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Simulation of freight trains with up to three traction units in radio communication

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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. The simulation results have been used to prepare an experimental test campaign to test the Distributed Power System (DPS) technology. The simulations refer to up/down and level track and they compare the LTD of trains with and without DPS, for different train operations and radio link conditions. The DPS technology is proved (by simulations and test) to be a very effective way to increase the efficiency of future freight trains.

1. Introduction

Railway Undertakings (RUs) are always interested to increase the efficiency of freight trains: one way to reach this goal is to increase the hauled mass by a single train, by lengthening it. Limits to increment of train mass and length are given, among others, by the in-train forces exchanged by consecutive or adjacent vehicles. These forces are caused by the fact that the traction and braking force are not the same for each vehicle: i.e., only Traction Units (TUs) apply traction force to accelerate the train and the braking force is not the same or (at least) not applied at the same time by all vehicles. The Longitudinal Train Dynamics (LTD), i.e., the oscillation of the vehicles along the direction of motion, and the longitudinal (or in-train) forces are the consequences of this situation, which is typical of freight trains but not of passengers’ trains. High compressive in-train forces (also known as Longitudinal Compressive Forces - LCF) cause derailments (i.e., safety problems) whereas high tensile in-train forces (also known as longitudinal tensile forces - LTF) cause train disruption (i.e., efficiency problems): both must be avoided during train operation. These in-train forces can penalize the freight train efficiency more than the infrastructure limitation, or, in other words, they do not allow to extract all the capacity from current railway infrastructures.

There are several initiatives in Europe to improve the efficiency of freight trains. One of them has been financed under the Shift2Rail (S2R) initiative “Moving European Railway Forward”, within the Innovative Program 5 (IP5). This Horizon 2020 Research and Innovation (R&I) initiative aims to develop the necessary technology to complete the Single European Railway Area (SERA). The Open Call Project, Marathon2Operation (M2O), has cooperated with the FR8RAIL II Call for Members Project to demonstrate the feasibility of freight trains equipped with Distributed Power System (DPS), using radio communication to control the Traction Units. By implementing the DPS it is possible to reduce the in-train forces.

The concept of DPS is under investigation in Europe since many years from major RUs, e.g., during the European Union Framework Programme 7 (FP7) MARATHON Project trains up to 1500 m were tested by SNCF: DPS increases the points from which the power is applied along the train, and it also increases the points from which the braking is initiated, by improving the synchronicity of braking application and reducing the in-train forces. The most versatile way to realize such idea is the realization of long freight trains made by coupling two or more trains: these trains have more TUs and can carry more load in a safe and efficient way.

Within the cooperation framework between M2O and FR8RAIL II, the simulations of in-train forces have been performed using the UIC TrainDy software [1], originally developed by the University of Rome Tor Vergata with the financial and technical support of Faiveley Transport of Italy (a Wabtec Company). This software has been validated against more than 30 experimental tests made available by the major European RUs: DB AG, SNCF and TRENITALIA; it has been also used to replicate the results of another experimental test campaign carried out by FFL4E Project, within S2R framework, in May 2019 [2].

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.

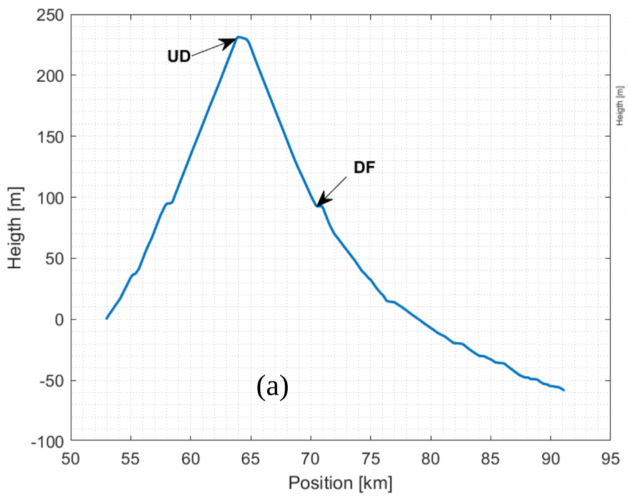
This paper reports the simulation of LTD performed with TrainDy to select the train configuration to test, within the experimental test campaign of FR8RAIL II, and to compute the in-train forces under various working conditions, experimentally replicated. Currently, the experimental results are not available for dissemination, but we can anticipate that the accordance with the simulations is (very) satisfactory. In order to evaluate the benefits of the new technology (i.e., the DPS), it is followed the approach of the UIC Leaflet 421 [5], which 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).

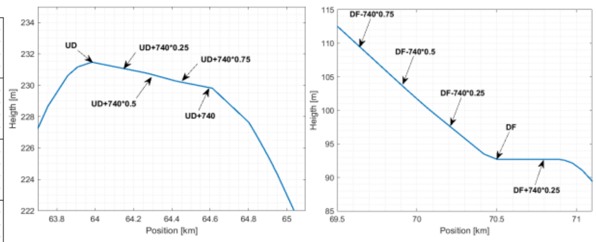
Several results reported in this paper can be found also in M2O deliverables [6] and [7]; however, this paper adds further insights to those results, highlights and systematizes the main assumptions and conclusions of these deliverables. The paper is organized as follows: a) section 2 is dedicated to explain the features of the train and of the track on which the train is tested; b) section 3 reports the way used to determine the experimental train make up and the train operations simulated; c) section 4 shows the main results in terms of in-train forces and stopping distances, for different working conditions of DPS; d) section 5 reports the conclusions and the future work on the subject.

2. Conditions for the experimental test campaign

Within the framework of collaboration among FR8RAIL II and M2O Projects, FR8RAIL II had the responsibility to organize and run the experimental tests and M2O the responsibility to determine the conditions under which these tests are executed in safe conditions (see M2O deliverables [7] and [8]). Consequently, the wagons and the types of TUs to test have been decided by FR8RAIL II, following availability considerations and industrial interests for future applications, whereas track was selected in agreement with M2O, to determine severe conditions for the DPS system in terms of availability of radio signals and effect of up/down hill on in-train forces. The track section (between the stations of Kronach and Probstzella) with the highest variations of slope (around 27 ‰) is reported in figure 1: numerical simulations have been performed both on level and on up/down hill track in order to study the effect of track on in-train forces.

The TUs selected for the tests were two BR187 (from family TRAXX AC3) and one BR188 (from family TRAXX MS3), very similar with respect to performances for in-train forces; then four types of wagons were selected: Eanos_x-59, Res-676, Facns-124, Facns-133. The wagons use composite brake shoes of type LL and are equipped with different types of buffers and draw gears but the exact correspondence with the used wagons was not known at the moment of the simulations, e.g., for Eanos_x-59 the different force-stroke characteristics reported in table 1 were possible (for the complete variability see Appendix A of [7]). This uncertainty is considered in the simulations by randomly considering different coupling elements for each wagon.

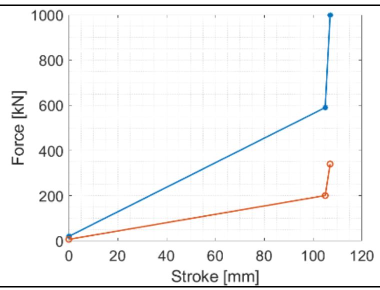
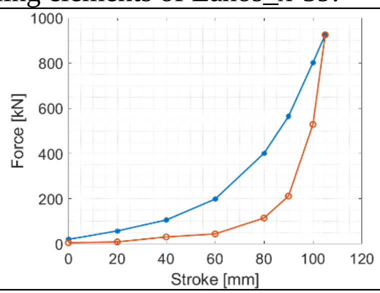
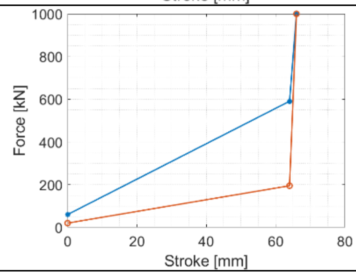
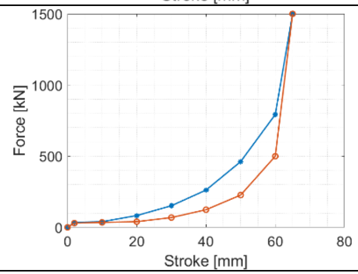




(b) (c)

Figure 1. Section of railway track with the highest variation of slope and indications of point UD and DF (a). Starting points around UD (b) and around DF (c).

Table 1. Force-stroke characteristics for coupling elements of Eanos_x-59.

Buffing gears		
Draw gears		

Only Eanos_x-59 wagons are fully loaded to reach the mass of 1731 ton and the length of 644 m (including the TUs). A train like this is already admitted to the traffic on the selected track and it has been tested with DPS functionalities to study the effect of this technology. Beyond the previous wagons, one measuring coach is placed close to the BR188 TU (at the beginning of the train) and it is used to store the devices needed to handle the measured quantities; the brake of measuring coach is not active.

The train make up is: BR188, Measuring Coach, Wagons of types listed before, BR187, Wagons of types listed before, BR187 (LWLWL acronym is used). It is tested moving the train in two directions (forward “FW” and backward “BW”), i.e., in FW the measuring coach, close to BR188, is at the beginning of the train; in BW it is vice-versa. Moreover, to increase the scope of experimental test campaign, the train is tested both in goods (G) and in Long Locomotive (LL) braking regimes (see [9] and [5], respectively).

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3. Determination of the trainset to test

Given the vehicles, the track, the braking conditions and the running directions of the train in the previous section, the positions of the wagons are permuted between the TUs in order to find a trainset which provides low in-train forces in all different test conditions. To find the best wagon order, four types of trainsets are considered: one is without the DPS functionality and represents a train currently admitted to the traffic (reference, REF, train), the other three are DPS trains. In accordance with the position of active TU, following nomenclatures are used (when the TU is not active it behaves as a wagon, therefore it does not vent the brake pipe):

- LWL indicates a trainset in which the active TUs are at the beginning and at the end. The TU in the middle is not active. Pictogram is , for reference system (REF) and it is  for DPS system.
- LWLW indicates a trainset in which the active TUs are at the beginning and in the middle. The TU at the end is not active. Pictogram is .
- LWLWL indicates a trainset in which all TUs are active. Pictogram is 

Trainsets of reference train family is LWL; trainsets of DPS family are LWL, LWLW and LWLWL.

About the train manoeuvres, the emergency braking from 30 km/h after the train acceleration is used as manoeuvre since it provides high levels of in-train forces. This manoeuvre is simulated considering a radio communication between the TUs () and assuming it is lost at the same time () the emergency braking is commanded by the Driver: these conditions are the worst in agreement with the experience and the results reported in [6]. When the radio link is on, the command at the leading TU, because of DPS technology, is replicated by the remote TUs with a delay given by the technology implemented (4G, LTE radio protocol has been used in the tests): consider that for REF trains, the venting of brake pipe at the remote TU is not allowed, unless the pressure in brake pipe is 3.5 bar. When the radio link is lost, the remote TU controls the pressure in brake pipe and DPS technology vents the brake pipe when a pressure drop is locally detected (0.2 bar is used in *TrainDy* simulations); local air pressure reduction in brake pipe is performed at steps (stepwise): target pressure is 4.5 bar, when a pressure drop in brake pipe of 0.2 bar is detected with respect to 5 bar; then the next target pressure is 4 bar, when another pressure drop in brake pipe of 0.2 bar is detected with respect to 4.5 bar and so on up to a full service braking with target pressure 3.5 bar. For REF train family, in order to simulate the radio link lost, a delay of 5 s between the actions of the two Driver is used, after an Experts' evaluation.

Summarizing, the trainsets are four (one REF and three DPS), the train operations used are two: assuming the radio link between the TUs is active or it is lost. The braking regimes are two (G and LL) and the working directions are two: forward and backward. Since the measuring coach does not brake (as said above), the braking regime LL is possible only in BW direction, according to the operational German rules.

Figure 2 and figure 3 report the in-train compressive (LCF) and tensile (LTF) forces for an emergency braking commanded when the train is at 30 km/h after an acceleration: each circle refers to a train, with a specific order of wagons. The figures provide a one-to-one comparison among the same train but with DPS technology activated or not. It is worthwhile to mention that, to have a fair comparison between REF LWL and DPS LWLWL, the percentage of traction force for each TU is around 67% the maximum value, in the latter case. In this way, the effect of DPS technology on in-train forces is enhanced, since it is the only variation in the comparison; in particular, if the point is below the bisectrix it means that the DPS train is safer than the REF counterpart. In figure 2 the radio link between the TUs is working, whereas in figure 3 it is not; the figures allow the following considerations:

- The in-train compressive forces are always worst in REF trains than in DPS trains, therefore the new technology reduces the risk of derailment, whatever is the condition of radio link. Of course, when the radio link is on, the in-train compressive forces are lower. This result applies also to trains in G regime, even if they are not shown here, for sake of brevity; furthermore, the in-train compressive forces are lower in G than in LL braking regime both for REF and DPS trains.

- The in-train tensile forces are usually better for DPS than for REF trains; the trainset LWLW (i.e., the typical situation obtained when two trains are coupled) provides higher LTF with DPS in some situations: depending on wagon mass arrangement (see figure 2) and on the conditions of radio link (see figure 3). Moreover, the values of LTF are higher when the radio link is on than when it is lost, even if this is a particularity of LL regime in which the LTF are higher than those in G regime.

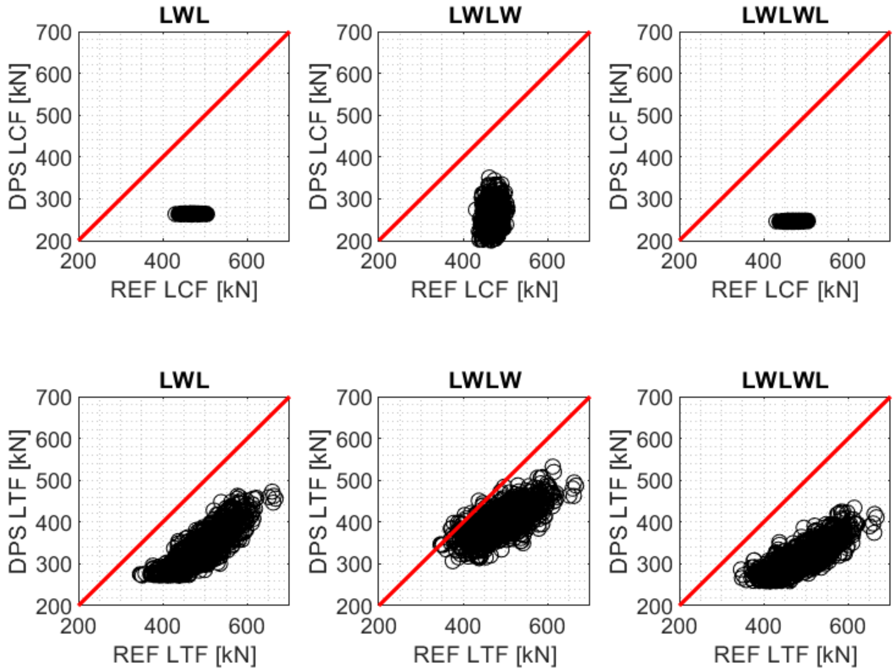

Figure 2. Acceleration up to 30 km/h followed by an emergency braking, braking regime LL and radio link working, “BW” direction.

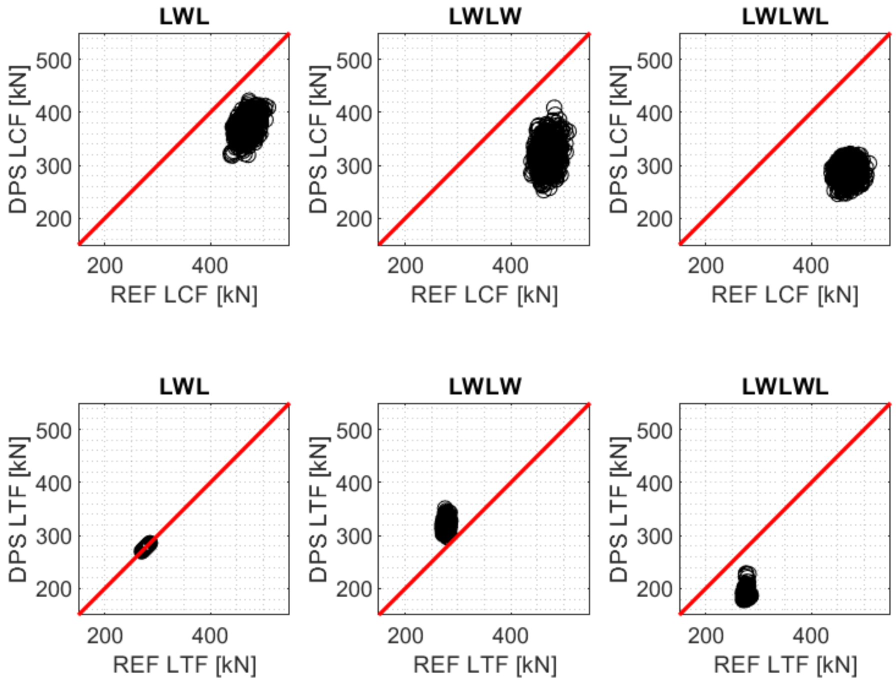

Figure 3. As in figure 2, but the radio link among TUs does not work.

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- The variability of in-train forces is given by the spreading of the points: it is higher for LTF when the radio link works, and it is higher for LCF when it is lost. Anyway, these results confirm the benefits of a specific wagons ordering on the in-train forces: a suitable wagon order (when it is possible) is an effective way to safely increase the train hauled mass.
- The one-to-one comparison here reported shows the benefits of DPS technology on in-train forces without the meaningful and overlapped effect of wagon mass arrangement. In case the REF train family would have been compared directly to DPS train family, using histograms or cumulative plots, an overlap between the in-train forces would have been witnessed, giving the wrong idea that for some wagons arrangements the in-train compressive forces of DPS train could have been higher than those of REF, which is not the case.

Figure 4 reports the screenshot, from *TrainDy* software, of selected trainset, which will be further simulated in the next sections: this specific trainset minimizes the sum of in-train tensile and compressive forces in all scenarios analysed: with and without DPS (REF), in G and LL braking regime, in both directions, and with and without radio link; in this way, the selected trainset is suitable to be tested in all experimental conditions.

Position	Type	Manoeuvre	Wagon Length [m]	Train Length [m]	Brake Pipe Length [m]	GP coupl. status	Load [t]	Tare [t]
1	BR188	Man01L	18.9	18.9	37.8		0	86
2	Measuring		26.4	45.3	29.04		0	63
3	Facns-133		16	61.3	16		0	22
4	Res-676		19.9	81.2	19.9		0	24.5
5	Facns-124		19.04	100.24	19.04		0	25
6	Facns-133		16	116.24	16		0	22
7	Res-676		19.9	136.14	19.9		0	24.5
8	Facns-124		19.04	155.18	19.04		0	25
9	Eanos x-59		15.74	170.92	15.74		60	23.56
10	Facns-124		19.04	189.96	19.04		0	25
11	Facns-124		19.04	209	19.04		0	25
12	Eanos x-59		15.74	224.74	15.74		60	23.56
13	Facns-133		16	240.74	16		0	22
14	Eanos x-59		15.74	256.48	15.74		60	23.56
15	Eanos x-59		15.74	272.22	15.74		60	23.56
16	Eanos x-59		15.74	287.96	15.74		60	23.56
17	Res-676		19.9	307.86	19.9		0	24.5
18	Facns-133		16	323.86	16		0	22
19	BR187	Man01G	18.9	342.76	37.8		0	84
20	Eanos x-59		15.74	358.5	15.74		60	23.56
21	Eanos x-59		15.74	374.24	15.74		60	23.56
22	Eanos x-59		15.74	389.98	15.74		60	23.56
23	Eanos x-59		15.74	405.72	15.74		60	23.56
24	Facns-133		16	421.72	16		0	22
25	Facns-133		16	437.72	16		0	22
26	Res-676		19.9	457.62	19.9		0	24.5
27	Eanos x-59		15.74	473.36	15.74		60	23.56
28	Eanos x-59		15.74	489.1	15.74		60	23.56
29	Facns-124		19.04	508.14	19.04		0	25
30	Facns-133		16	524.14	16		0	22
31	Res-676		19.9	544.04	19.9		0	24.5
32	Res-676		19.9	563.94	19.9		0	24.5
33	Res-676		19.9	583.84	19.9		0	24.5
34	Res-676		19.9	603.74	19.9		0	24.5
35	Facns-124		19.04	622.78	19.04		0	25
36	BR187	Man01G	18.9	641.68	37.8		0	84

Figure 4. *TrainDy* software screenshot of the selected trainset.

4. Simulations of LTD for selected trainset

In this section, two types of results are shown: the results in terms of in-train forces on up/down hill track of figure 1 and the stopping distance on level track. The results in terms of in-train forces on up/down hill are reported since this type of track is capable to enhance the LTD, whereas the results on stopping distance are provided to compare the DPS and REF trains for different working conditions of radio link.

4.1. In-train forces on up/down hill, with technical parameters

In this section, two train operations are considered (for the complete list of simulations needed to check the in-train forces of DPS trains against those of REF trains refer to [6]).

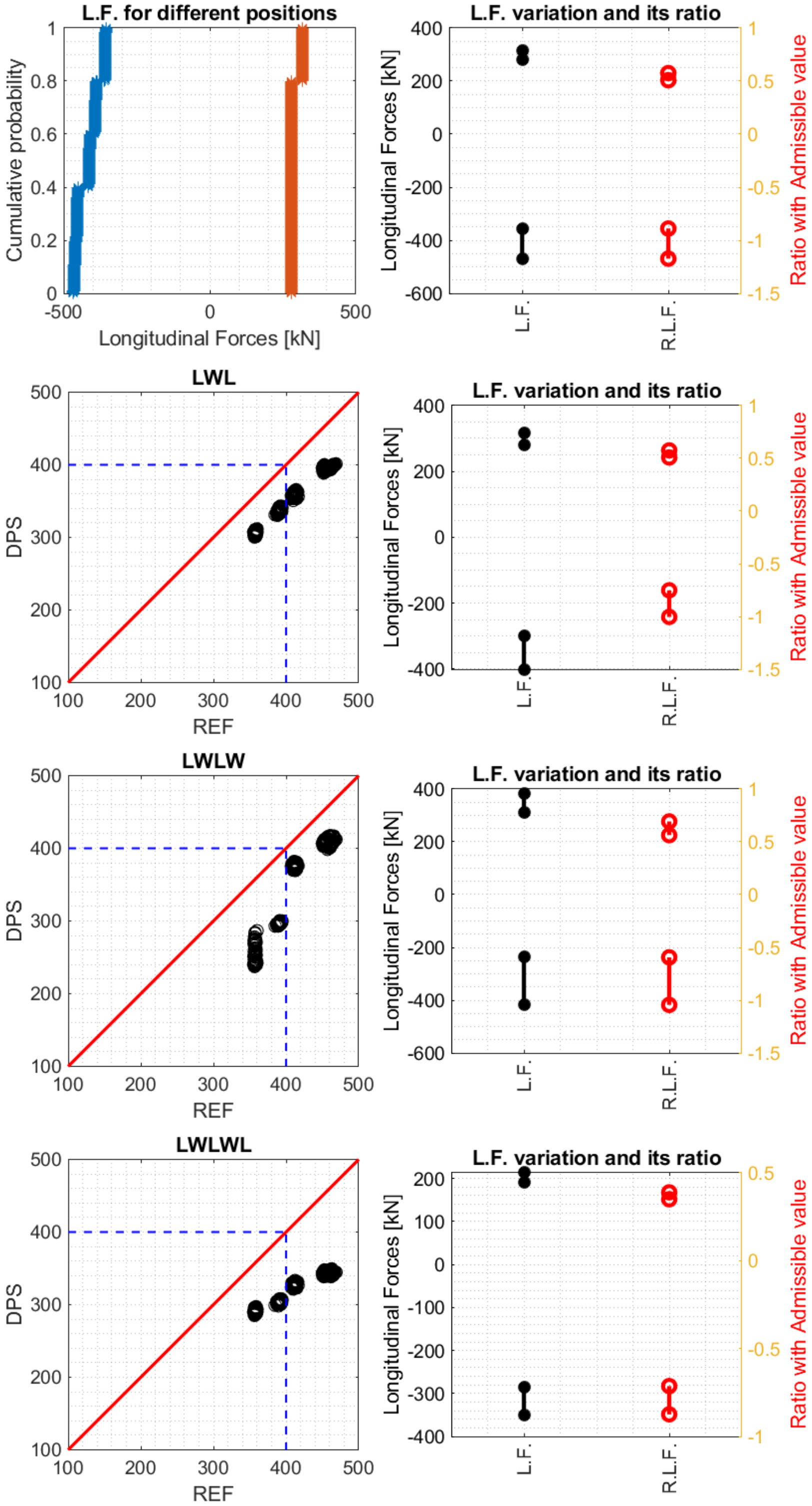

Figure 5. *Braking regime is LL, train position around point UD of figure 1. On the left the forces are reported, in [kN] for REF and for the different arrangements of DPS; on the right, the minimum and maximum Longitudinal Forces (left axis) and the ratios against their admissible values (right axis).*

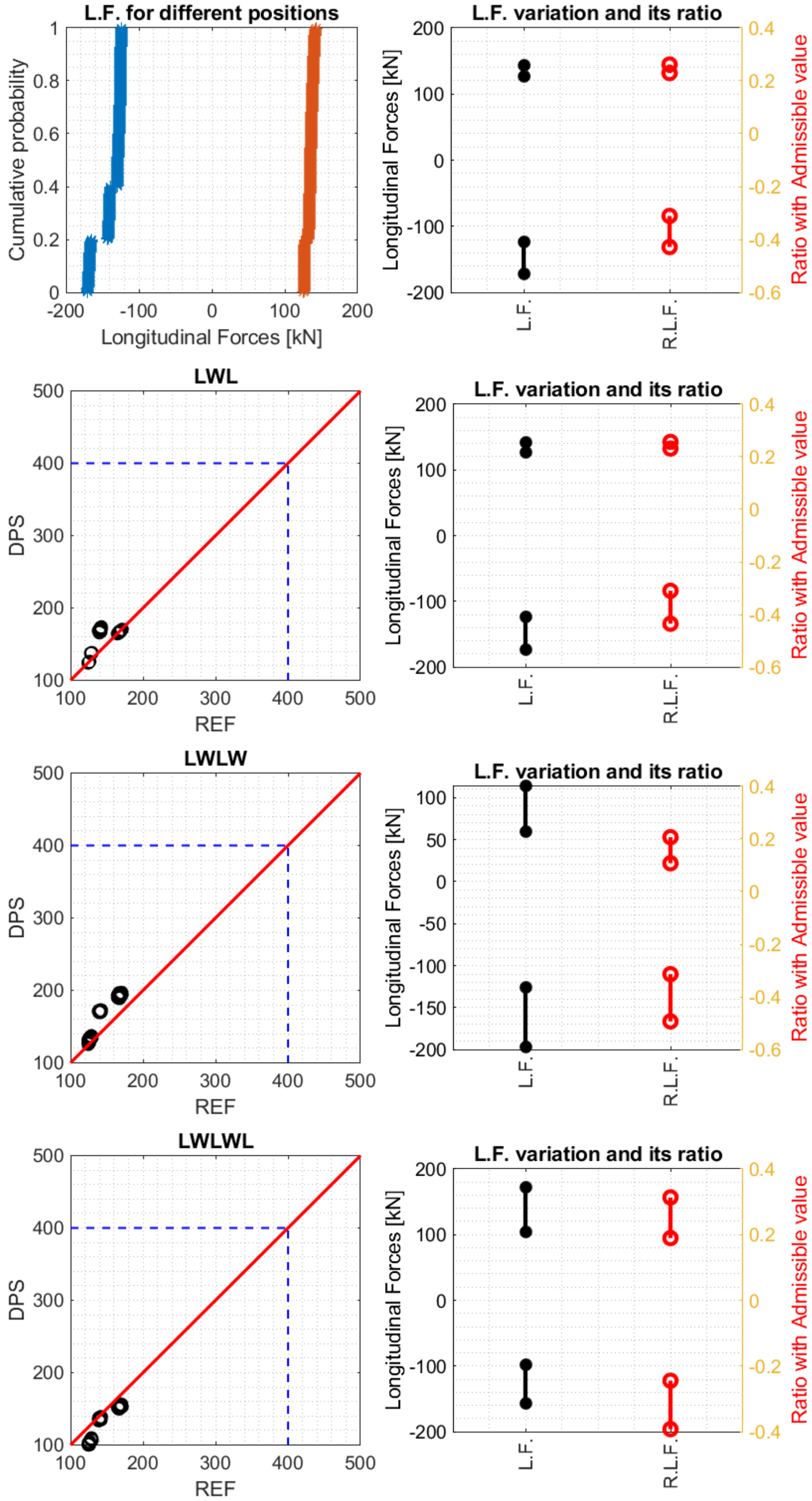

Figure 6. *Braking regime is G, direction is FW, train position around point DF of figure 1. The content is like figure 5.*

Namely:

- Traction up to 30 km/h followed by an emergency braking, when there is a radio communication loss (emergency braking is applied when the radio link is lost) and train is around point UD (see figure 1)

- Electrodynamic braking + First Application Step of braking (target pressure in brake pipe is 4.5 bar) followed by an emergency braking, when the speed is 30 km/h. In this scenario, the radio link is lost before the emergency braking is applied: for this combination of train operation and track (the train is around point DF of figure 1) this condition is the worst, according to simulations reported in [6].

Figure 5 reports the comparison of in-train forces between REF and DPS trains for different positions around point UD where the emergency braking is commanded, figure 1 (b), and for different variations of the technical parameters considered most influencing for the in-train forces, see [10]: the first row shows the cumulative frequency for REF trains on the left and the variability of LCF and LTF on the right (LTF are positive and LCF are negative, in this representation). On the right column of this figure, the ratio between in-train forces and their admissible values is also reported: when this ratio is bigger than +1, there is a risk of train disruption, whereas when it is lower than -1, there is a risk of train derailment. The other graphs of this figure report the one-to one comparison between REF and DPS trains, as in previous figures, only in terms of LCF (and not LTF, for brevity): the values of 400 kN for LCF are highlighted since these values are the maximum LCF mentioned in the UIC 421. Since the simulated trainset is always the same, the dispersion of in-train forces is given by a) the different positions on the track where the emergency braking (EB) is commanded and b) the variation of technical parameters; since the results are clustered according to the position at which the EB is commanded they show that, for this application, the position on the track where the emergency braking is commanded influences in-train forces more than the technical parameters variation. As before, the LCF of DPS trains are lower than those of REF trains.

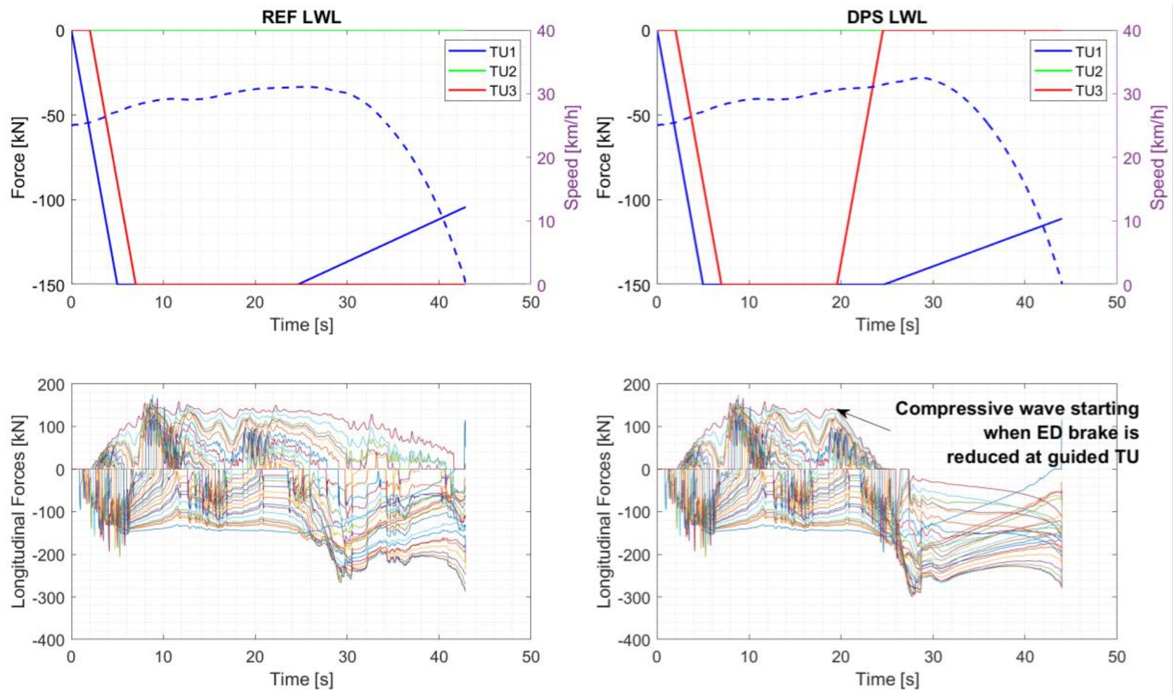

Figure 7. *Force at TUs and train speed (top); time evolution of LF (bottom), for REF (left) and DPS (right) train.*

Figure 6 is like figure 5 but the train performs the other manoeuvre listed before; moreover, it operates in G regime and in direction FW. For this manoeuvre, the DPS train is usually worse than the REF train and this is confirmed also by other results reported in [6]. The reason for this behaviour is the current implementation of DPS: when the radio link is lost, the electrodynamic force reduces automatically, and this causes a compressive wave (an example is given in figure 7), resulting in higher LCF.

The automatic removal of electrodynamic brake (and of traction force) when there is a radio link problem for some seconds (currently 2 s) is a conservative behaviour that can cause non-necessary in-train forces. This behaviour can be improved with a future development of DPS system in different ways, e.g., reducing the gradient of TU force reduction.

4.2. Considerations on stopping distance

This section analyses the performance of DPS in terms of stopping distance (table 2), considering the occurrence of DPS failure in detecting the pressure drop of 0.2 bar in brake pipe. The analysis is deterministic and only in regime G, where the highest stopping distances are expected. There is no need to employ a statistical analysis to show the benefits of DPS solution, since changing the parameters changes the numeric results but not the conclusions about the benefits of DPS with respect to reference system (REF). REF system is considered in nominal mode and in degraded mode (the TU *interlock* intervenes at 4.5 bar reducing the force at TU and braking is commanded by second Driver when pressure in brake pipe is 3.5 bar).

DPS system is considered working in three ways:

- On, radio link in “on”.
- Off, radio link is “off”. When DPS is activated the stepwise reduction of pressure is triggered by the detection of air pressure drops in brake pipe.
- Fail, DPS fails in detecting the pressure drop of 0.2 bar in brake pipe: the traction force is reduced by the intervention of TU interlock system.

Two train operations are considered:

- Emergency braking from (full) acceleration.
- Emergency braking from coasting.

Emergency braking is commanded when train speed is 100 km/h and it is assumed that the DPS does not perform any action on TU force unless there is an air pressure drop in brake pipe.

Table 2. Comparison of different stopping distances

Emergency braking at 100 km/h from full traction				
		Nominal	Degraded	
REF	LWL	863	864	
		On	Off	Fail
DPS	LWL	812	847	864
	LWLW	811	841	855
	LWLWL	833 (806)	875 (844)	898 (860)
Emergency braking at 100 km/h from coasting				
		Nominal	Degraded	
REF	LWL	793	794	
		On	Off	Fail
DPS	LWL	768	789	794
	LWLW	766	792	794
	LWLWL	762	790	794

The results on stopping distance (measured as difference between the final running distance and the position where the air pression drop starts in brake pipe at the first TU), show that:

- When radio is working, the stopping distances with DPS are always better than the reference train. Above consideration usually stands also when radio communication is lost; when this is not true the red colour is used. When the DPS is not able to detect the air pressure drop of 0.2 bar (see Fail column), the stopping distances are the same or lower than the REF system (except for LWLWL in emergency braking after full traction).
- For REF system and train length around 650 m there is no meaningful difference between nominal and degraded condition.

- For emergency braking from full traction, looking at DPS LWLW, when DPS fails detecting the air pressure drop, the stopping distance is lower than case LWL, since the activated TU is in the train middle, and it detects before the air pressure drop coming from the leading TU and traction force is removed before than case LWL.
- For emergency braking from full traction, looking at DPS LWLWL, there are two sets of results:
  - For full traction: the provided traction force is higher than the REF case (since there are three TUs)
  - For 67% of maximum traction at each TU: the provided traction force is roughly the same of REF case. Results are displayed within parentheses.

  Providing the same amount of power of the reference case results in lower stopping distances also for this trainset. It is important to note that also results on Longitudinal Forces have been computed considering, for traction force, the same amount of reference case, therefore, this result does not provide a bigger constraint.

  Looking at UIC 544-1 [11], for this type of train, having a percentage of braked weight around 80%, the allowed stopping distance in brake position G is around 920 m, which is higher than all simulated values.
- For emergency braking from coasting, when the radio connection in on, the stopping distances decrease from LWL to LWLWL: having closer or higher number of discharge points in brake pipe, improves the braking efficiency.
- For an emergency braking from coasting, when the radio connection in lost, the stopping distances are very similar for all positions and number of activated TU: small differences seem caused by a different internal dynamic, which has a minor effect on stopping distance.

5. Conclusions

The main conclusion of this paper is that the Distributed Power System (DPS) described here always improves the safety of freight trains currently in service when radio communication is available, with respect to Longitudinal Compression Forces (LCF). When there is a radio communication loss, the DPS train is usually better than the reference (REF) train with respect to LCF: the scenarios in which this conclusion is not valid refer to an initial application of electro dynamic brake, which can be optimized. Above conclusions do not depend on the track gradient, i.e., the DPS train is better than the REF train with respect to LCF, even if the LCF values depend on the track gradient. The section on stopping distance has shown that DPS technology is able to reduce the stopping distance and this statement is true for all the working conditions of DPS analysed. In general, an optimized mass arrangement is beneficial also with DPS technology and it can increase the hauled mass, safely. Further studies are needed to optimize the behaviour of DPS brake to better consider the trainset in which this technology is implemented: i.e., different and more optimized behaviours are possible according to different trainset layouts (LWL, LWLW or LWLWL).

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6. References

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