowed by IRS 40421.

Figure 3 shows that the trains allowed by the IRS 40421 have a different degree of safety and the safest trains are those in G with a hauled mass between 2500 and 4000 T. These results have been obtained by statistically generating three families of virtual trains, hence applying the "relative approach" classically, i.e., as foreseen by the IRS 40421. The following sections show different ways to apply the "relative approach" method.

3.3.1. Effect of train operation. Before showing different ways to apply the "relative approach" method, this subsection shows that this method's results do not usually depend on the train operation. The train operation (highly) affects the probability of train derailment, but usually, it does not affect the comparison between different train families. If this is not the case, it is better to consider a new train family safer than the reference train family when this statement is true for different train operations, e.g., for emergency braking or full-service braking from coasting and acceleration.

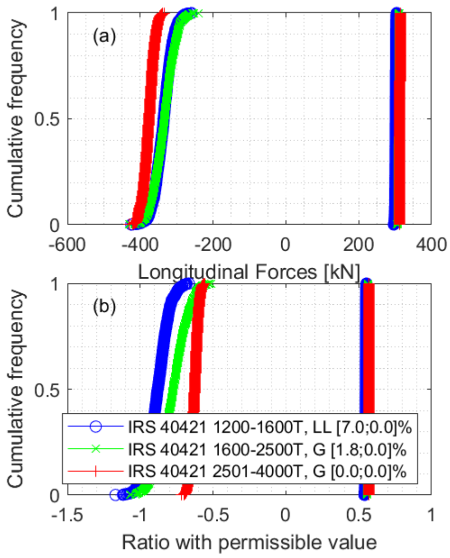

Figure 4. Trains explicitly allowed by IRS 40421, performing an emergency braking from 30 km/h after an acceleration.

Figure 4 shows the LF in (a) and the ratio with the permissible value in (b) for the same trains as Figure 3, but performing an emergency braking from 30 km/h after an acceleration. As anticipated, the safest train family is the one running in G and hauling a mass between 2500 and 4000 T. The main effect of this new train operation is to increase the LFs and the probabilities of a train derailment but not to change the result of the relative approach application, in this case.

3.4. Benefits of DAC

The European DAC Delivery Program (EDDP) from Shift2Rail (S2R) is currently developing the Digital Automatic Coupler (DAC), intending to increase productivity in freight operations in a safe way. Depending on the DAC level (see Figure 5), DAC may reduce LCF generated in operated trains. In the figure, “AC 1” and “AC 2” refer to automatic couplers (AC) that are just “mechanical DAC”, and the label “DAC2” is used in this paper. Any level of DAC increases and even doubles the PLCF of the wagons. “AC 1”, “AC 2”, and “DAC 3” are the same in terms of mechanical characteristics and PLCF.

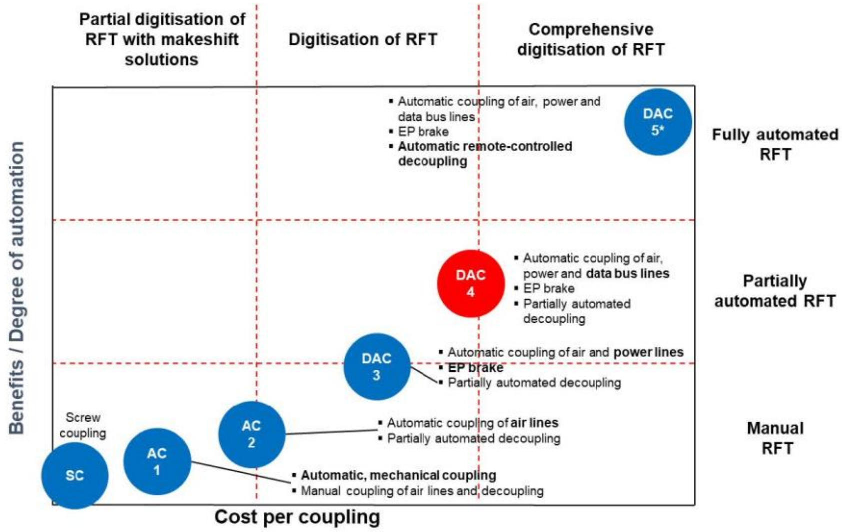

Figure 5. Different levels of train automation depending on DAC type

As DAC is not yet in production, this paper presents results in which the PLCF of wagons equipped with DAC equals 1.5 times the PLCF of corresponding non-DAC wagons. This figure must be confirmed by subsequent studies, even if it is realistic.

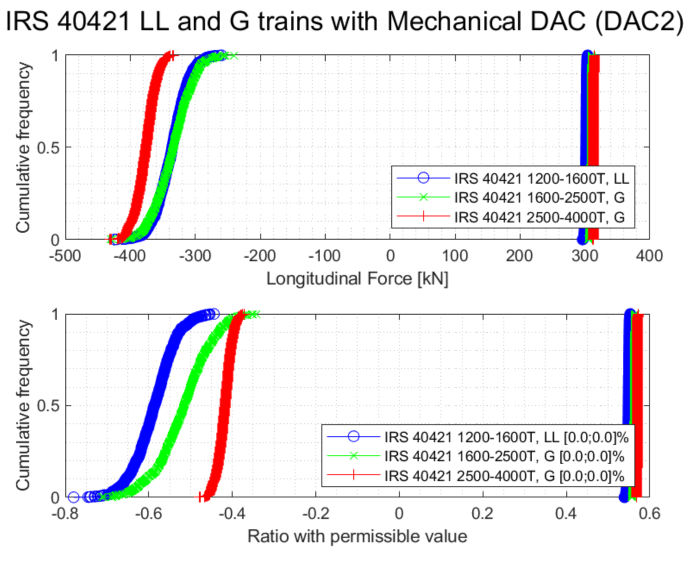

Figure 6. Trains, explicitly allowed by IRS 40421, and performing an emergency braking from 30 km/h after acceleration and equipped with mechanical DAC (DAC2).

Figure 6 shows on top LFs and below the corresponding ratios with permissible values. The trains and the operating conditions are identical to Figure 4, but the PLCF has been increased by DAC2, resulting in a lower probability of train derailment for all train families. Consequently, it is possible to find an upper value bigger than 1600 T for trains with DAC2, keeping the same level of safety and proving the benefits of DAC2.

It is important to note that the results of Figure 6 assume that the mechanical characteristic of DAC is identical to the set "side buffers plus draw gear" and that only the wagon PLCF changes. DAC should have substituted the current couplers for a more realistic comparison, but this was not the case since official mechanical DAC characteristics are not yet available. This way, the benefits of just PLCF increment can be promptly and correctly measured.

3.5. Implementation of radio communication in Traction Units

Reference [7] describes the set of simulations performed to study the LFs of an experimental train equipped with three radio-controlled TUs with a length of 640 m and a train mass of 1735 T. To perform this study by applying the "relative approach", the train is simulated considering the 2nd and 3rd TU as wagons during the braking (i.e., they do not discharge the brake pipe); hence as a train allowed to traffic (REF). The trains with radio-controlled TUs (DPS) have three different layouts:

- LWL indicates a trainset where the active TUs are at the beginning and the end. The TU in the middle is not active.
- LWLW indicates a trainset where the active TUs are at the beginning and middle. The TU at the end is not active.
- LWLWL indicates a trainset in which all TUs are active.

Randomly changing the wagon's position and performing the simulation of LF for an emergency braking from 30 km/h and after an acceleration, it is possible to compare the two systems (with and without radio-controlled TU) comparing the same trains but having different technologies for TUs. Figure 7 reports the LF for the REF train on the x-axis for each train and the corresponding LF for the DPS train on y axis: first row refers to LCF, the second to LTF. If the point, representing a train with a specific wagon order, is below the bisectrix, it means that the REF train is worst than the corresponding DPS. Depending on wagon ordering, the DPS train is usually safer than the corresponding REF train, even if, for some wagon arrangements (LWLW and LTF), it is vice-versa.

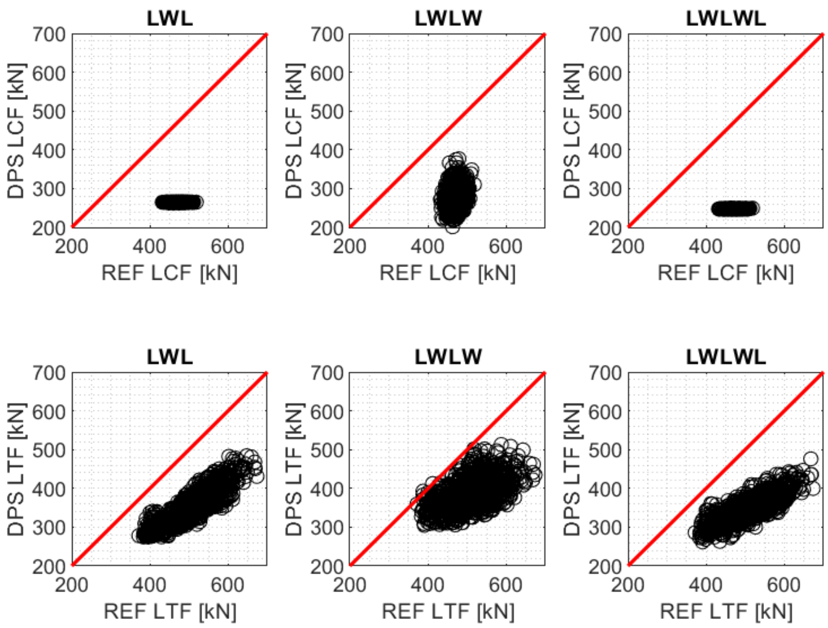

Figure 7. Comparison between classic (REF) trains and trains with radio-controlled traction units (DPS), for different train layouts. 1st row refers to LCF, 2nd to LTF.

It is essential to note that the "relative approach" application differs from the standard way: only one family of trains is generated just by permuting the wagons' position from an initial train configuration. The comparison is achieved by activating or not the radio-controlled communication for DPS and REF, respectively.

3.5.1. Effect of radio technology. The following results compare the LFs of trains formed by coupling two long trains with a total length of up to 1500 m, with a TU placed at the end of the train (the label "SW" applies). The TUs are radio-controlled. The radio link uses GSMR, the current standard, or LTE, as bridge technology for the 5G network (FRMCS). Figure 8 illustrates the probability of potential derailment for IRS 40421 [1200-1600] T trains in LL as blue and red vertical broken lines for TEB and EB, respectively. It also shows trains in which the TUs communicate via GSMR (a) or LTE (b). It is worth noting that the delay in radio communication between the TUs is considered constant for each train: 1.6 s for GSMR and 0.8 s for LTE (see [14]). This time is required to discharge the brake pipe where the guided TU is located and is not just the communication time between the radios. Therefore, the radio technology gives the only difference between the trains in (a) and (b).

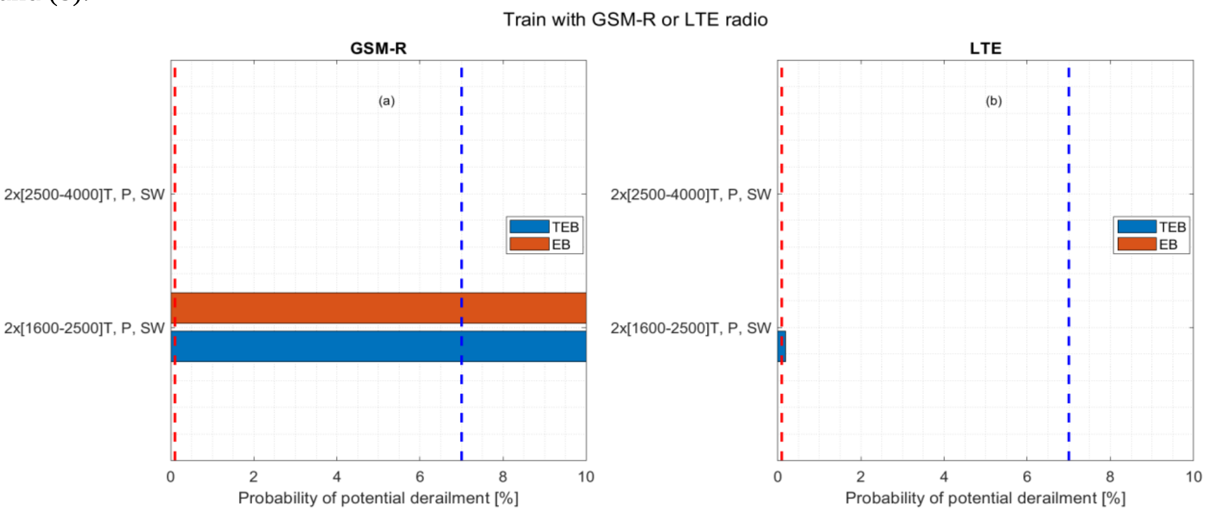

Figure 8. Different probabilities of train derailment according to radio link technology.

As before, there is just one generation of virtual trains; only the radio link technology changes to improve the consistency of the comparison. All families of trains listed in the figure are safer than the reference train family (IRS 40421 LL) independently from the radio technology used, except the trains family formed by coupling two trains running in P, each with a hauled mass of [1600-2500]T and with a 3rd TU at the train end.

3.6. The Iterative Proportional ("IP") Algorithm

This paper proposes an algorithm to change the train mass from an initial value, *m*, to a final value *M*. This algorithm is called Iterative Proportional (IP). The initial mass *m* is the hauled mass of a general train within the reference train family; the new mass *M* is the corresponding mass of the train in the new train family, computed by linear interpolation as:

$$M = M_1 + \frac{M_2 - M_1}{m_2 - m_1}(m - m_1) \tag{3}$$

Where m_1, m_2 and M_1, M_2 are the mass boundaries for reference and new train families, respectively.

Through the "IP" algorithm, it is possible to modify the train mass from *m* to *M*, iteratively. Figure 9 reports the flowchart of this algorithm. If *M*>*m*, the ratio β between the target mass *M* and the mass of the new train is computed. If this ratio is 1, the new train already has the target mass, and the algorithm ends. If the ratio is bigger than 1, the ratio between the maximum wagon mass and the current mass is computed: β_{wi}. Then, the minimum of these ratios is computed: β_i. If this ratio is lower than β, it means that there is a few difference in terms of the maximum loaded wagon and its maximum capacity; if this is the case, $\beta = \beta_i$ and the mass of each wagon is incremented as: $m_{wi} = \beta \cdot m_{wi}$; therefore, the new hauled mass is $m^* = \sum m_{wi}$. The process can restart computing $\beta = \frac{M}{m^*}$. With this algorithm, wagons having the higher mass have a mass increment up to their maximum value. In this process, all wagons having a mass lower than their maximum value have a mass increment proportional to their value ($m_{wi} = \beta \cdot m_{wi}$), until the target mass is reached.

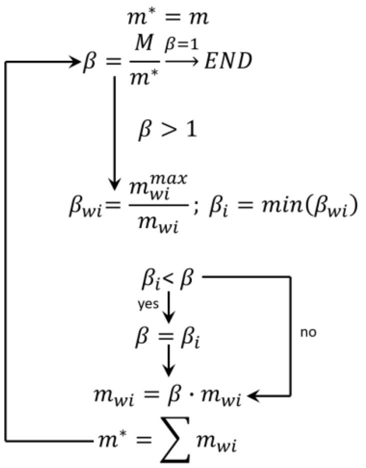

Figure 9. Flowchart of Iterative Proportional (IP) method.

3.6.1. Articulated wagons in the trainset. The IRS 40421 provides explicit values for PLCF only for axle and bogie wagons but not articulated wagons. The results shown in previous sections have proved that the LFs of a train are affected by the wagon type and position. If articulated wagons are in the trainset, the proposed way to apply the "relative approach" is to consider in the reference system the articulated wagons, e.g., trains in the LL regime having a mass between 1200 and 1600 T.

This system is compared in Figure 10 with another train system having a higher mass (1600-1800 T) and obtained applying or not the IP algorithm. The new system has a different braking regime: the Extended Long Locomotive (ELL), with 7 wagons in G (instead of 5) at the beginning of the trainset. The PLCF of articulated wagons are computed following §3.1. The probability of derailment considerably increases for IRS 40421 LL trains, and it is like that of new trains, depending on the assumption made on the PLCF of articulated wagons. If the PLCF of articulated wagons is like that of axle wagons, the new system is equivalent to the reference; otherwise, this statement is not valid, even if this conclusion depends on how the new trains are generated. In Figure 10, the label "noIP" means that the train family has been generated using the classic IRS 40421 algorithm without any guarantee that the number of articulated wagons per train is the same and that they are placed in the same positions along the trainset. Therefore, the results labelled with "noIP" should be discarded.

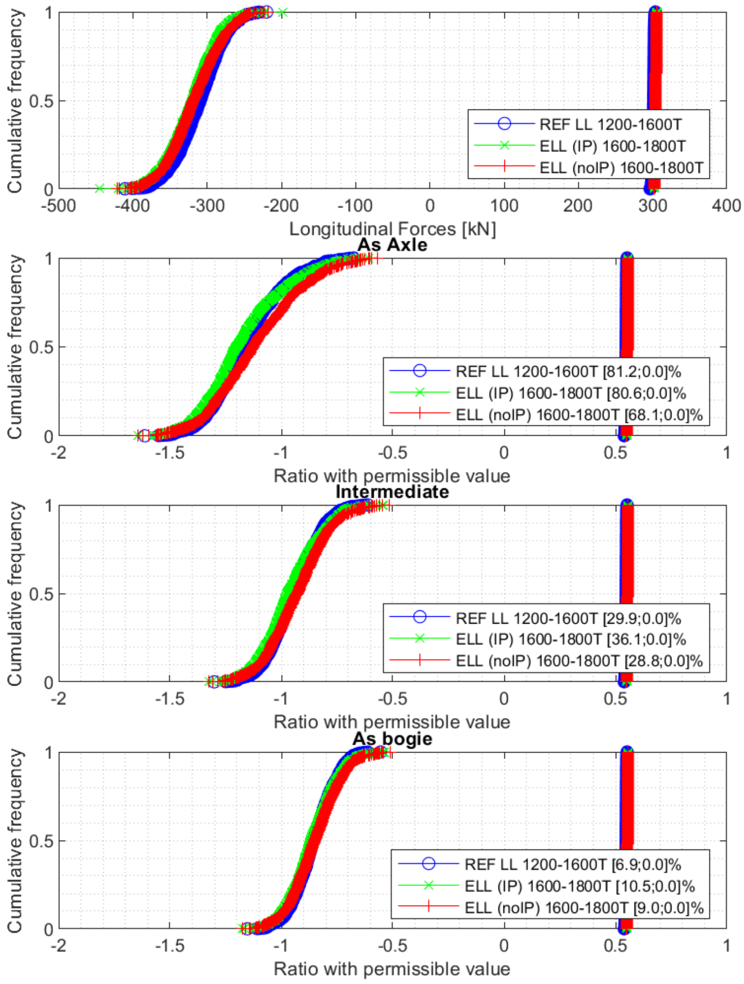

Figure 10. Longitudinal forces for IRS 40421 trains in LL and 1600-1800 T trains in ELL with and without IP algorithm.

3.6.2. Trainset with just articulated wagons. Suppose the trainset is made of only articulated wagons. In that case, the comparison with IRS 40421 LL and ELL (1600-1800T) is given in Figure 11, for emergency braking from coasting (cruising) conditions commanded at 30 km/h.
The figure shows that changing the assumption on the PLCF of articulated wagons, in this case, does not affect the comparison considerably: the mass interval of 1600-1800 T in ELL has the same level of safety as 1200-1600 T in LL. This statement is also true for emergency braking following an acceleration, even if the results are not reported here.

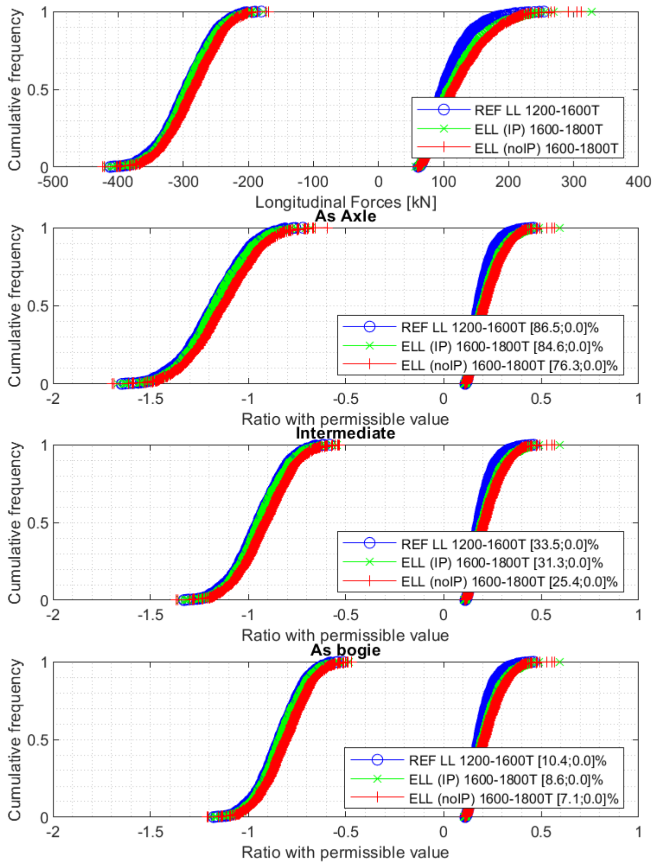

Figure 11. Longitudinal forces for IRS 40421 LL trains, having articulated wagons, applying or not the IP algorithm, compared to 1600-1800 T trains with ELL, performing an emergency braking from 30 km/h.

3.6.3. Application of IP to trains listed by IRS 40421. In this last section, Figure 12 reports the LFs and the ratios with permissible values for IRS 40421 trains, obtained by 1200-1600 LL trains applying ("IP" is used in the label) or not the IP algorithm ("noIP" label is useed). Unlike previous results, the assumption made on the PLCF of articulated wagons does not affect the comparison of train families, and the application of the IP algorithm does not affect the derailment probabilities significantly; therefore is useless. The main reason for this behaviour is that the train families are too different in hauled mass and brake regime; therefore, the number and position of articulated wagons are masked by those other and more relevant differences.

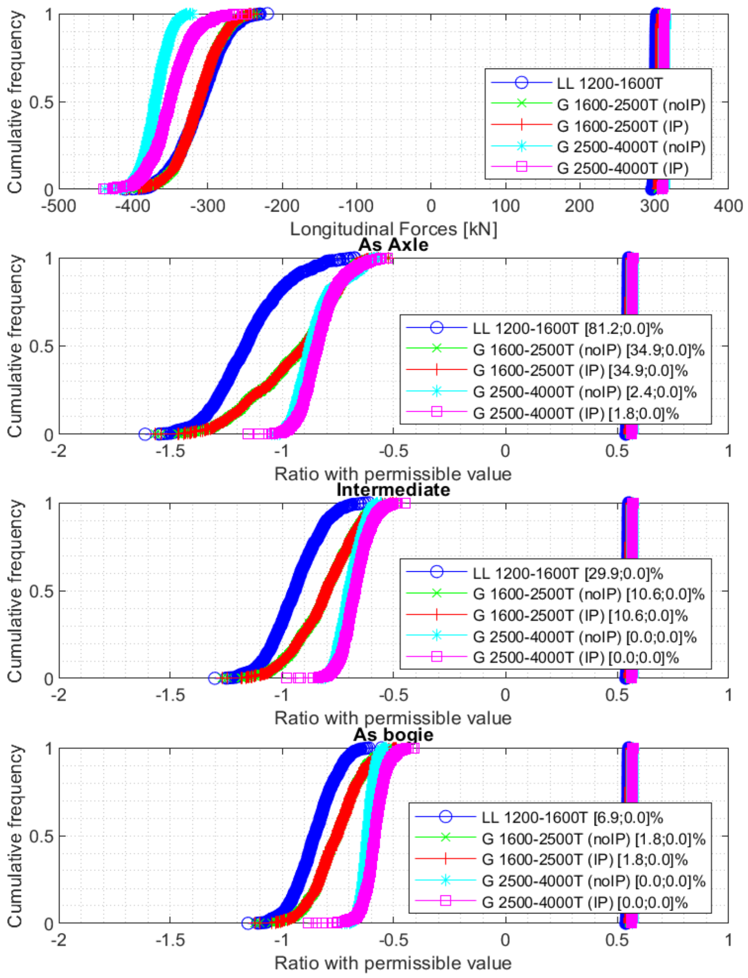

Figure 12. Longitudinal forces for IRS 40421 trains, having articulated wagons, applying or not the IP algorithm.

4. Conclusions

This paper recalls the “relative approach” method envisaged by [11] and [12], which are essential reference documents for Railway Undertakings when a new trainset has to go into service. It provides several use cases of this method application, including the Digital Automatic Couplers (DAC) and radio-controlled traction units. It shows that it is critical to minimize the differences when comparing two families of trains to make the comparison consistent. Moreover, for articulated wagons, which are not explicitly considered by [11], the paper introduces the Iterative Proportional (“IP”) algorithm to generate new trains from a given family of trains, keeping the position and type of wagons but changing the hauled mass. After the introduction of the Extended Long Locomotive (ELL) regime, considering trains with only articulated wagons, the paper finds the equivalence between the IRS 40421 LL trains and [1600-1800] T trains in ELL, using the “IP” algorithm. Finally, the paper shows that the “IP” algorithm is helpful when the two families of trains are similar, e.g., it is not necessary when the comparison happens between LL trains and G braked trains.

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