Deliverable D 3.1
LTD simulations report

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0.3	17/12/2019	First results of the simulations
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Summary

1. Executive Summary

The project Marathon 2 future Operation (M2O) developed in close collaboration with FR8RAILII is asked to prepare the grounds for future operation of certain types of standard and long trains with distributed traction up to 4 locomotives connected by GSM-R. In this project M2O is responsible for the communication safety in the global architecture of the train and of the global safety of the consist. This implies that data on the characteristics of the locomotives have either to be provided by FR8RAILII partners or otherwise issued from general locomotive characteristics. To reach that goal and to be able to give guide lines to Railway Operators to create safe consists, the project is using the UIC software TrainDy, recognized by the European railway undertaking community as delivering results insuring train consists safety as regards derailment risks or train integrity, to simulate in-train forces during the most critical operational scenarios, considering also the random variation of the most relevant parameters impacting the Longitudinal Train Dynamics, according to the previous sensitivity analysis developed in D2.2 of M2O.

The first part of this deliverable shows the comparison of TrainDy simulations with the measurements of in-train forces made during the experimental tests of May 2019 carried out by FFL4E. These tests have been used to assess the results of TrainDy simulations on selected tests of the full experimental campaign (more than 100 tests) and to provide further inputs for the simulations such as the gap among the buffers, the braking efficiency and so on.

The results of the TrainDy simulations, showed in the second part, employ the selection of most relevant parameters for in-train forces, developed in D2.2 of M2O. These parameters are the delay in the communication between the Traction Units, the time to fill the brake cylinders, the efficiency of the braking and the pressure in brake cylinders at the beginning of the filling.

In the second part of this deliverable it appeared, from simulations made for previous projects, that for whatever type of train running on the network the most critical operational situations are the emergency braking and the full traction followed by an emergency braking in nominal or degraded mode (like a loss of communication among TUs). To be able to cover the large variety of trains running on the networks composed of all sorts of wagons and all types of loaded mass, a random generation of train families has been created using train mass, all types of wagons and their payload mass of a data base of more than 230000 trains running in Germany. Then, categories of trains, lengths of trains, type of train braking systems: G, LL, GP or P have been considered to cover the classical types of consists running on the European Networks. The basic sub-trains thus generated have been connected to create the virtual train consists to be simulated with up to four TUs and a length up to 1500m.

The analysed train lengths of the whole train (TU included) are: 740, 840, 1000, 1200 and 1500 m. Other task of the project, progressing in parallel in WP2, having shown that the actual radio communication by GSM-R was not able to cope with more than 2 TUs, other new technology characteristics have been used to simulate more than 2 TU trains: LTE and 5G. The second radio solution based on LTE (used as bridge technology for FRMCS* based on 5G radio) and the third radio solution based on 5G have been used for simulations for more than 2 TU trains of the various lengths knowing that the first one based on GSM-R is ready for present operation.

The results of some hundred thousands simulations enabled to define a field of possibilities to create a safe train.

For every number of TU in the whole train (up to four and 1500 m), a train family with distributed power and braking (i.e. with DPS) safer than the current running trains has been found, at least in nominal mode.

LTE which is being developed for public use (which entails to introduce some safety protections) proved to be more effective than GSM-R in terms of in-train forces, for all train families simulated. The third based on 5G, will be available in the near future proved to be even better than LTE.

The best results in terms of hauled mass and overall train length have been obtained when the wagons of the whole train run in G (goods) regime.

In the last part of the deliverable it has been shown that, in all degraded mode cases, mitigation solutions simulated will involve operational driving strategy which will result in significant reductions of in-train forces.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
TU	Traction Unit
LTD	Longitudinal Train Dynamics
LCF	Longitudinal Compressive Forces
LTF	Longitudinal Tensile Forces
DPS	Distributed Power System
EB	Emergency Braking
T-EB	Full traction followed by an emergency braking
DBV	Driver's brake valve

3. Background

The present document constitutes the Deliverable D3.1 "LTD simulations report" in the framework of the TD5.4, of IP5.

This deliverable also contains in section 5 a comparison between the Longitudinal Forces computed by the UIC TrainDy software and the experimental measurements performed by FFL4E in May 2019.

4. Objective/Aim

This document has been prepared to provide a technical basis for the decision of the Partners of FR8RAIL II to perform the experimental tests to be conducted in 2020 (TD5.4). Therefore, this deliverable analyses different trainsets created by the coupling different sub-trains having different length and hauled mass. In these consists the overall number of Traction Units (TU) could reach 4, variously placed along the train which may have an overall length up to 1500 m.

Moreover, the deliverable analyses different radio technologies for the communication between the TUs, to show the benefits of each one in terms of Longitudinal Train Dynamics (LTD) and namely in terms of Longitudinal Forces (LF) or in-train forces. Also according to the simulations results, the Partners of FR8RAIL II can choose the most suitable radio technology to be implemented in the experimental tests foreseen in 2020.

Upon decision of the Partners of FR8RAIL II, from the train families analysed in this deliverable, one or more trains will be selected and will be subject to a more specific analysis (considering a specific track) in order to prepare the safety case in D3.3.

5. Comparison TrainDy vs S2R Experimental Tests May 2019

In this section, a review of the simulation activity performed with TrainDy to reproduce the S2R tests of May 2019 is provided. The aim is to quantify the agreement of TrainDy with experimental tests and to extract the data of the actual behaviour of the DPS system, mainly in terms of communication delay for the activation of the brake pipe venting.

Section 6.1 shows some comparisons among TrainDy and experimental tests. These comparisons are better when the forces are high and not when they are small, as already observed during the validation process of TrainDy software in 2018. This is not a problem, since the small longitudinal forces, which TrainDy predicts with a low accuracy, are not relevant neither for derailment nor for disruption risk.

From the comparison with experimental tests several data have been extracted (section 5.2) and they will be used for the simulations of the virtual trains in the next sections. These virtual trains are possible trains that can run with DPS technology.

5.1. Train composition and simulated tests

In May 2019 the Consortium FFL4E has tested a train equipped with DPS system (employing the GSM-R radio) and two Traction Units (TU) between Rotenburg (Bremen) and Buchholz (Hamburg). The train has a "sandwich" configuration with leading Traction Unit (TU) at the beginning and guided TU at the end of the train consist, showed in Fig. 1 (screenshot from TrainDy GUI).

The complete test report is given by the document "S2R Experimental Report (draft) 57985-TVP21-192786-PR01_mit Anlagen Komm DB.pdf", where more data on the tests can be found.

Only some tests have been simulated with TrainDy, in agreement with the Partners of FR8RAIL II. Tab. 1 reports the list of the simulated tests along with their mean features: 20 tests have been simulated with TrainDy, whereas experimental tests were around one hundred. First column of Tab. 1 reports the number of tests according to the previously quoted pdf: more tests indicated that the same test conditions have been repeated more times. Differences in the results provide a measure of tests scatter. Train operation is provided in the next column. All tests have been executed on a straight and planar track. Among these tests, only tests from 058 to 061 refer to degrade mode conditions (DPS is OFF), where the DPS system has been put out of service, artificially; the others refer to nominal conditions (DPS is ON) where the TU communicates via radio link. Last column reports the braking regime of the train, according to UIC nomenclature.

Fig. 1   S2R train May 2019, from TrainDy GUI

Tab. 1 Test table.

Tests	Manoeuvre (Train Operation)	Speed	DPS	Regime
066 068 075 081	Emergency braking (EB)	100	ON	LL
058 059	Acceleration up to 30 km/h, DPS off, reduction of traction force at guided TU, then EB from the leading TU. Guided TU reduces pressure step-wise (after complete reduction of power)	30	OFF	LL
060 061	Acceleration up to 30 km/h, emergency braking from the leading TU and simultaneous DPS off. Guided TU reduces the power and when it is zero, it starts the step-wise reduction of pressure.	30	OFF	LL

049 051 057 062	Service braking (SB)	100	ON	LL
019 022 032 034	Emergency braking (EB)	60	ON	G
036 042 043 044	Emergency braking (EB)	30	ON	G

5.2. Data extracted from the tests

In order to improve the comparison among the TrainDy simulations and the experimental tests, some inputs provided by DB Systemtechnik, containing general assumptions on train data, have been adjusted according to the simulation results. These inputs will be used for the massive simulations test campaign described in the next sections. For sake of clarity, it is worthwhile to mention that some inputs here listed are typical of TrainDy software and they could be not immediately understandable, even by an Expert in Longitudinal Train Dynamics (LTD) that does not use TrainDy software.

A gap (space) of 40 mm is considered among the buffing gears heads of each coupling.

Tab. 2 Force-Speed characteristic

Force [kN]	300	280	220	150
Speed [km/h]	0	40	90	140

Tab. 2 reports the Force-Speed characteristics of the Traction Units. This curve has been taken from the test 058.

In order to simulate tests 059-060, the percentage of traction application for the 1st TU has been set to 98% and for the 2nd to 94%. For test 061 94% is used for both TU. The value of 100% will be used later on.

Traction is applied by both TU with a gradient of 15 kN/s and it is removed with 200 kN/s for emergency braking in leading TU and with a gradient of 33.81 kN/s and 900 kN/s for guided TU, during the degraded mode. Gradients in degraded mode will be changed in order to find a gradient value that improves the LTD.

Tab. 3 reports the changed parameters of the distributors:

Tab. 3 Distributors parameters

Equivalent volume of acceleration chambers [l]	0.3
Diameter of the equivalent nozzle of acceleration chambers [mm]	3
Pressure drop for activation of acceleration chambers [bar]	0.3
Time to reach 95% of pressure in brake cylinder in P [s]	3.8
Time to reach 100% of pressure in brake cylinder in P [s]	4
Time to reach 95% of pressure in brake cylinder in G [s]	21
Time to reach 100% of pressure in brake cylinder in G [s]	23

To simulate with TrainDy the emergency braking of the TU, it has been modelled as a succession

of two manoeuvres: an emergency braking up to a pressure of 1.2 bar, followed by a service braking with target pressure 0.5 bar. The equivalent diameter of the Driver's Brake Valve has been set to 25 mm and the timings for the service braking are 0.1s and 0.3s. If the emergency braking follows the acceleration, then it has been modelled as an emergency braking up to 2.2 bar and then by a service braking up to 0.5 bar.

For degraded mode, the guided TU performs a service braking with an equivalent diameter of 5mm and timings 0.1s – 0.3s. Effect of these parameters is investigated during the massive simulation plan.

Wagons are equipped with composite brake blocks type LL; even if TrainDy is capable to model this type of shoe, quicker simulations and better agreement with stopping distance have been obtained by using Karwatzki model (suitable for cast iron brake blocks). An increment of braking force of 15% has been employed when the initial speed of the braking is 30km/h and 60km/h.

Tab. 4 reports the communication delay between the two TU for each test, i.e. according to TrainDy software the delay in brake pipe venting among the two TU. Experimental data, according to MATLAB chi2gof and ztest, are extracted from a Normal probability distribution having average value of 1.604s and standard deviation of 0.1612s: these results are not so far from the sensitivity analysis, where the average value of 1.7s and the standard deviation of 0.17 where employed for GSM-R, see [1].

Tab. 4 Tests and communication delays

Test	066	068	075	081	049	051	057	062	019	022	032	034	036	042	043	044
Delay	1.82	1.62	1.72	1.52	1.65	1.87	1.84	1.61	1.55	1.45	1.46	1.3	1.4	1.55	1.7	1.6

It is worthwhile to mention that once the parameters are set, each TrainDy test requires simply to adjust the train operation to what happened in the real tests.

6. Main data used for the simulations of virtual trains

From the comparison activity between TrainDy and the experimental tests, it is possible to "extract" the following parameters for the simulations in section 7:

- Force-speed characteristic of the traction units as in Tab. 2.
- Percentage of application of power: 100% for both TU.
- Gradient for the traction application 30 kN/s per train (with 4 TU a gradient of 7.5kN/s per TU is applied).
- Gradient for the traction removal of 200 kN/s in nominal mode and of 60 kN/s in degraded mode, latter gradient can be adjusted because of LTD.
- Distributors' parameters follows the data provided by DB Systemtechnik with TrainDy wagon data.
- Emergency manoeuvre simulated as an emergency braking up to 2.2 bar and then by a service braking up to 0.5 bar for both TU, if this manoeuvre follows an acceleration. If the emergency braking is commanded from coasting conditions, the target pressure is 1.2bar and then 0.5bar for the service braking.
- Degraded mode, on guided Traction Unit, is modelled as a service braking with equivalent diameter of 5mm and timings for the service braking of 0.1s and 0.3s.

- Brake blocks of wagons will be simulated as cast iron, with the increment of 15% of braking force when the braking starting speed is lower than 100km/h.
- Communication delay: normal distribution with average 1.604s and standard deviation 0.1612s

Moreover, most relevant parameters for LTD, according to the Sensitivity Analysis [1], are considered with their statistic variation. Next bullet points list the parameters with their statistic variation:

- Time to fill the brake cylinders at 95% of their maximum value is a Gaussian distribution with mean and standard deviation as follows, according to the brake regime [2]:
  - Passengers brake regime: mean value 5 s, standard deviation 0.33 s.
  - Goods brake regime: mean value 24 s, standard deviation 2 s.
- Pressure in brake cylinder at the end of in-shot function: A Gaussian variation of this parameter is applied with standard deviation equal to 1/3 of the reference value and mean value equal to the reference value.
- Mean efficiency of the rigging ratio (typically the reference value is 0.83): A Gaussian variation of this parameter is applied with standard deviation equal to 0.08/3 times the reference value and mean value equal to the reference value.
- Time delay in the venting of brake pipe: from experimental tests (according to Tab. 4) a mean value of 1.604 s and a standard deviation of 0.1612 s are employed in a Gaussian distribution.

6.1. Comparisons TrainDy – Experiments, results

In this section, the comparison of TrainDy simulations and experimental measurements are provided for following tests:
- 066, EB from 100 km/h in nominal mode
- 058-059, degraded mode with loss of communication <u>before</u> the emergency braking commanded by the leading TU.
- 060-061, degraded mode with loss of communication <u>after</u> the emergency braking commanded by the leading TU.

For each result, the solid line is used for the experimental measurements ("EXP" label is also used) whereas the dashed line for TrainDy results ("TDY" label is also used). Same colours refer to the same wagon or coupling; Loco 1 (or L1) refers to the leading TU and Loco 2 (or L2) refers to the guided TU. For each test, three types of results are reported: a) mechanical results, i.e. TU force vs time and speed vs time; b) pneumatic results, i.e. pressure in brake pipe and pressure in brake cylinders; c) in-train forces results, i.e. the LCF and/or the LTF of the measured couplings.
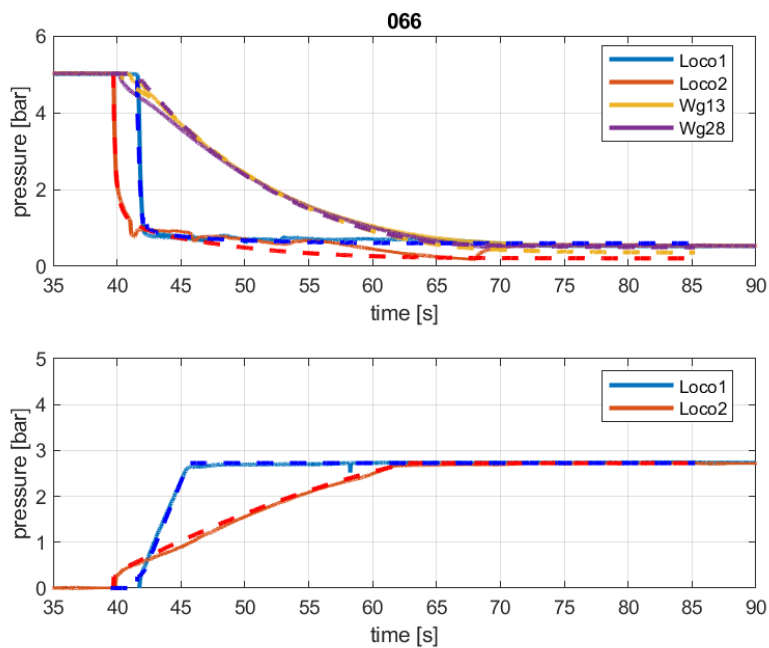
6.1.1. Test 066
In this test, the in-train forces computed by TrainDy considerably differ from those measured (see Fig. 4): this causes no concern since the forces are small and they are not dangerous neither for derailment nor for disruption risk.
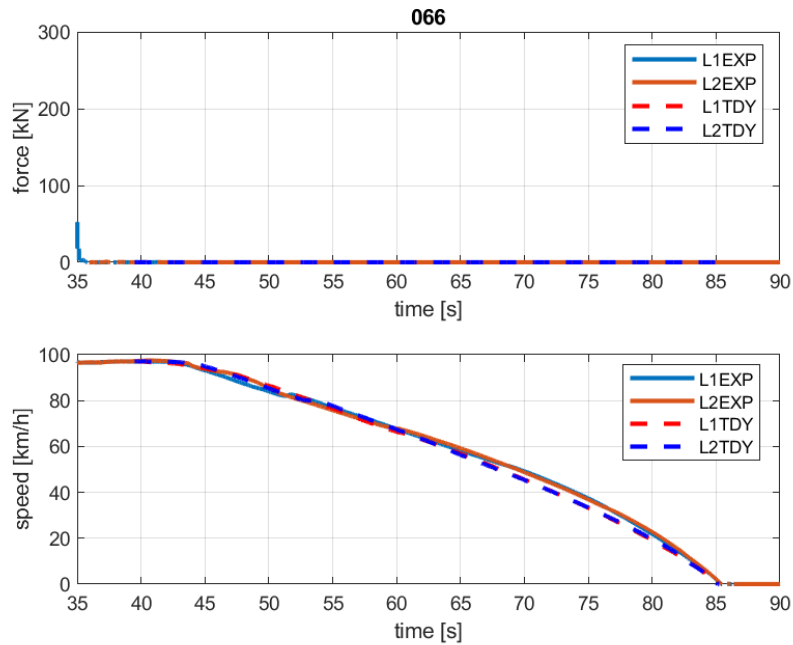
Fig. 2   (a) Traction force and (b) speed vs time

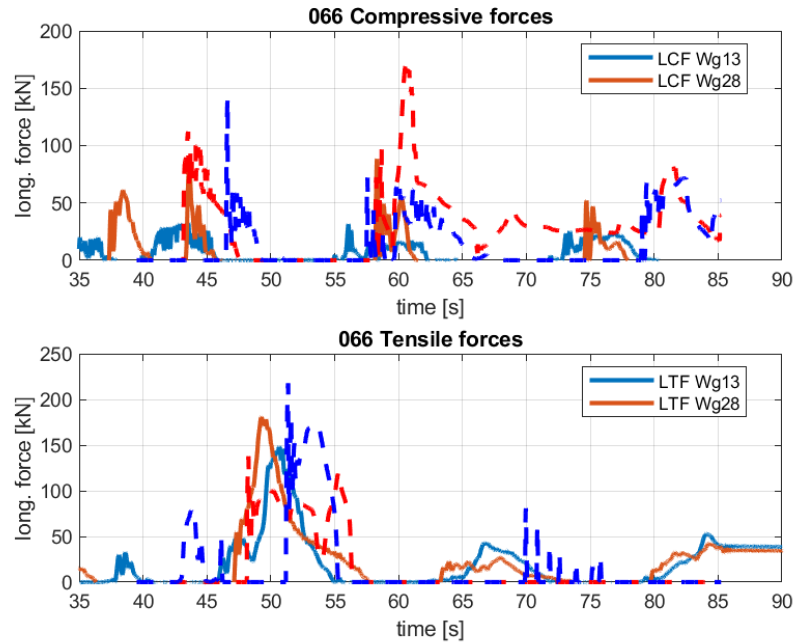*Fig. 3   (a) Pressure in brake pipe and (b) in brake cylinders vs time*

Fig. 4   (a) LCF and (b) LTF vs time

6.1.2. Tests 058-059

These tests refer to a communication loss among the TU which is characterized by a traction force reduction at the guided loco. After some time, the leading loco commands an emergency braking: the DPS reduces the pressure in brake pipe by a stepwise approach (see oscillations in bottom part of Fig. 6). Each test is the repetition of the same (nominal) train operation. Fig. 7 and Fig. 10 show the measured (solid line) and computed (dashed line) instantaneous LCF: good agreement in the shapes of the time evolution make difficult to see the differences on the peak values (for test 058). Errors on peak values are reported in Tab. 5.

Fig. 5   (a) Traction force and (b) speed vs time
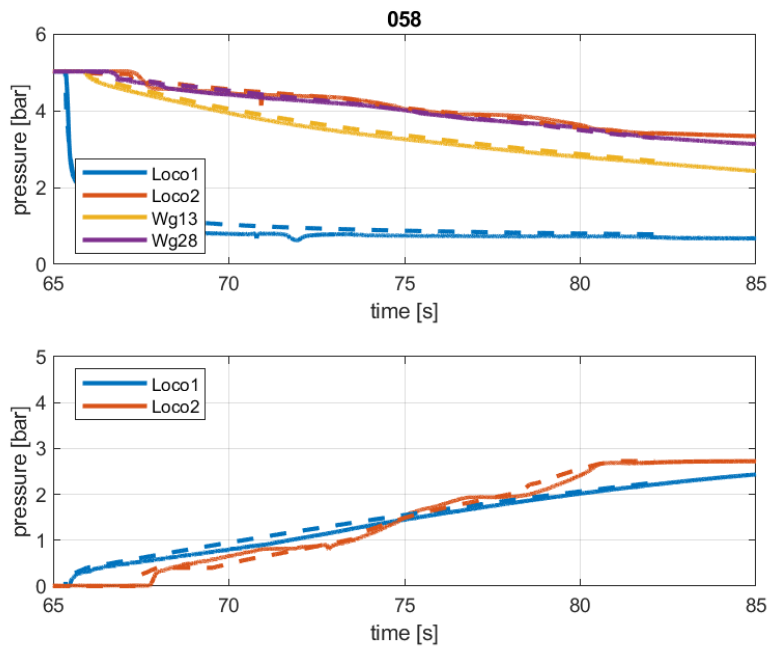
Fig. 6   (a) Pressure in brake pipe and (b) in brake cylinders vs time
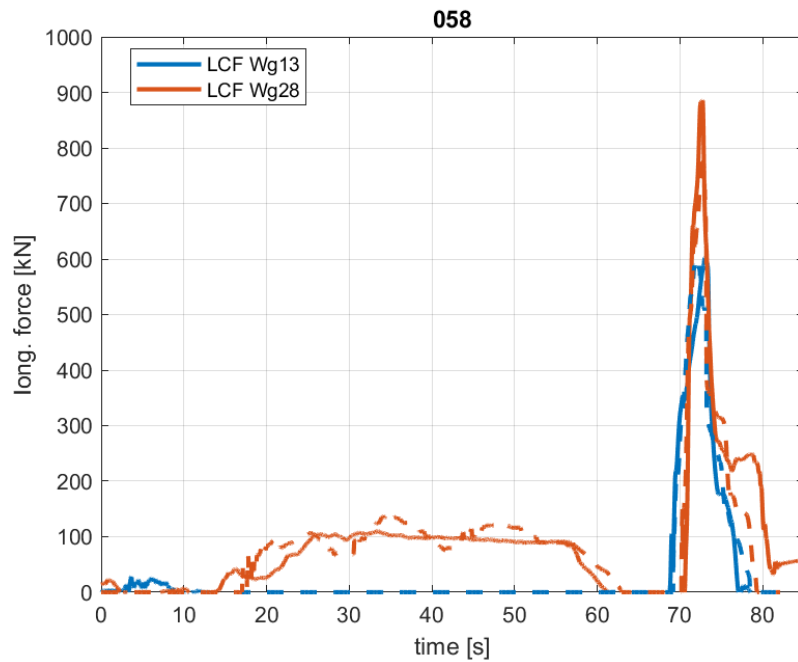
Fig. 7   LCF vs time

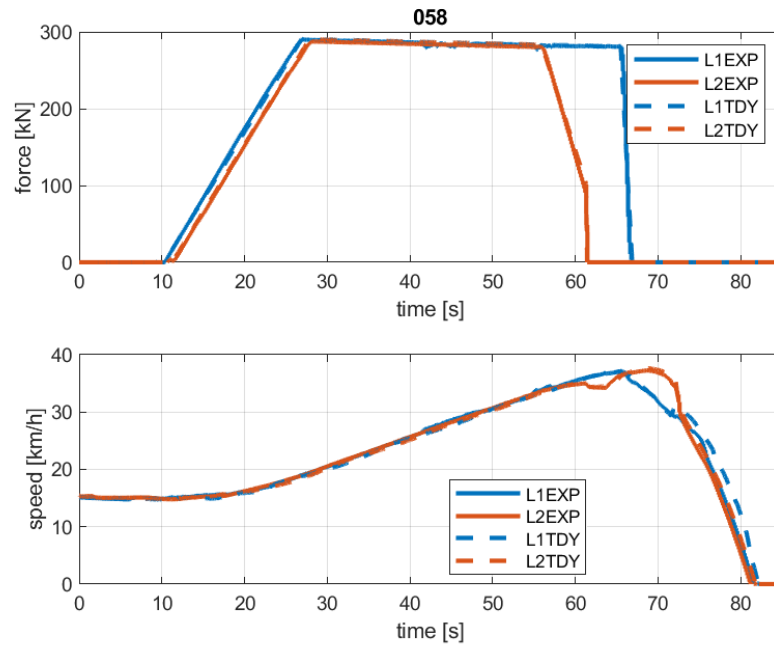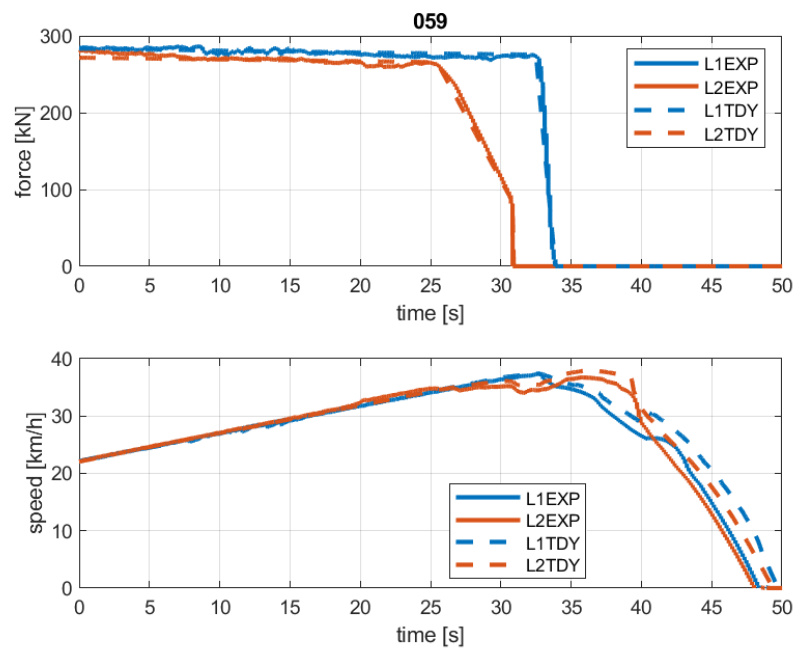*Fig. 8   (a) Traction force and (b) speed vs time*
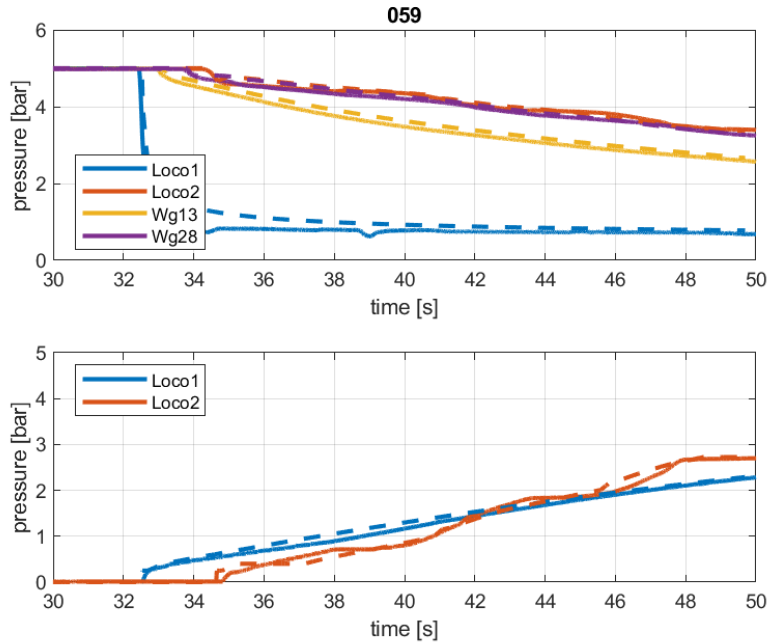
Fig. 9   (a) Pressure in brake pipe and (b) in brake cylinders vs time
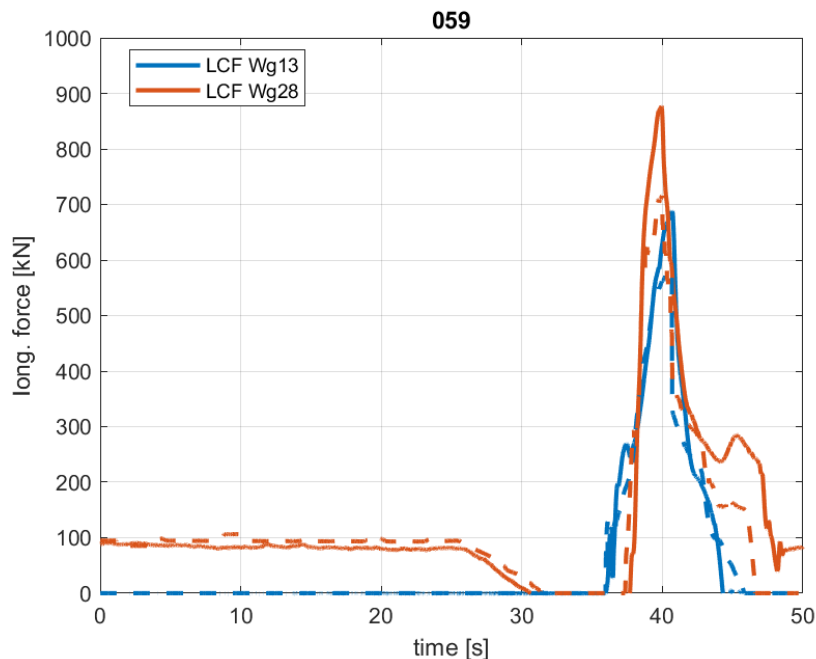
Fig. 10 LCF vs time

6.1.3. Tests 060-061

These tests refer to a communication loss among the TU when the leading loco performs an emergency braking after a full traction. When the guided loco detects that there is no more communication it reduces the traction force gradually and when it detects a pressure drop in brake pipe, it performs a stepwise reduction of pressure in brake pipe. Each test is the repetition of the

same (nominal) train operation. Fig. 13 and Fig. 16 show the measured and computed instantaneous LCF (with same convention as above). Errors on peak values are reported in Tab. 5.
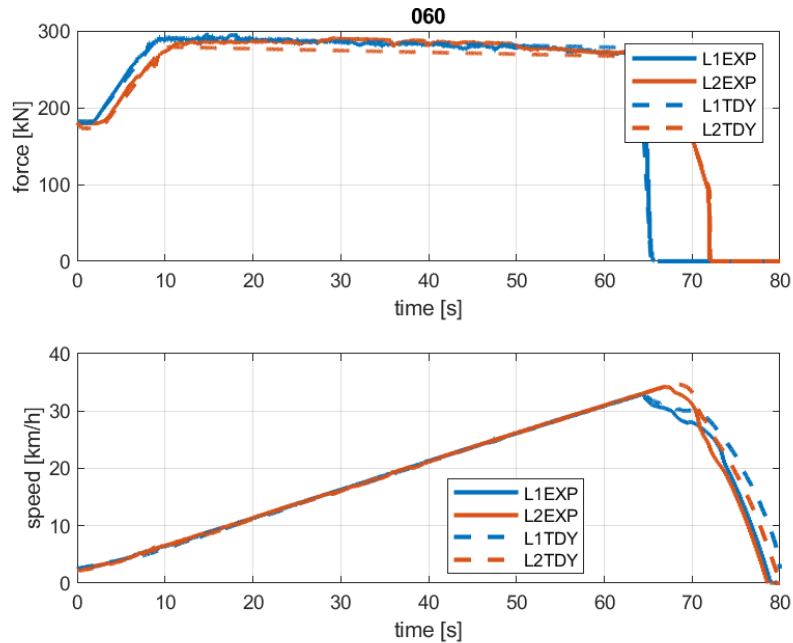
Fig. 11 (a) Traction force and (b) speed vs time
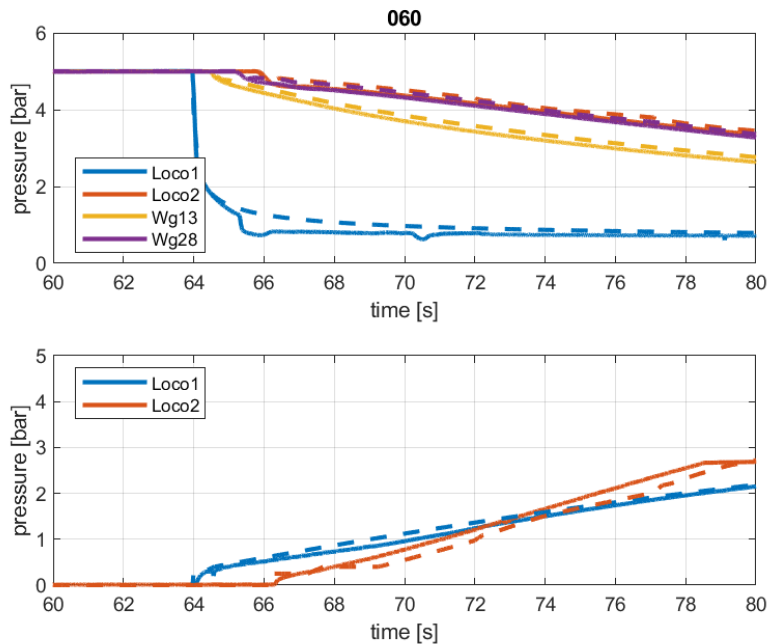
Fig. 12 (a) Pressure in brake pipe and (b) in brake cylinders vs time
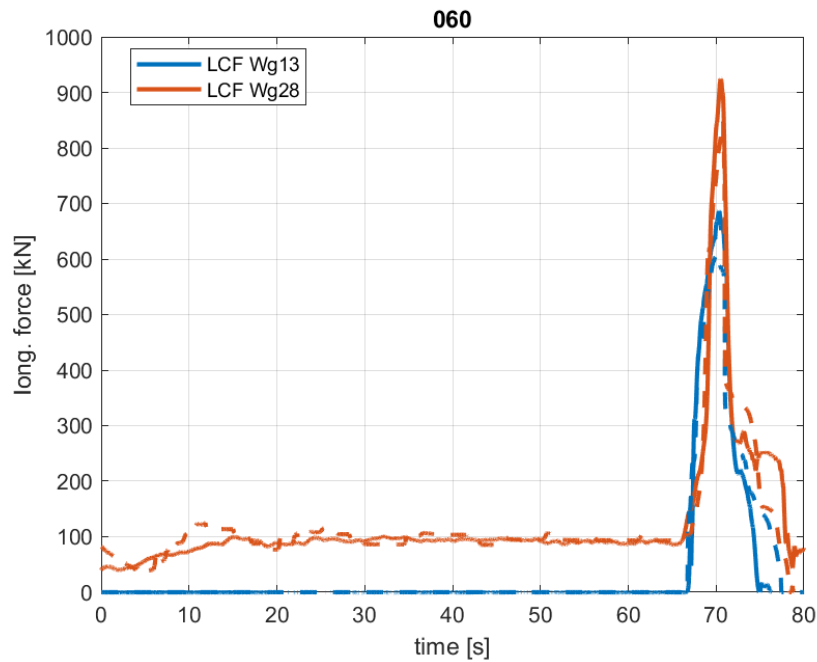
Fig. 13 LCF vs time
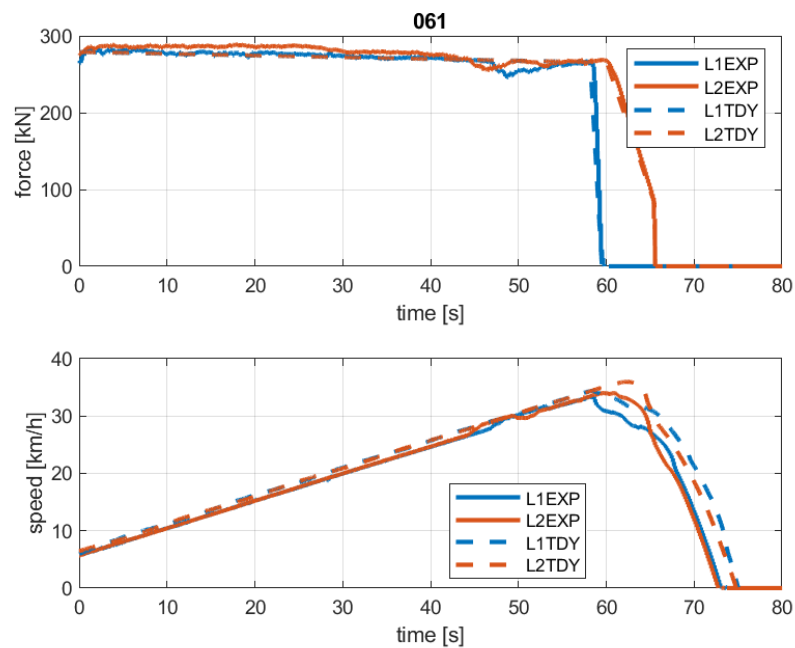
Fig. 14 (a) Traction force and (b) speed vs time
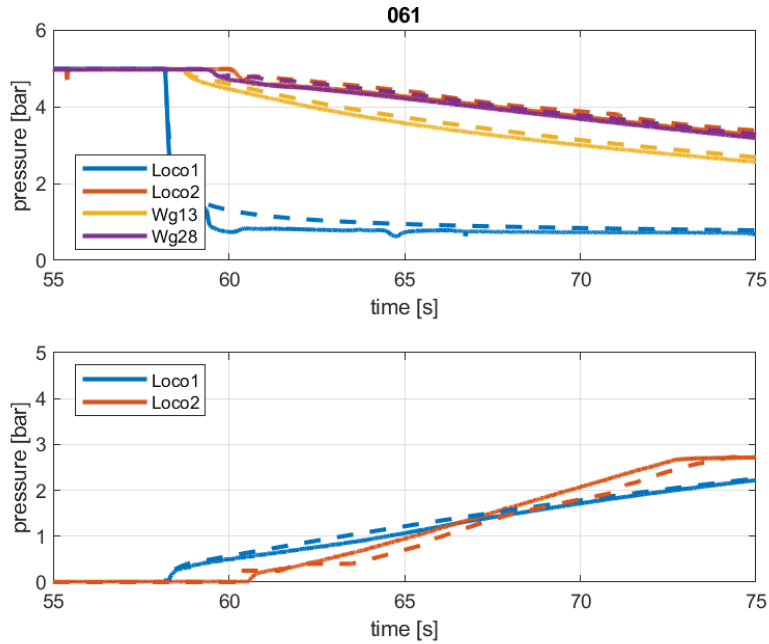
Fig. 15 (a) Pressure in brake pipe and (b) in brake cylinders vs time
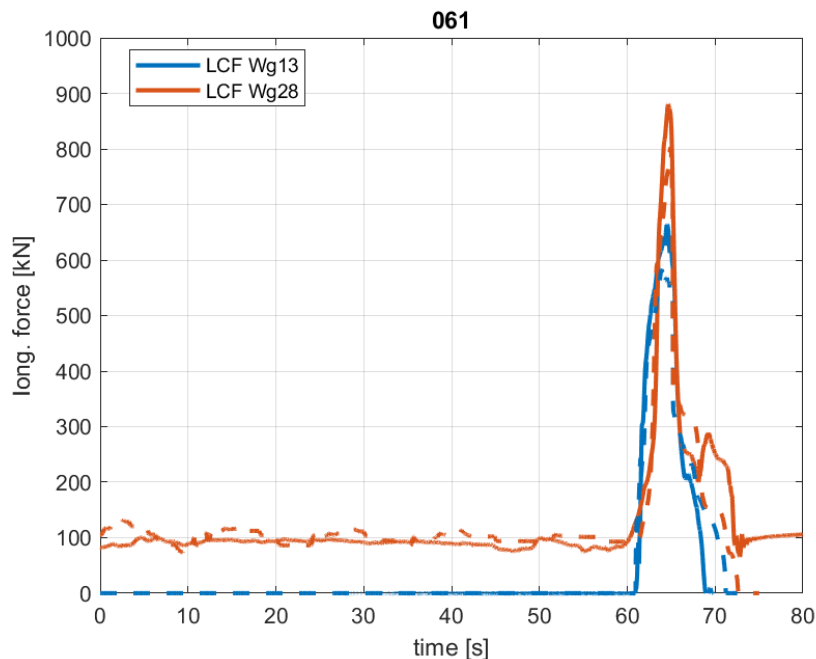
Fig. 16 LCF vs time

Tab. 5 reports the percentage errors of LCF computed and measured, for tests 058-061: these errors are comparable to those obtained during the certification of TrainDy [4] where a maximum error of around 25%, in one test, was obtained and considered as tolerable for UIC certification. In a comparison against experimental data, in general, it is important the overall shape of the curves and not only the peak values. Moreover, it is worthwhile to note that differently from tests 060 and 061 where the scatter on error is small, it is bigger on tests 058 and 059: most probably,

there is one or more parameter that in tests 058 and 059 was not measured but it affected the results in terms of longitudinal forces. This topic will be further addressed in D2.3, considering the effects of these uncertainties. Lastly, it is important to remember that those compared are the instantaneous LCF, whereas the LCF 10 m are relevant for the risk of train derailment.

Tab. 5 Percentage error

	Percentage relative error TrainDy vs Experimental measurements			
	058	059	060	061
Coupling 13	-1.10	-16.45	-10.94	-11.57
Coupling 28	-10.68	-16.86	-6.73	-6.95

7. Simulation of virtual trains

Previous section showed TrainDy results about a real train. This section shows TrainDy results about virtual trains that have different specified features. Common feature of these trains is that they are statistically generated from the DB AG train database of real trains (made available to UNITOV), i.e. the trains do not exist but the statistic distributions of: train mass, wagon type and their payload (weighted with covered distance) are taken from real trains. The trains are generated following the Leaflet UIC 421 statistic approach [3]. All wagons are assumed equipped with LL shoes, as the wagons of experimental tests showed in section 5: this assumption does not constitutes a limitation, in the spirit of relative approach where a reference system is compared against a new system.

Virtual trains are divided according to the number and the position of TU. Train consists are the results of the connection of several sub-trains: the label 1T is used when the train is made of just one sub-train (reference condition); the label 2T is used when the train is obtained by connecting two trains; 3T and 4T follow the previous scheme. The label SW is used when there is a loco at the end of the overall train, i.e. 1T-SW is a classic train with a second TU added at the end. Aiming to study up to 4 TU, there are 7 different combinations addressed in this deliverable: 1T, 1T-SW, 2T, 2T-SW ad so on.

The effect of end-of-train devices is outside the scope of this deliverable since it requires an updating of the UIC TrainDy software, but the simulations with the "sandwich configuration" are a kind of end-of-train device.

Each train family is characterized by a string according to section 7.1.

Train operations considered are: the emergency braking (EB) from 30 km/h in coasting conditions and the full traction from zero speed up to 30 km/h followed by an emergency braking (T-EB). These train operations are applied both to reference trains (1T) and to trains with DPS in nominal and degraded mode. These parameters have been agreed with FR8RAIL II Partners, see also section 7.2.

The selection process of a train family is performed in two steps: initially, the full traction followed by emergency braking is considered with a reduced size of train family (100), then if the performance in terms of derailment and disruption risk are satisfactory a new generation of 1000 trains is performed in order to assess the results. Of course, trains with DPS are compared to reference trains also considering the emergency braking: in this computation the train consists are

the same and only the train operation is changed to better study the effect of the train operation on LTD.

Each figure is provided with a highly explicative title and it is divided in two parts: on top the cumulative probability (CP) of the ratio between the LCF and admissible LCF is showed on the left (negative values) and the ratio between LTF and admissible LTF is showed on the right (positive values); see also section 7.2. The bottom part of each figure displays only the minimum LCF (negative values) and the maximum LTF (positive values) of each train, in order to have a quick idea of the absolute in-train forces. An estimation of derailment and disruption probability is also provided.

For each different combination of TU, the option of having a "synchronous" braking of the TU is explored: for DPS with GSM-R technology, synchronous braking means that the braking of the leading TU is delayed of 1.6 s with respect to the command of the Driver; this option is not allowed by actual TU, but it is interesting to evaluate the benefits of such technology.

In some cases, the derailment risk is also computed considering the exclusion of 2 axle wagons.

The big number of different possible combinations do not allow a systematic and comprehensive study in this deliverable. The different train families are generated considering the experience and the possible market uptake of the reported solution.

Section 8 provides some proposals about train operations to run DPS trains.

7.1. Alpha-numeric string for the identification of a train family

Each train family is uniquely identified by an alpha-numeric string. An example of this type of string is: ***BR187_400_300_G_LL_3_2_4_0_1_5_0_0_1_70_5***. Following bullet points describe the content and meaning of each field (separated by underscores "_"):

- First field is the type of Traction Unit: in most of the cases the Traction Unit is the model BR187 already used during the S2R experimental tests of May 2019. In some cases, a virtual TU is used, the BoBoMax; this TU has a constant traction force of 350 kN and represents the maximum traction force that a BoBo TU can apply, because of adhesion limitations.
- After the type of TU, the average lengths of the sub-trains are listed. In the example, 400 m and 300 m; following the same convention adopted in the UIC Project LongT, this means that the first sub-train has a length from 380 m and 420 m.
  - Sometimes the length of the sub-train can be also directly expressed in terms of boundaries, e.g. 0_740 means that the sub-train length can be maximum 740 m.
- After the sub-train length, the string reports the sub-train mass. In the example, the letters refer to the brake regimes as defined in UIC Leaflet 421. According to this leaflet, the trains having a length up to 700 m (TU excluded) and with hauled mass respecting the following limits are admitted to the international traffic:
  - 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.

Of course, different Railway Undertakings can have other internal rules and limits, by applying further limitations such as the minimum load per axle. It has been decided to follow the UIC limitations in order to make the results more rapidly applicable to international freight traffic.

Since in Germany there are several trains having a hauled mass between 2500 and 5500 ton the acronym "GH" has been introduced to indicate these trains, characterized by wagons heavily and almost uniformly loaded.

As before, the sub-train mass can be specified also in terms of train mass boundaries, e.g. 3000_4000 means that the sub-train mass can be between 3000 and 4000 ton. It is also possible to define the average value of sub-train mass, e.g. 3500 means that the sub-train mass is between 3250 ton and 3750 ton and the wagons are heavily and almost uniformly loaded: the cumulative probability of wagons payload is the same of GH.

These different possibilities increase the number of possible trains that can be simulated.

- After the sub-train length and mass, the string reports the number of TU of the *whole* train.
- Then "1" is used to indicate that the sub-trains are just coupled, "2" indicates that at the end of the whole train there is a TU; later on, the label "SW" (sandwich) is used to easily recognize this condition.
- Then a number between 1 and 4 is used to represent the brake regime of the whole train: 1, for P regime, …, 4 for G regime. If this value is 0, it means that the next value has to be different from zero and the sub-trains have *different* brake regimes.
- If the next string is different from zero, it means that the sub-trains have different brake regimes:
    - 1, the first sub-train is in G and the other(s) are in P
    - 2, the first sub-train is in G and the other is in GP
    - 3, the first sub-train is in G and the other is in LL
    - 4, the first sub-train is in G and the other is in GH (i.e. wagons are heavily and almost uniformly loaded)
    - 5, the first sub-train in LL and the other(s) are in P.
- Next string is 1 for Nominal mode and 2 or 3 for degraded mode: see, 2)b and 2)a, respectively in section 8.
- Next string is 4 for the Emergency Braking (from 30 km/h) and 5 for the full traction up to 30 km/h followed by the emergency braking.
- Next string is 1 if the axle wagons are excluded and 0 otherwise. In this deliverable, trains with both axle and bogie wagons are considered.
- Next string is 1 if the braking is synchronous, i.e. the first TU vents the brake pipe after some time the command is issued. This time depends on the radio technology; for GSM-R it is 1.6 s.
- Next string is the radio technology: 1 for GSM-R, 2 for LTE, 3 for 5G. For LTE, the communication delay has been modelled as a uniform distribution between 0.5 and 1 s, according to Funkwerk advice. For 5G, the boundaries of the uniform distribution are 0.01 and 0.02 s: these values have been assumed on the basis of an almost instantaneous communication with 5G.

- Next two strings are meaningful only for degraded mode and they represent the gradient of traction reduction and the equivalent diameter of the nozzle, respectively. In the example, these values are 70 [kN/s] and 5 [mm], respectively.

7.2. Considerations on derailment and disruption probabilities

Derailment and disruption risks are estimated by computing the LTD of the trains and by comparing the maximum LCF and LTF of each train to their admissible counterparts. The admissible LCF is computed according to [3] considering a track radius of 190 m and radius of buffers heads of 1500 mm, whereas for admissible LTF is taken the value of 550 kN for all draw gears, according to the operational experience of SNCF. Please be aware that the value of 550 kN, by itself, it is not capable to disrupt the train, i.e. to break the coupler or the hook; this value damages it, so that several repetitions of LTF comparable or greater than 550 kN can bring to a train disruption, because of a fatigue failure. Moreover, since this work follows the "relative approach" of Leaflet UIC 421, the choice of the limiting value for LTF is the same for reference and DPS trains.

Moreover, for train derailment risk, since the admissible LCF values have a certain degree of safety, in order to have a derailment in the reality, it has to happen that: a) the train performs the specific train operation (typically this occurs when a full traction is applied up to 30 km/h and then an emergency braking is commanded); b) the wagons among which the highest LCF is experienced is placed on curve with short radius (190 m); the admissible value is equal to the value computed as in [3], which is conservative with respect to some values reported in [5].

A train virtually derails if the lowest ratio between LCF and admissible LCF is below "-1"; a train virtually disrupts if the highest ratio between LTF and admissible LTF is above "+1".

7.3. Reference trains (1T)

Results showed in this section refer to classic train consists having one TU in front of the train. Different braking regimes are considered: the hauled mass for each braking regime follows the limitation of [3], except for the braking regime labelled as "GH", which is not mentioned in the Leaflet UIC 421 and that is characterized by almost uniformly loaded wagons with hauled mass up to 4000 ton, braking in regime G. About derailment and disruption probabilities refer to section 7.2.

In order to evaluate the effect of different TU on LTD, Fig. 17 to Fig. 21 refer to TU BR187 whereas Fig. 22 to Fig. 26 refer to a virtual TU having a constant traction force of 350 kN and labelled as "BoBoMax". This more powerful TU causes higher LCF and LTF, i.e. higher derailment and disruption percentages, during the train operation T-EB, since during the full traction phase the train stores more elastic energy that has to be later on dissipated during the emergency braking phase.

Fig. 17 Trains in P regime

Fig. 18 Trains in GP regime

Fig. 19 Trains in LL regime
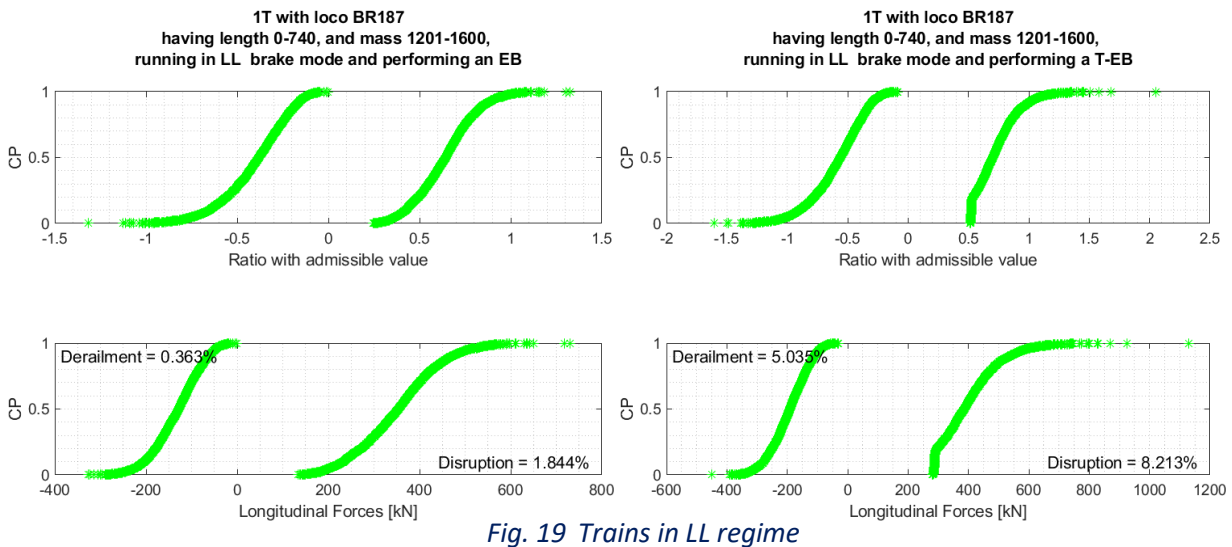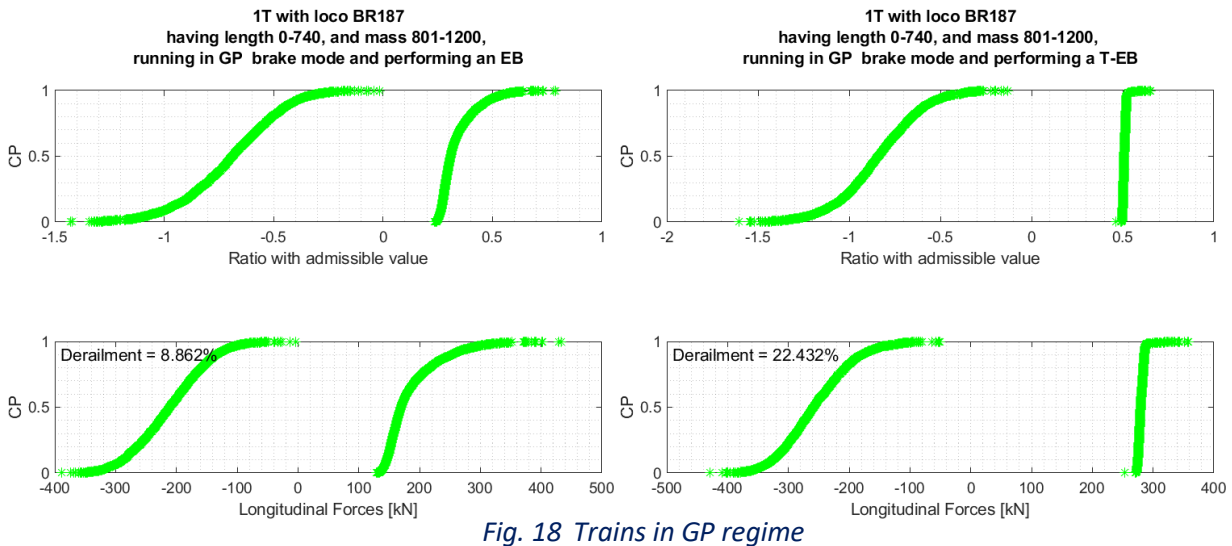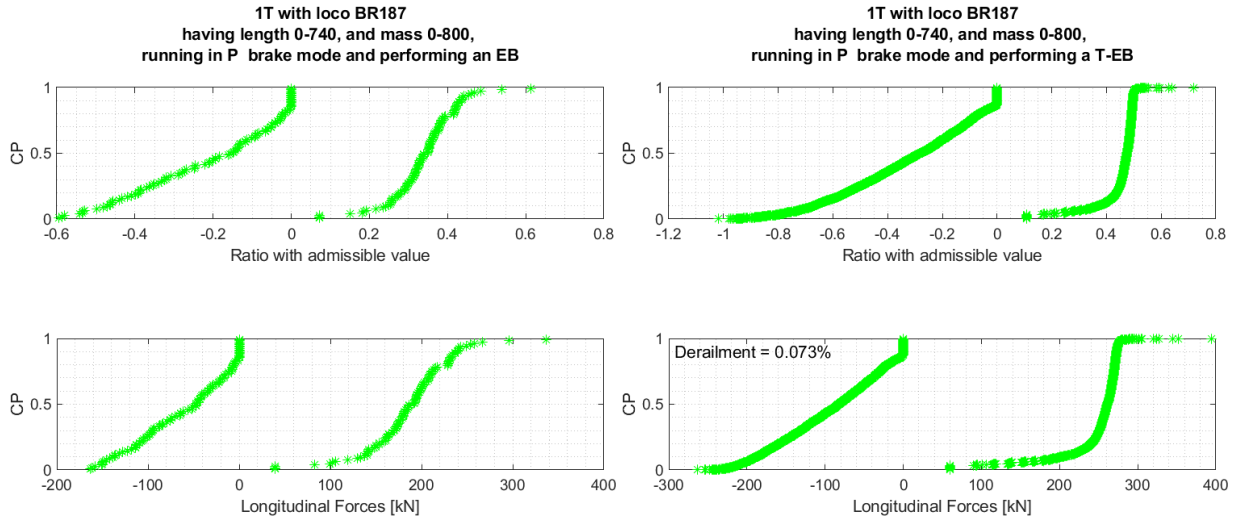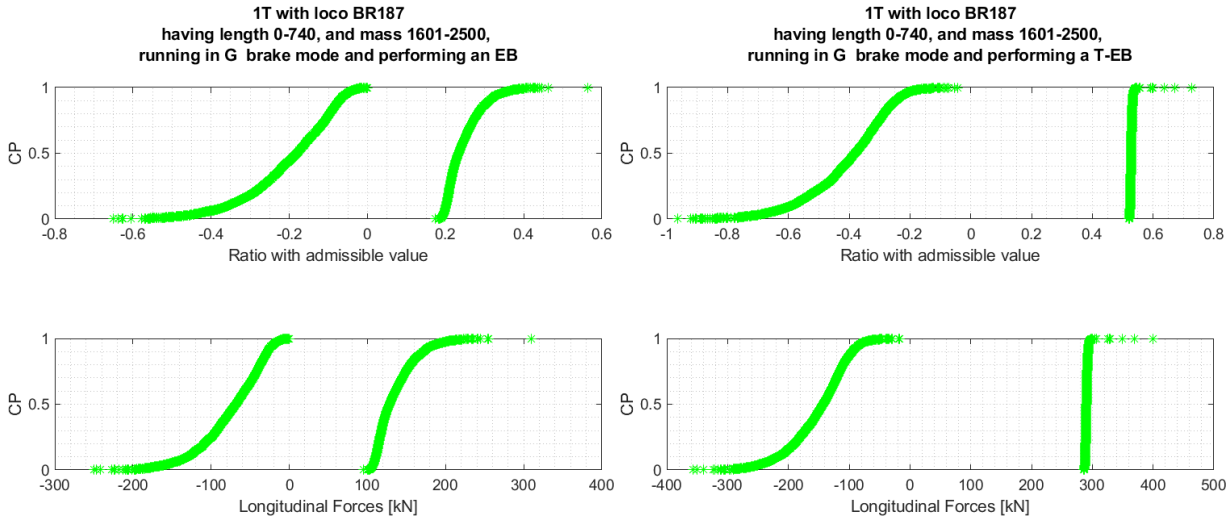
Fig. 20 Trains in G regime
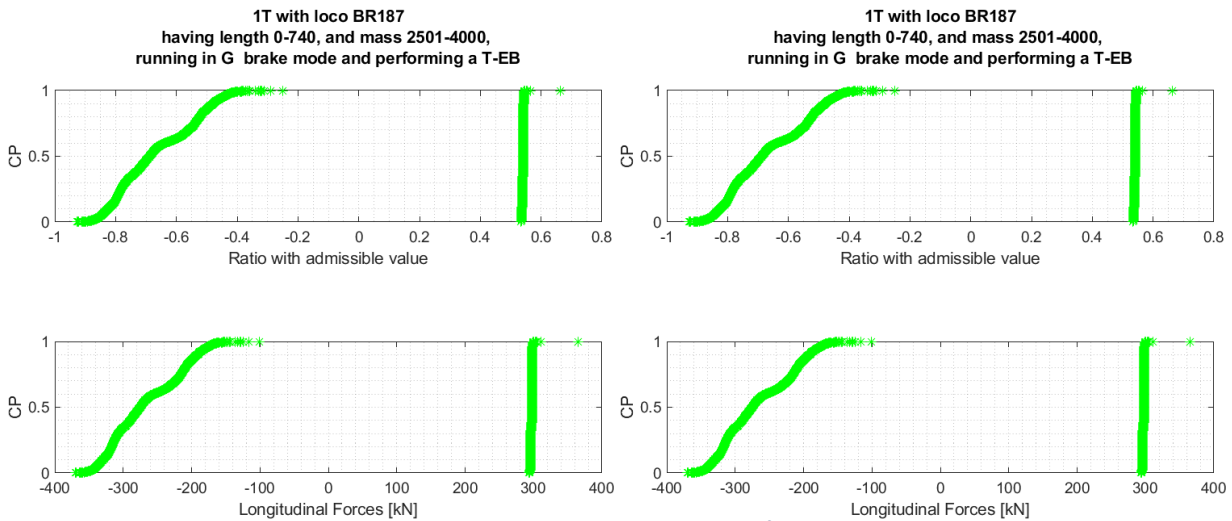
Fig. 21 Trains in G regime with almost uniformly loaded wagons

Following figures refer to TU BoBoMax and display only train operation T-EB since the emergency braking is not affected by a TU having a different traction power. As mentioned before, with this TU the LTD is enhanced. The LTD increment occurs also when more than 1 TU is used (i.e. 1t-SW, 2T, and so on), as it is shown in the document D3p1_TrainDy_Extended_Simulations.pdf.

1T with loco BoBoMax
having length 0-740, and mass 0-800,
running in P brake mode and performing a T-EB
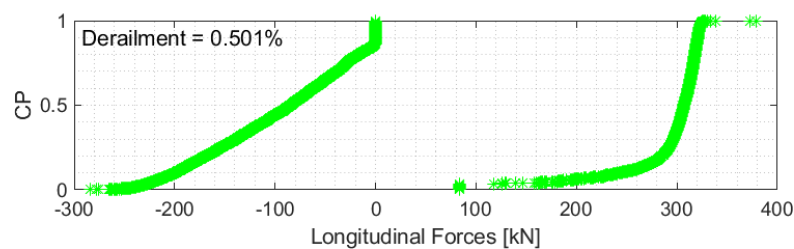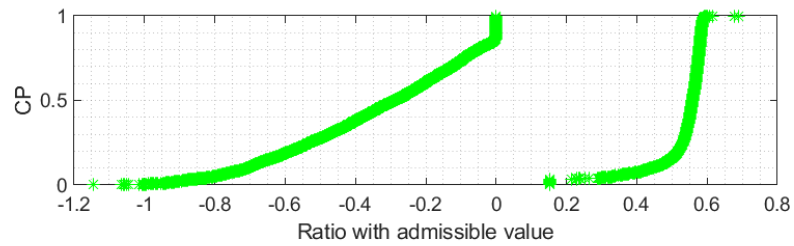
Fig. 22 Trains in P regime

1T with loco BoBoMax
having length 0-740, and mass 801-1200,
running in GP brake mode and performing a T-EB
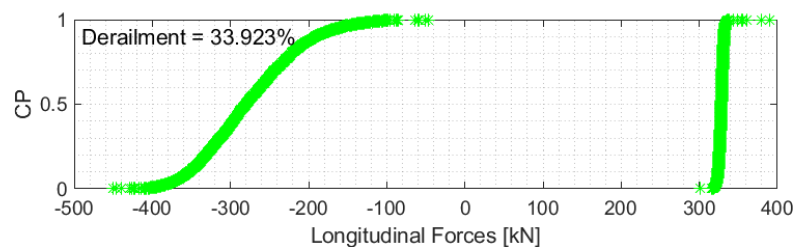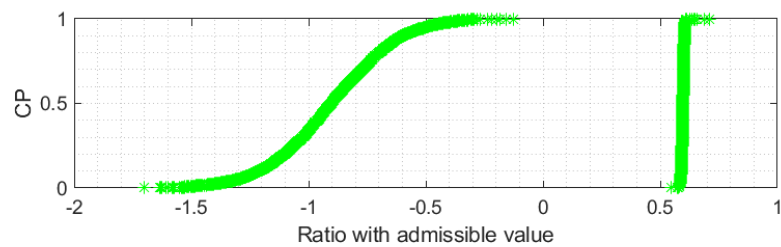
Fig. 23 Trains in GP regime

1T with loco BoBoMax
having length 0-740, and mass 1201-1600,
running in LL brake mode and performing a T-EB

Fig. 24 Trains in LL regime

1T with loco BoBoMax
having length 0-740, and mass 1601-2500,
running in G brake mode and performing a T-EB
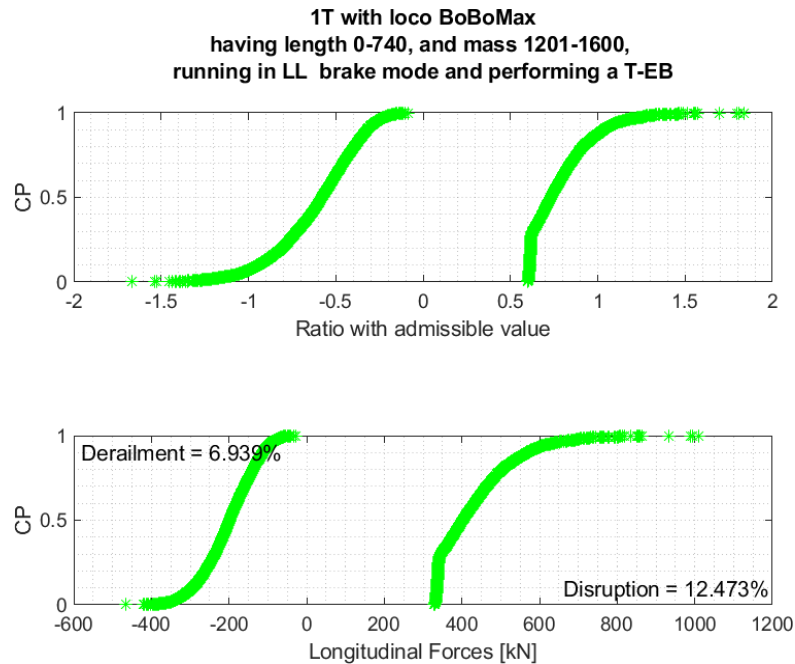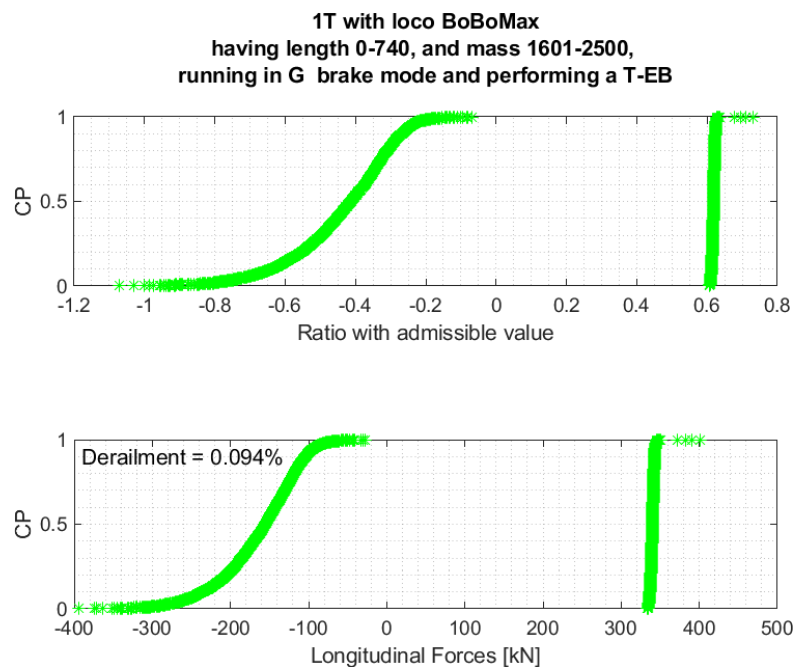
Fig. 25 Trains in G regime
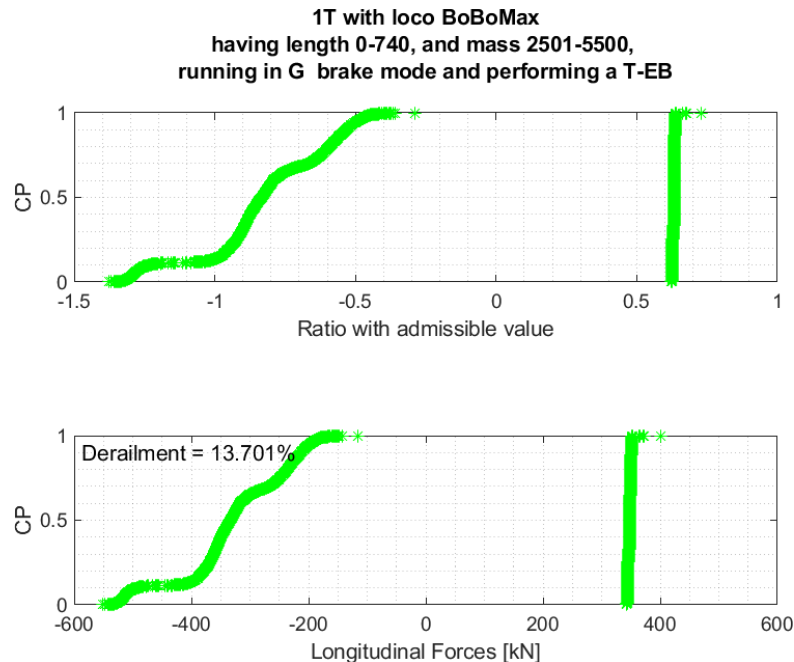
Fig. 26 Trains in G regime with almost uniformly loaded wagons

Considering the occurrence of each type of train in the real train database provided by DB, the derailment and disruption percentages according to the train operations are as in Tab. 6, if the TU BR187 is employed. These percentages will be used as boundaries (displayed as vertical dashed lines) in the next figures, for the train operation T-EB.

Tab. 6 Virtual derailment and disruption of reference trains

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

7.4. 1T-SW

This train configuration is also called "sandwich train" since the train has a TU at its beginning and its end. Following figures shows the cumulative probabilities of some of the most interesting train consists in terms of efficiency and market uptake among those simulated. The complete series is available on the document D3p1_TrainDy_Extended_Simulations.pdf. Only T-EB train operation is showed for sake of brevity. Please consider that the length interval in the title of each figure is without TU, moreover the mass interval 2501-5500 ton, as written in section 7.1, refers to trains almost homogeneously loaded. Furthermore, to respect the constraints on train length, short trains (see labels 0-500) haul a mass that is lower than 5500 ton, as can be seen in D3p1_TrainDy_Extended_Simulations.pdf.
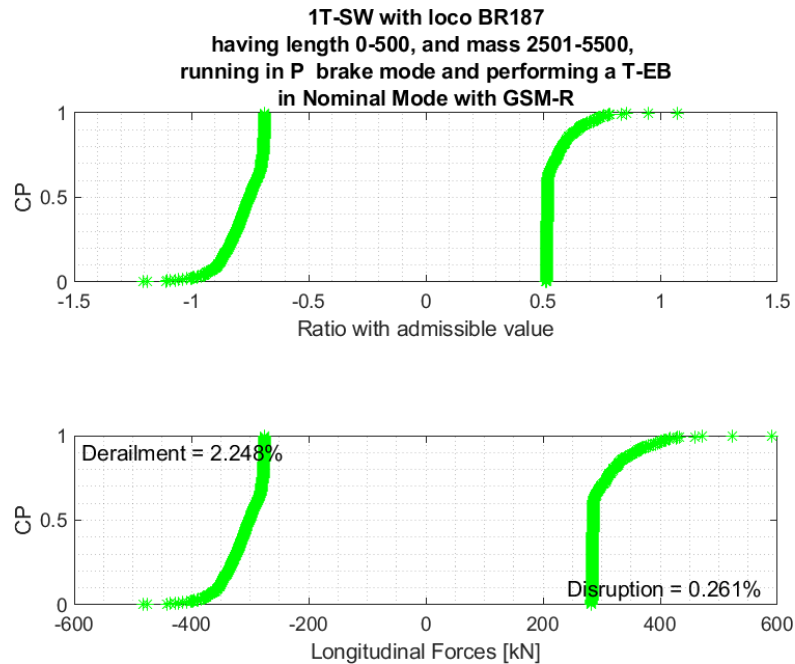
Fig. 27 Trains in P regime

Fig. 28 Trains in GP regime

**1T-SW with loco BR187
having length 0-690, and mass 2501-5500,
running in LL brake mode and performing a T-EB
in Nominal Mode with GSM-R**

Fig. 29 Trains in LL regime

**1T-SW with loco BR187
having length 0-740, and mass 2501-5500,
running in G brake mode and performing a T-EB
in Nominal Mode with GSM-R**
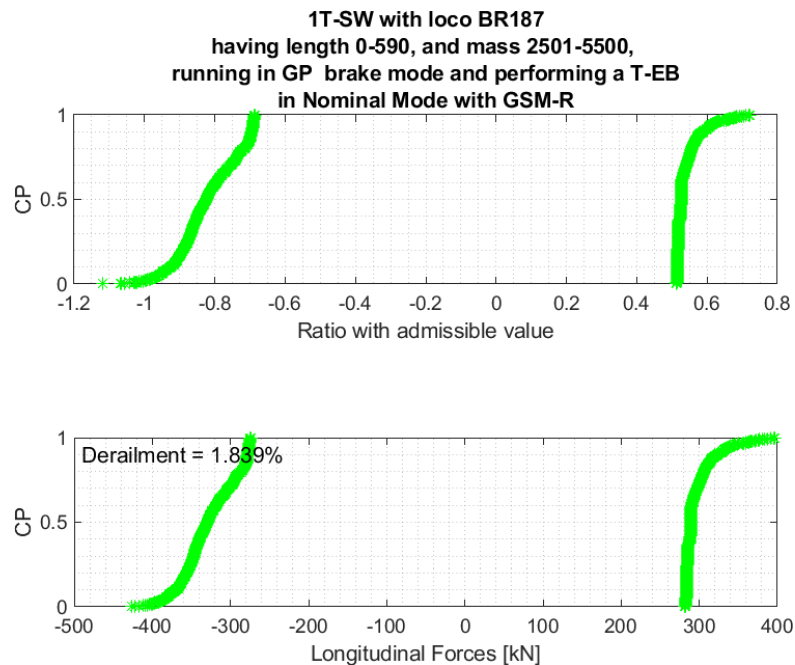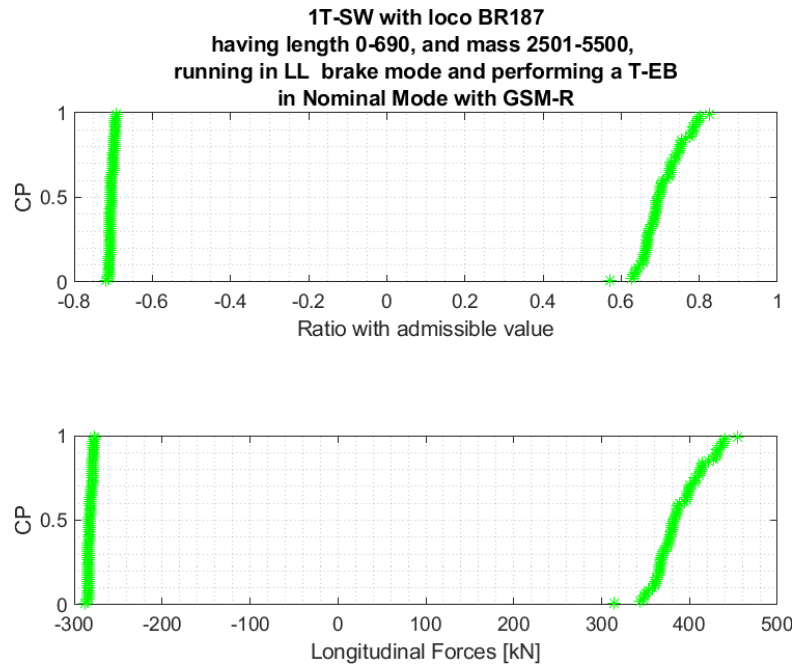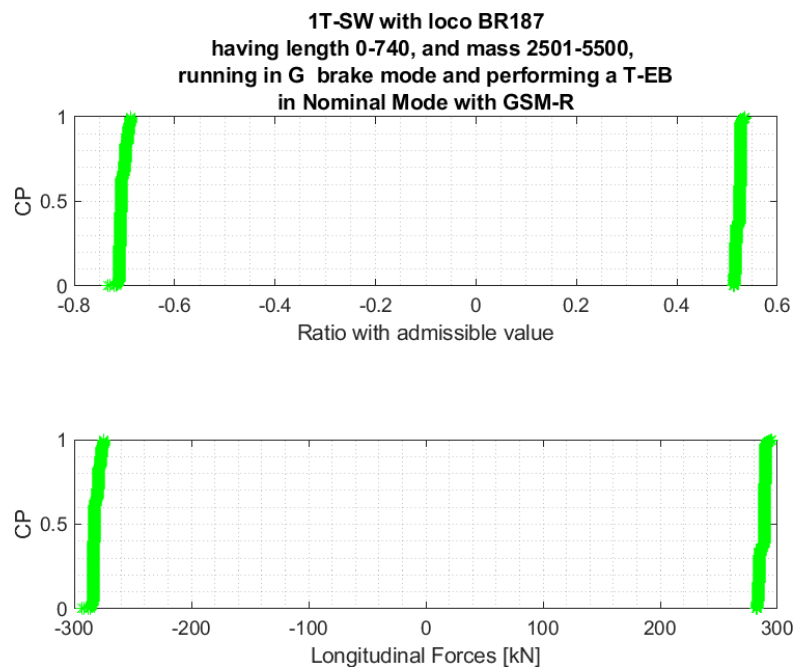
Fig. 30 Trains in G regime

Trains reported from Fig. 27 to Fig. 30 employ GSM-R radio; the train in Fig. 31 is similar to that of Fig. 27, but the train family is equipped with an LTE radio, in Fig. 31: the benefits of this new radio technology are clear.
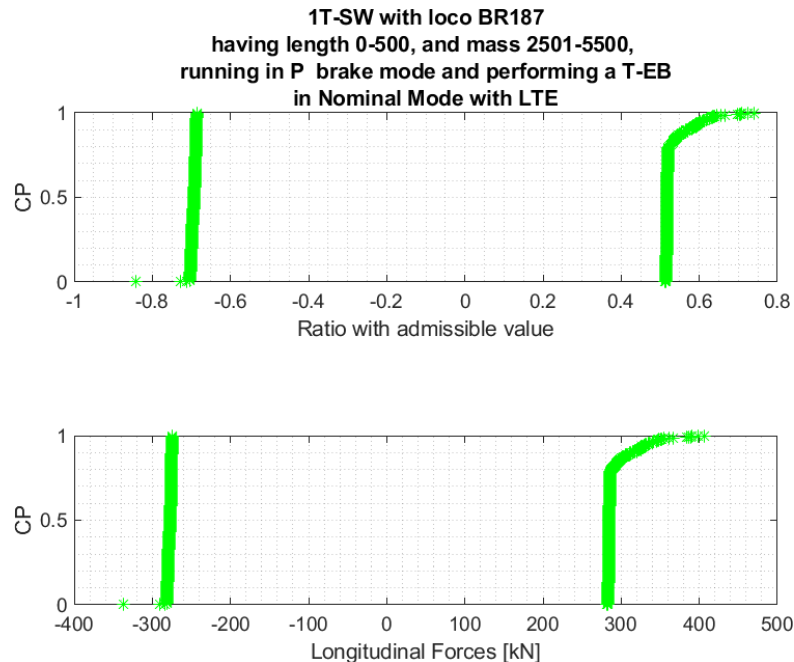
Fig. 31 Trains "uniformly" loaded in P regime, with LTE

Fig. 32 shows a Tornado Plot of other train families just highlighting the percentages of derailment and disruption for each family (see also 7.1): the boundaries of reference system, displayed in Tab. 6, are reported with dashed vertical lines. Displayed trains have an almost uniform load among the wagons and two TU: one at the beginning and the other at the end of the train. The vehicles brake in G regime and the average (±20 m) lengths of the trains are: 620, 720, 820 and 960 m, whereas the average (±250 ton) hauled masses are 3500, 4500, 5500 and 6500 ton, respectively. The trains are performing a full traction up to 30 km/h followed by an emergency braking, in nominal mode, employing the GSM-R technology.
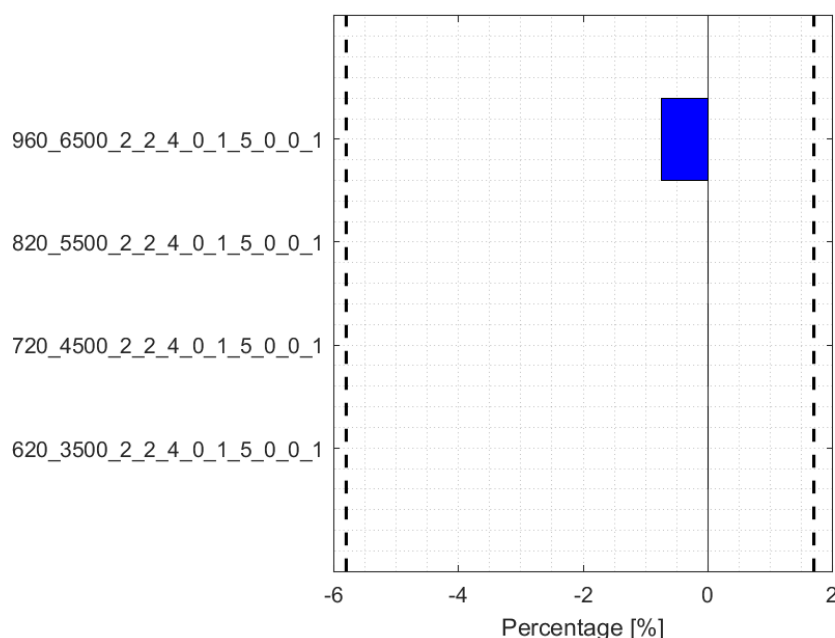
Fig. 32 Trains in "sandwich" configuration, G regime

7.5. 2T

This train configuration is characterized by the coupling of two sub-trains, as a consequence, the guided TU is "within" the train. Previous experience has showed that the "best" position of the guided TU is around 2/3 of the whole train length; results of this section confirm this experience. Fig. 33 shows a Tornado Plot of train families running in brake mode G (see also 7.1) and having an overall length of 740 m (TU included): the first two numbers are the average lengths (±20 m) of the two sub-trains. The letters, as LL, provide information on the hauled mass of the sub-train: P is lower than 800 ton, GP is between 801 and 1200 ton, LL is between 1201 and 1600 ton and G is between 1601 and 2500 ton. When the sub-trains are coupled the brake mode of each wagon <u>has to be</u> switched to G (see the number 4 between 1 and 0). Keeping the original brake mode has dealt to short and not heavily loaded train configurations. The train operation is a full traction followed by an emergency braking, in nominal mode.

All displayed train families belong to container traffic; for two train families (450_250_LL_GP and 450_250_LL_GP), the synchronous braking has been tested, too (see the "1" in the second-last position of string name of last two rows of Fig. 33): it is clear the benefit of such possible future technology. For this type of train families, the LTE technology has been simulated, as well: see the last number of the label that changes from 1 to 2 in the fourth label from top of Fig. 33. Therefore, benefits of LTE technology are proved also for the coupling of two trains.
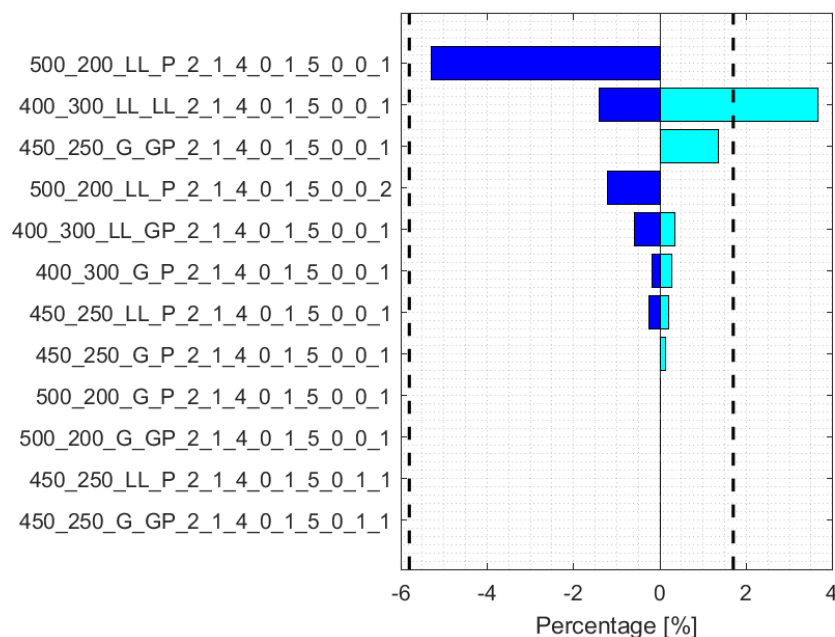
Fig. 33 Trains formed by two sub-trains, all wagons are in G regime

Train families showed in Fig. 34 are similar to the previous ones, except for overall train length that now is 840 m and 1000 m (TU included). As before, the benefits of synchronous braking are proved, as well as those of LTE technology (see the last 2 in the fourth label from the bottom). The

types of trains displayed belong to container traffic, when letters are used after the first two numbers, or to a mixture of bulk trains and container trains, when a third number is used after the first two: this number is the average (±250 ton) hauled mass of the first sub-train which is almost uniformly loaded (as for ore trains). Latter trains are safer against derailment than disruption if the ore train is the first sub-train (among the two). These train "suffer" of train disruption more than the reference system and synchronous braking is effective in reduction of both compressive and tensile in-train forces: see the second-last "1" at the end of the alpha-numeric string.
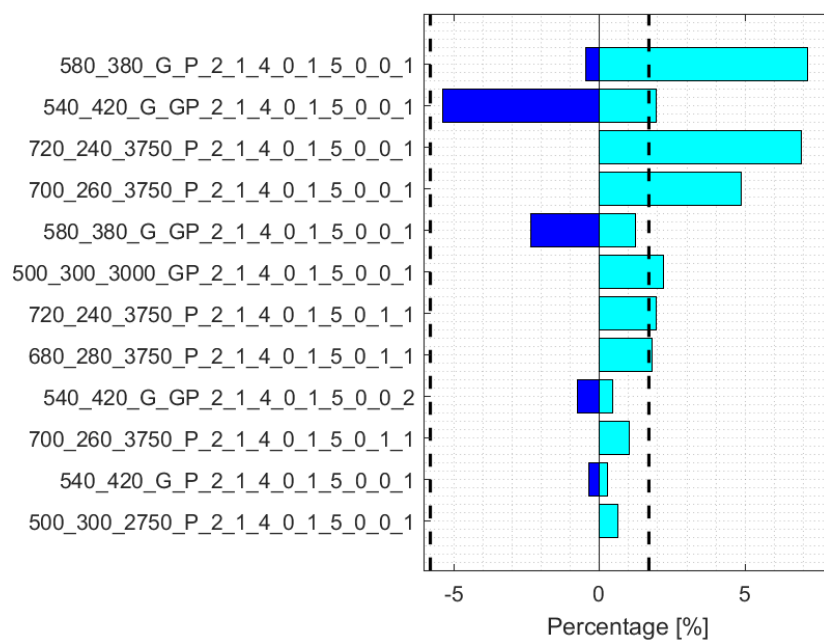
Fig. 34 Trains formed by two sub-trains with overall length up to 1000 m

Finally, train families showed in Fig. 35 are similar to previous trains except for the maximum overall length of 1200 m; they are obtained by coupling two trains of container traffic. Of course, increasing the length, it is necessary to reduce the mass of the sub-trains in order to reduce the probability of derailment and disruption. Benefits of LTE technology are proven also in this case: see for example the comparison among 720_440_G_LL_2_1_4_0_1_5_0_0_1 and 720_440_G_LL_2_1_4_0_1_5_0_0_*2*.

Fig. 35 Trains formed by two sub-trains with overall length up to 1200 m

7.6. 2T-SW

This train configuration is characterized by the coupling of two sub-trains with the addition of a second guided TU at the end of the train (label "SW" is used). The whole train has three TU.

The train families showed in Fig. 36 have an overall length of 1200 m (as before) and they are mainly obtained by coupling trains of container traffic (see the exception of 720_720_3750_3750_3_2_4_0_1_5_0_0_1, which is an ore train).

As before, the first two numbers are the average lengths (±20 m) of the two sub-trains. The letters, as LL, provide information on the hauled mass of the sub-train: GP is between 801 and 1200 ton, LL is between 1201 and 1600 ton and G is between 1601 and 2500 ton. When the sub-trains are coupled, the brake mode of each wagon has to be switched to G (see the number 4 between 1 and 0). The train operation is a full traction followed by an emergency braking, in nominal mode. Exaggerating with the hauled mass, the train can experience a derailment, of course. Benefits of LTE are proven also in this case: see the comparison among 640_520_LL_GP_3_2_4_0_1_5_0_0_1 and 640_520_LL_GP_3_2_4_0_1_5_0_0_*2*. "Synchronous" braking is proved to be effective also in this case: see the second-last "1" at the end of the alpha-numeric string. It is worthwhile to mention that, with this type of arrangement of TU (one at the beginning, one in the middle and the third at the end), it is possible to couple two long ore trains having hauled mass between 3500 and 4000 ton, in a safe way: see second last row in Fig. 36.
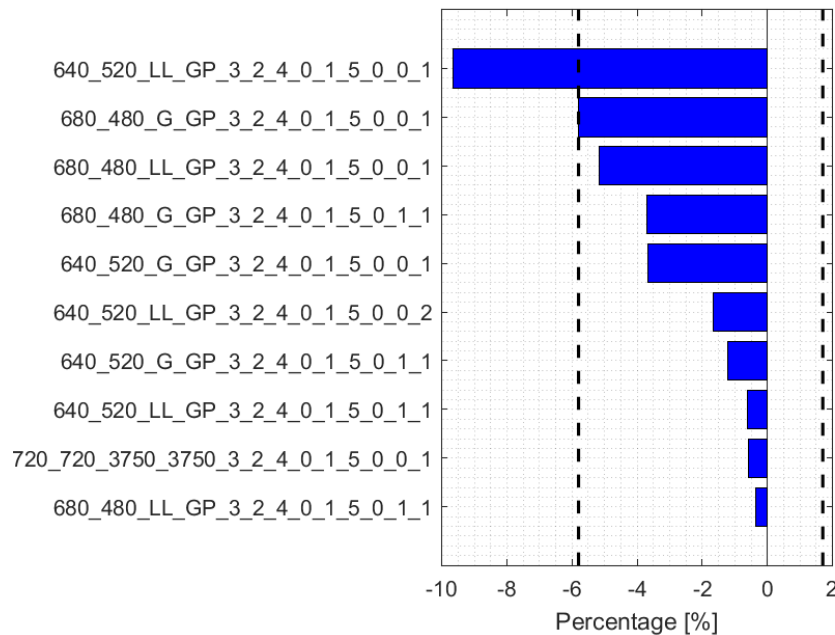
Fig. 36 Trains formed by two sub-trains with a 2nd guided TU at the end of the train

7.7. 3T

This train configuration is characterized by the coupling of three sub-trains.

The train families showed in Fig. 37 have a length of the whole train that can be maximum 1000 m or 1200 m and have wagons heterogeneously loaded (as in container traffic).

The first three numbers are the average lengths (±20 m) of the three coupled sub-trains. The letters, as LL, provide information on the hauled mass of the sub-trains: P is lower than 800 ton, GP is between 801 and 1200 ton, LL is between 1201 and 1600 ton and G is between 1601 and 2500 ton. When the sub-trains are coupled, the brake mode of each wagon has to be switched to G (see the number 4 between 1 and 0). The train operation is a full traction followed by an emergency braking, in nominal mode.

Increasing the number of coupled sub-trains, the non-linear elastic behaviour makes the LTD not easily predictable. As a result, it is necessary to further investigate the possible solutions by automatically generating the train families in order to better explore all possibilities. Anyway, it seems better to have longer and heavier sub-trains in front.

Benefits of LTE are proven also in this case, where the effectiveness of this technology is proved against the risk of train disruption: see the comparison among 480_480_180_G_G_P_3_1_4_0_1_5_0_0_1 and 480_480_180_G_G_P_3_1_4_0_1_5_0_0_*2*.
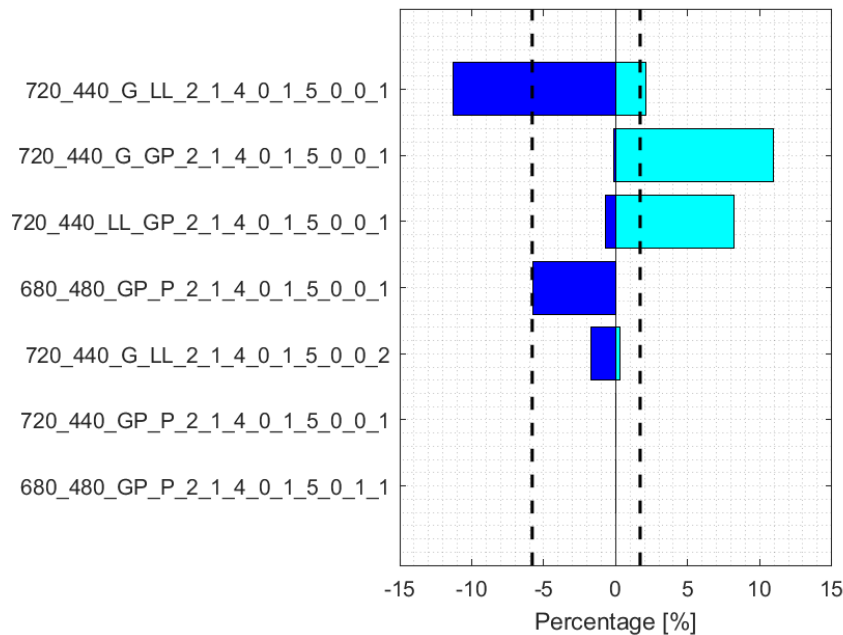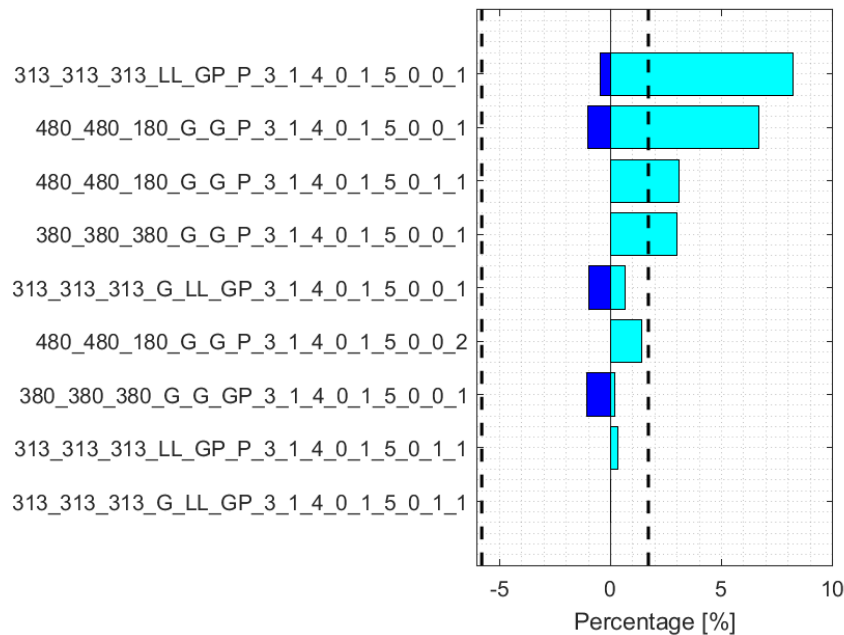
Fig. 37 Trains formed by three sub-trains with overall length of 1000 m and 1200 m

7.8. 3T-SW

This train configuration is characterized by the coupling of three sub-trains and adding a TU at the end of the whole train, therefore having 4 TU, all in all.

The train families showed in Fig. 38 have a maximum length of 1500 m and haul a not-homogeneous payload, usually (see the exception of trains with labels GH where the load is almost homogeneous among wagons).

As before, the first three numbers are the average lengths (±20 m) of the three coupled sub-trains. The letters, as LL, provide information on the hauled mass of the sub-trains: LL is between 1201 and 1600 ton, G is between 1601 and 2500 ton, GH is between 2501 and 4000 ton and the payload is almost homogeneously distributed among the wagons (as it happens in ore trains). When the sub-trains are coupled, the brake mode of each wagon has to be switched to G (see the number 4 between 1 and 0). The train operation is a full traction followed by an emergency braking, in nominal mode.

Also for these train families, it is difficult to find general good train configurations, but rather several "localized" good train configurations, since the in-train dynamics is more complex. Because of non-linear dynamics of in-train forces, the simulations show that the train family obtained by coupling three trains in G (with no restriction on the type of wagons and the minimum hauled mass) is less dangerous, with respect to train derailment, than the configuration obtained by coupling three trains in LL (with no restriction on the type of wagons and the minimum hauled mass). Consequently, it is necessary to further investigate the possible solutions, in order to better explore all possibilities. For this and also for the next train family, 5G technology has been introduced as well (look for the number 3 at the end of the alpha-numeric string): this technology

is better than LTE which is in turn better than GSM-R. The fifth row of Fig. 38 shows that it is possible to run a 1500 m train hauling up to 10000 ton with a marginal risk of train disruption.
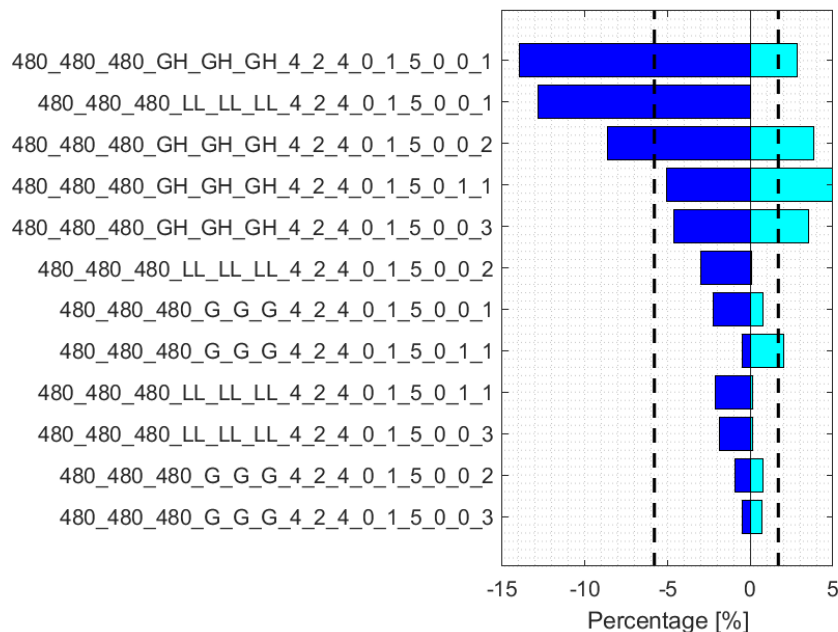
Fig. 38 Trains formed by three sub-trains and a TU at the end, with overall length of 1500 m

7.9. 4T

This train configuration is obtained by coupling four sub-trains and therefore have 4 TU.

The train families showed in Fig. 39 have a maximum length of 1500 m and haul a not-homogeneous payload.

The first four numbers are the average lengths (±20 m) of the four coupled sub-trains. The letters, as LL, provide information on the hauled mass of the sub-trains: P is lower than 800 ton, GP is between 801 and 1200 ton, LL is between 1201 and 1600 ton and G is between 1601 and 2500 ton. When the sub-trains are coupled, the brake mode of each wagon has to be switched to G (see the number 4 between 1 and 0). The train operation is a full traction followed by an emergency braking, in nominal mode.

Results show that, for these train families, the best solution is not to couple sub-trains of the same length and hauled mass. Better results can be obtained if also the hauled mass of the sub-trains is different. Displayed results show that if 4 TU are available to create a 1500 m train, it is better to use them to couple four sub-trains, as in this section, then to couple three sub-trains and adding a TU at the end, as in previous section. Anyway, also in this case, even if there are several "promising" trains, it is necessary to further investigate the possible solutions, in order to better explore all possibilities. 5G technology (as LTE) brings benefits with respect to GSM-R: Fig. 39 allows comparing the improvements that can be obtained by switching from GSM-R to LTE, to 5G or to a "synchronous" GSM-R. Even if this scenario is not explored in this deliverable, some further improvements can be obtained by using 5G technology and implementing a sequence in brake application, e.g. the first TU to brake is the second, then the fourth TU brakes, then the first brakes

and lastly the third TU brakes.
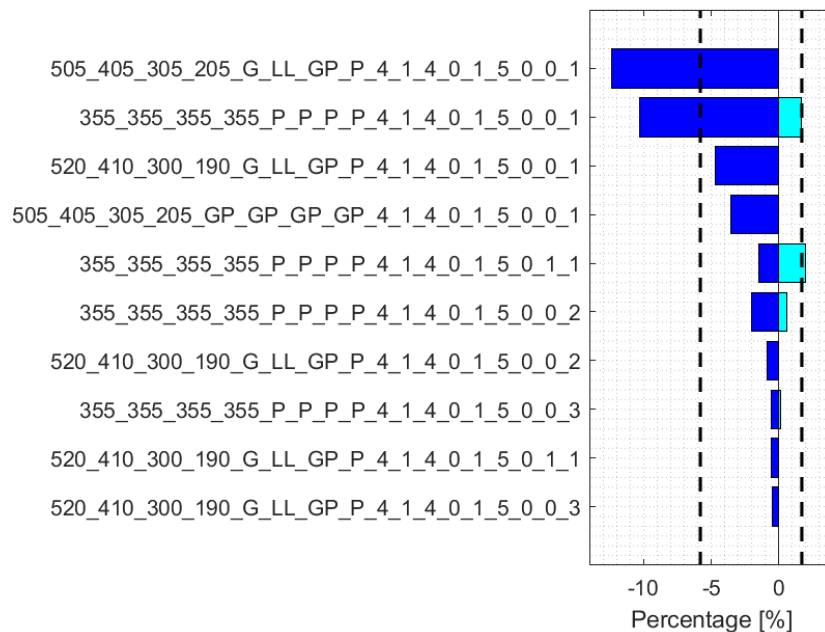
Fig. 39 Trains formed by four sub-trains, with overall length of 1500 m

8. Occurrence of degraded mode

Degraded mode may occur because of a not correct behaviour of DPS that causes a failure in the activation of remote driver's brake valve(s), because of a "failure" of radio or of the activation system of DBV, in general. These degraded modes are dangerous both for train derailment and for train disruption and their occurrence has to be limited.

Fig. 40 shows a Tornado Plot of some of the previous train families in degraded mode: a comparison with the previous counterparts shows the danger of degraded mode. This statement is general even if the results do not refer to all train families. Two degraded modes are considered:

1) Leading TU applies an Emergency braking and at the same time there is a failure in DPS: look for the number 2 (degraded mode) before the number 4 (emergency braking) in the labels.

2) Train is in full traction until all wagons overcome 30 km/h (roughly after 2 s the first vehicle overcomes 30 km/h), an emergency braking is commanded and at, the same time, there is a failure in the DPS, hence the guided TU do not receive the braking command via DPS and continue their full traction. For this scenario, two implementations of this degraded mode 2) are considered:

    a. The guided TU wait for 1 s before reducing the traction force (with a gradient that is changed parametrically); at the same time, when the guided TU detect a pressure drop in brake pipe of 0.2 bar (with respect to the reference value), it applies a "stepwise" service braking (having as target 4.5 bar, 4.0 bar and 3.5 bar). The "quickness" of the brake pipe emptying from guided TU is changed parametrically, too. Look for the number 3 (degraded mode) before the number 5 (traction - emergency braking) in the labels.

   b. The guided TU reduces the traction force and applies a stepwise service braking as soon as it detects a pressure drop in brake pipe of 0.2 bar. Look for the number 2 (degraded mode) before the number 5 (traction - emergency braking) in the labels.

It is worthwhile to mention that the official TrainDy version, used to provide the results of this deliverable, is not currently capable to handle 2)a and 2)b at the same time, so they are considered as two separate degraded modes. Most probably, the actual DPS will be capable to handle 2)a and 2)b at the same time, i.e. it can react as soon as it detects a pressure drop of 0.2 bar or as soon as the communication is lost by 1 s. It is clear that, if a train consist has two TU and these TU are far away, 2)a is quicker than 2)b; the contrary occurs if the TU are "close" each other.

Please consider that in Fig. 40 the labels with degraded mode have two extra numbers at the end: 70 is the gradient of traction reduction (in kN/s) and 5 is the diameter, in mm, of the equivalent nozzle of the guided TU: this value has been identified during the comparison against the experimental tests.

Fig. 40 (a) reports family of trains having length up to 500m (without TU, with one TU in front and the second at the end, they reach 540m), almost homogeneously loaded. First two rows refer to degraded mode, the other two to the same train family, but in nominal mode: increase of longitudinal compressive forces is clear. In Fig. 40 (b) there is one train family obtained by coupling 2 sub-trains, with overall length of 740 m. The results show the benefits of the approach 2)b with respect to 2)a (see labels 500_200_G_GP_2_1_4_0_*3*_5_0_0_1_70_5 and 500_200_G_GP_2_1_4_0_*2*_5_0_0_1_70_5 in first and second row from the top). Moreover, the figure shows the benefit of increasing the gradient of traction removal (from 70 to 150 kN/s) and also the benefits of venting the brake pipe quickly, see the equivalent diameter from 5 to 15 mm: it is worthwhile to mention that these different equivalent diameters used by TrainDy correspond to different gradients of DPS system. Last three rows of Fig. 40 (b) represent the train performances in nominal mode. Similar considerations apply also to the other figures (c) and (d). Please note that in Fig. 40 (d) the approach 2) b is worst then the approach 2) because of the "distance" of the two TU. As already specified before, this is a current limitation of TrainDy and it should not occur in the actual DPS. A last remark for (d) is that the hauled mass is considerably lower than the hauled mass from (a) to (c).

(a)-1T-SW

(b)-2T 700 m
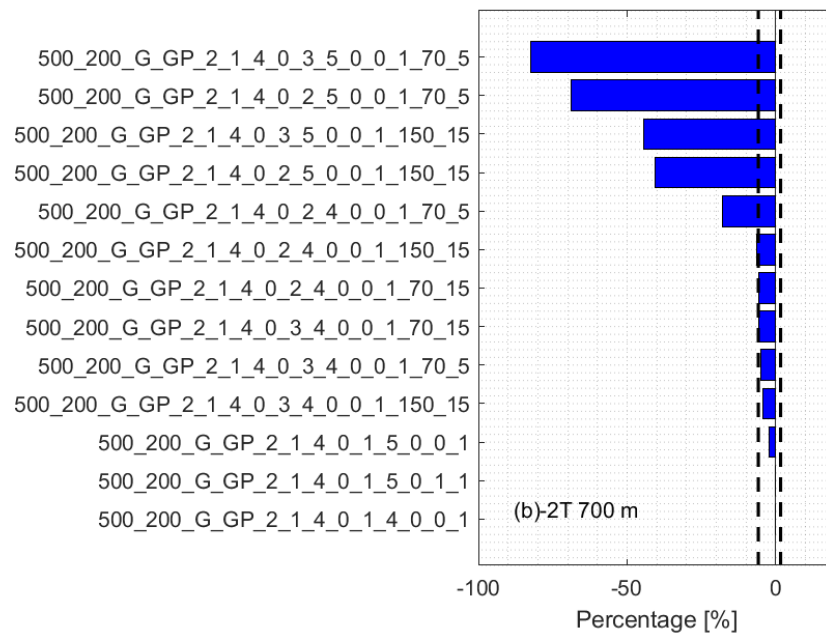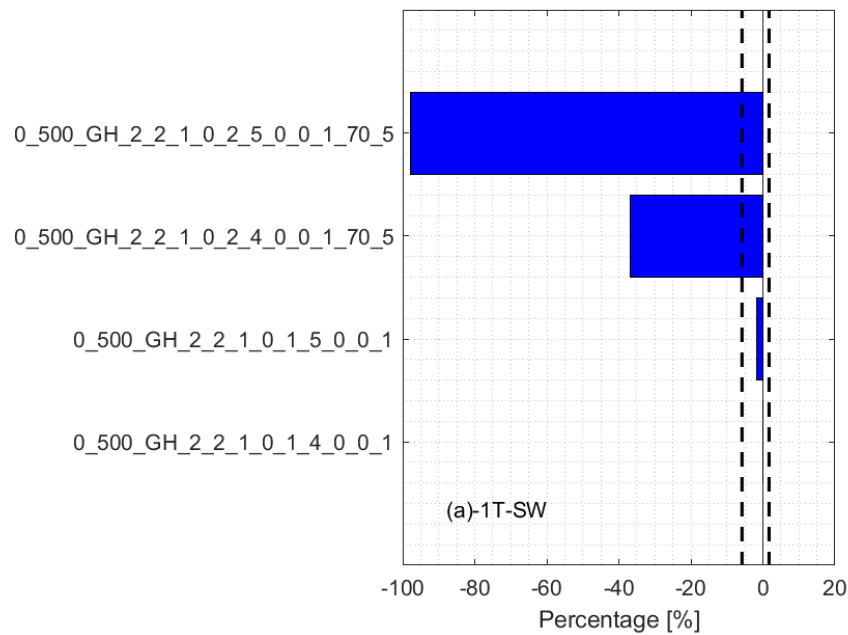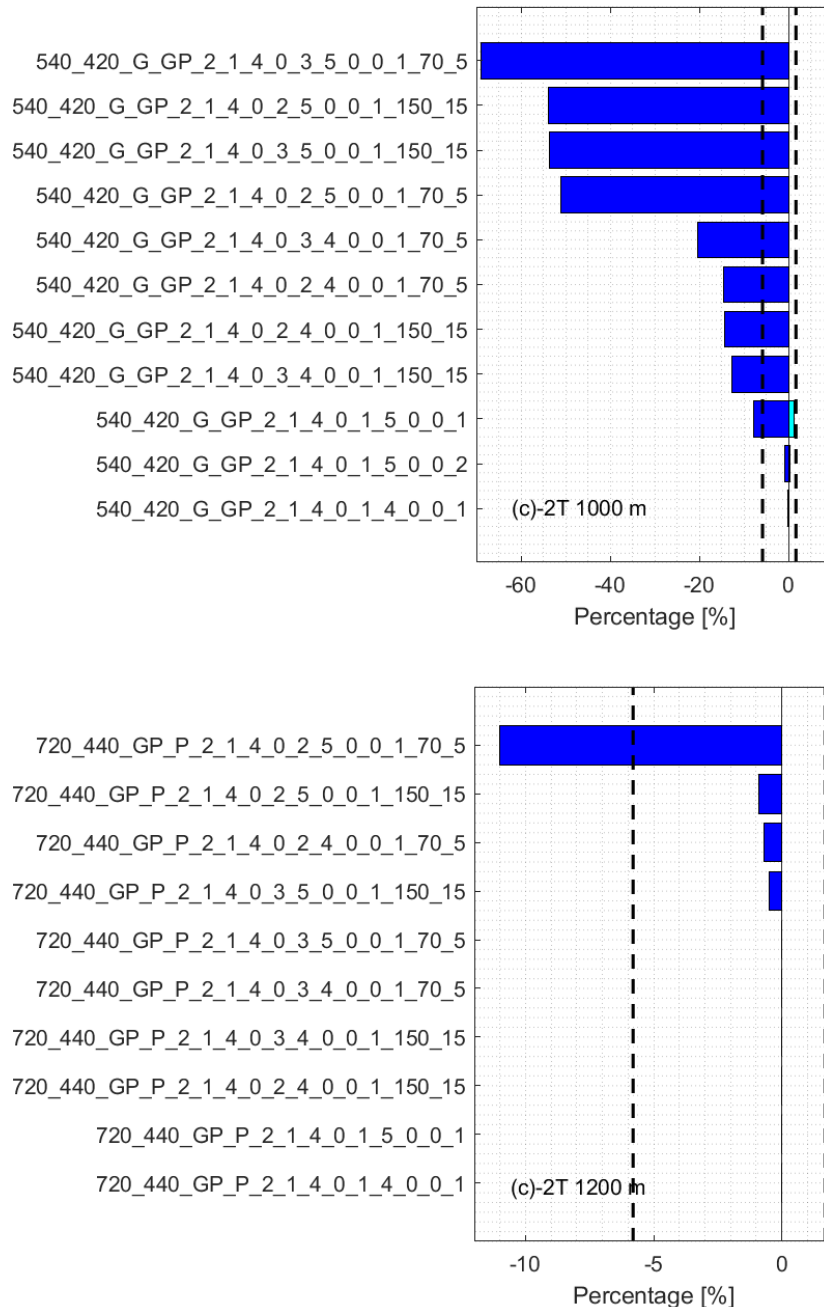
Fig. 40 Tornado plots of some train families in nominal and degraded mode

Applying the methodology of section 12.2, it is possible to compute the maximum value of the occurrence of degraded mode so that the trains with DPS are safer than the reference trains. As an example, we consider the train formed by coupling two sub-trains: the first having an average length of 500 m and a hauled mass between 1601 and 2500 ton, heterogeneously loaded, and the second having an average length of 200 m and a hauled mass between 801 and 1200 ton, heterogeneously loaded; once coupled, the whole train runs in G mode. Probabilities of virtual derailment and disruption are:

- For a full traction followed by an emergency braking, the virtual derailment probability in nominal is mode 2.11 %
- For the same manoeuvre, but in degraded mode and:
    - managed as in 2) a, the derailment is 82.37 %
    - managed as in 2) b, the derailment is 68.61 %
- Increasing the equivalent nozzle of the guided TU (from 5 mm to 15 mm) and increasing the removal gradient of traction force (from 70 to 150 kN/s) and managing the degraded mode according to pressure or time:
    - managed as in 2) a, the derailment is 44.48 %
    - managed as in 2) b, the derailment is 40.56 %

The Tab. 7 lists, using the exponential notation, the different values of maximum occurrence of degraded mode in order to have the previous DPS train safer than the reference trains. Of course, higher is the number better is. Even if the probability of occurrence of degraded mode is not known, currently, it can be assumed that in the reality it will be much lower than the number displayed in Tab. 7.

Tab. 7 Maximum occurrence of degraded mode

	Derailment risk	
	As in 2) a	As in 2) b
Traction removal Gradient is 70 kN/s Diameter nozzle is 5 mm	4.59e-02	5.54e-02
Traction removal Gradient is 150 kN/s Diameter nozzle is 15 mm	8.70e-02	9.59e-02

9. Operational considerations

Above results show that it is possible to safely operate DPS trains if the occurrence of degraded mode is smaller than the values of Tab. 7. Nevertheless, if the degraded mode occurs, there can be a risk of derailment (and in general also of train disruption), since the high values of LCF (and also LTF, in general).

In this last section, we analyse, very quickly, just one DPS train, having string: 500_200_G_GP_2_1_4_0_2_5_0_0_1_150_15. As before, the train is formed by coupling two sub-trains: the first having an average length of 500 m and a hauled mass between 1601 and 2500 ton, heterogeneously loaded, and the second having an average length of 200 m and a hauled mass between 801 and 1200 ton, heterogeneously loaded; once coupled, the whole train runs in G mode. The train is in degrade mode according 2) b, see the red 2 in the alpha-numeric string, and the gradient of traction removal and the diameter of equivalent nozzle are 150 kN/s and 15 mm, respectively.

Such train family is characterized by a train that has a minimum LCF 10m of 597.51 kN (minus sign has been removed); this value can bring to a derailment if it is experience on a curve of short radius.

In order to reduce this value, several strategies are possible:

- ▪ Reduction of power request from TU: 50% of maximum force is requested as an example.
- ▪ Apply a full-service braking after the full traction.
- ▪ Reducing the pressure in brake pipe not stepwise, but with a full-service braking. Stepwise reduction seems more convenient at high speed.

Fig. 41 shows the time evolution of the LF 10m for the above options: there negative values represent LCF (dangerous for derailment risk) and positive values represent LTF (dangerous for disruption risk). In this figure, (a) is the reference: since the 10 m LF are plotted, at the beginning, the in-train forces are zero. Among the previous options, the most beneficial is the application of a full-service braking after the traction, then the reduction of the power requested to the TU and lastly the application of a full-service braking when a degraded mode occurs.
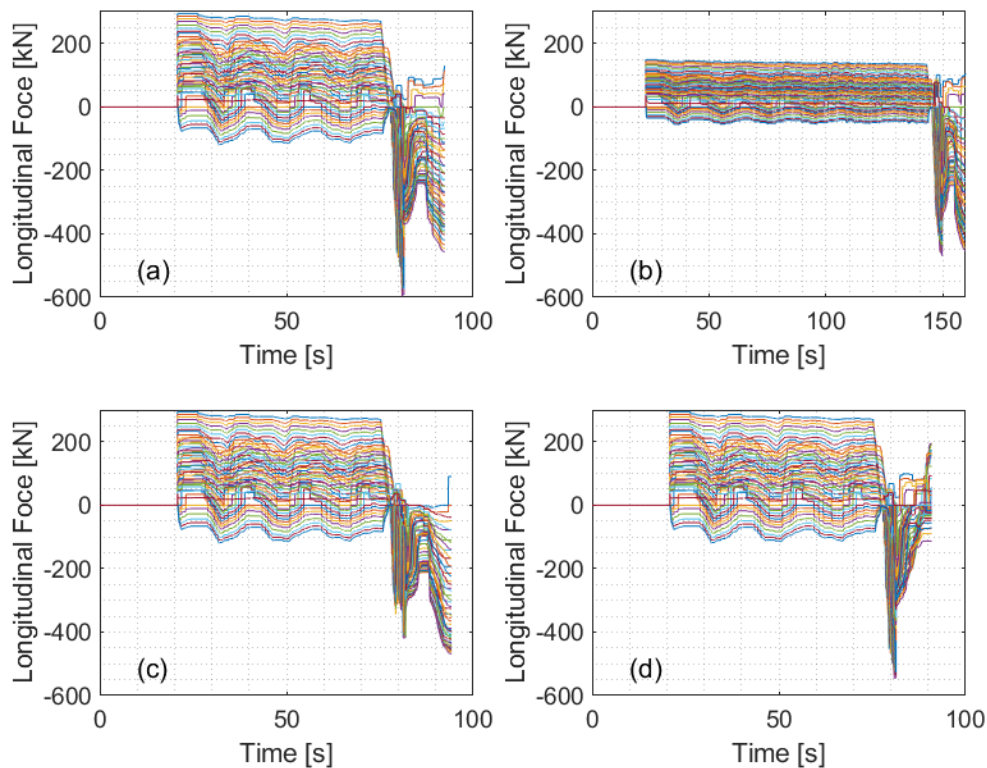
Fig. 41 Time evolution of LCF 10m according to the different degraded modes: (a) reference, (b) half power, (c) service braking; (d) No stepwise reduction

Before concluding this section, it is worthwhile to mention the increase of stopping distance in case of full-service braking after full traction instead of an emergency braking: the stopping distance (measured from the start of the braking) changes from 104.6 m to 116.2 m. If the full-service braking is applied without a stepwise reduction of pressure, the stopping distance reduces to 109.6 m, i.e. 5% more than the reference case (full traction followed by an emergency braking). What reported is just an example, but it shows the way to run DPS trains that are safe also in degraded mode.

10. Conclusions

This deliverable reports a wide list of trainsets suitable to be operatively used, according to the technology available, mainly in terms of radio communication and railway infrastructure (in the sense of allowed train length). Therefore, it is not limited only to:

- o Single trains with 1 TU at each end connected by radio
- o Coupling of two trains up to 1500m overall length.
- o Coupling of two heavy trains with addition of one TU at the end
- o Creating a train of 1500m length with two TUs in the train and one at each end
- o Standard 740m very heavy train with one TU at each end

For the single trains with one TU at each end the possible configurations in nominal mode are summarized here under:

Long homogeneous trains, running in G mode, with 1T-SW , of up to 7 T/m weight which length is up to 960 m with one locomotive at each end weighing 100T each and 20 m length each to add (BR187)

Mass T	2500/5500 Bk G	4000/4500 Bk G	4250/4750 BK G	5000/5500 BK G	5250/5750 BK G	6250/6750 BK G	7750/8250 BK G
Length M	GSM-R	GSM-R	GSM-R	GSM-R	GSM-R	GSM-R	GSMR
0/740	Fig.30						
700/740		S25	Fig. 32				
800/840				S29	Fig.32		
940/980						Fig.32	
1140/1180							S46

In picture above, red is used for train consists that may experience problems, green is used for safe consists and yellow is used for consists that could be considered safe, but they have not been simulated, actually. Reference with S# refer to the slide number in the attached document.

By the way, the maximum train length reached with two TU is 1200 m and the (virtual) probabilities of derailment and train disruption are reported in Fig. 35; they employ both GSM-R (e.g. 720_440_GP_P_2_1_4_0_1_5_0_0_1, i.e. train made by coupling two trains; the first having a length of 720m -loco excluded- and a hauled mass between 801 and 1200 ton, the second having a length of 440 m -loco excluded- and a hauled mass lower than 800 ton) and LTE radio (e.g. 720_440_G_LL_2_1_4_0_1_5_0_0_2, i.e. train made by coupling two trains with the same lengths of previous train but with hauled mass of the first train between 1601 and 2500 ton and of the second train between 1201 and 1600 ton). Fig. 42 reports a summary in matrix view. In this figure, yellow boxes are placed when the corresponding mass and train length were equal or lower than

the simulated one with a high probability to constitute a safe train consist: anyway, they should be simulated effectively before any test.

Coupled trains of combined transport with 2TUs 100km/h homogeneous wagons flat with bogies 2.6T/m average load but random loading or heavy ore homogeneous trains coupled with container trains behind

Nominal mode LL shoes for all wagons   **Direction**

Maximum length 1200M

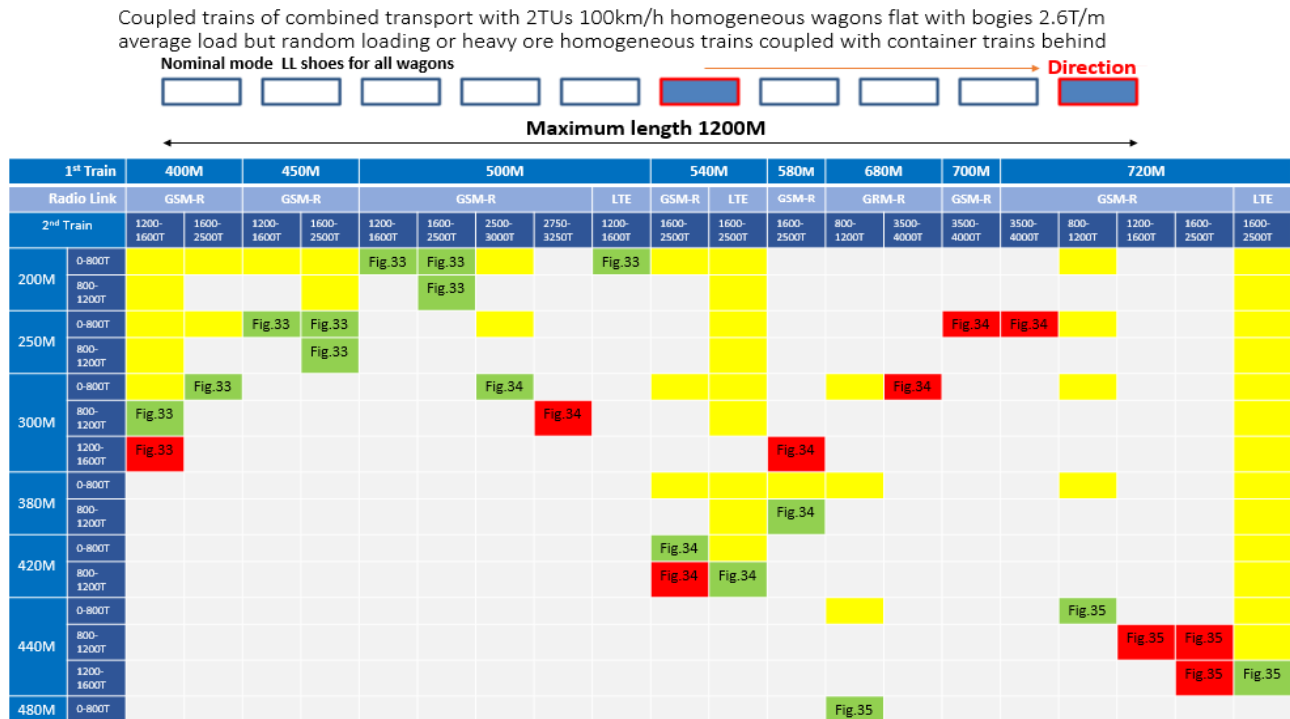| 1st Train		400M		450M		500M				540M		580M	680M		700M	720M			
Radio Link		GSM-R		GSM-R		GSM-R			LTE	GSM-R	LTE	GSM-R	GRM-R		GSM-R	GSM-R			LTE
2nd Train		1200-1600T	1600-2500T	1200-1600T	1600-2500T	1200-1600T	1600-2500T	2500-3000T	2750-3250T	1200-1600T	1600-2500T	1600-2500T	800-1200T	3500-4000T	3500-4000T	3500-4000T	800-1200T	1200-1600T	1600-2500T	1600-2500T
200M	0-800T					Fig.33	Fig.33			Fig.33										
	800-1200T						Fig.33													
250M	0-800T			Fig.33	Fig.33											Fig.34	Fig.34			
	800-1200T				Fig.33															
300M	0-800T		Fig.33				Fig.34							Fig.34						
	800-1200T	Fig.33																		
	1200-1600T	Fig.33										Fig.34								
380M	0-800T																			
	800-1200T											Fig.34								
420M	0-800T									Fig.34										
	800-1200T									Fig.34	Fig.34									
440M	0-800T															Fig.35				
	800-1200T																Fig.35	Fig.35		
	1200-1600T																	Fig.35	Fig.35	
480M	0-800T										Fig.35									

Fig. 42 Matrix view of the coupling of two trains

The *coupling of two heavy trains with addition of one TU at the end* allows the overall train length of 1480m (loco included), as displayed in Fig. 36; in this figure, the train 720_720_3750_3750_3_2_4_0_1_5_0_0_1 is equipped with a GSM-R radio and it is made by coupling two similar trains having each a length of 720m -loco excluded- and a hauled mass of 3750 ton (average) almost uniformly distributed.

Using both GSM-R and LTE radio, by coupling three trains having a hauled mass (each) between 1601 and 2500 ton, it is possible to form *a train of 1500m length with two TUs in the train and one at each end*, as displayed by Fig. 38. In this figure, the lines 480_480_480_G_G_G_4_2_4_0_1_5_0_0_1 (or 2 for LTE) reports the (virtual) probabilities of derailment and train disruption of these train families. These consists studied in the report seem less competitive than some of those reported before, therefore these data are not further reported here.

The other conclusions reached at this stage of the R&I carried out in WP3 of M2O and highlighted in this report are:

- The results of UIC TrainDy simulator are consistent with the experimental measurements carried out in May 2019 by FFL4E. Maximum difference in degraded modes, on the peak values, is 16.9 %, the main error is 10.2 % and the minimum error is 1.1%. This topic will be further addressed in D2.3, by means of a statistic investigation.

- From these experiments performed in May 2019, a probabilistic distribution of the communication delay in the activation of the brake pipe venting, at Traction Units, has

been achieved. This distribution is consistent with the work of Funkwerk on the integration of radio technology within existing Bombardier Traction Units (BR 187).

- The pneumatic performances of Driver's Brake Valve, deduced from the experimental tests, are different from those initially assumed in the simulations. Current performances, deduced from the experimental tests, have been used for all results of this deliverable and will be used also for future TrainDy simulations in M2O.

- Several train families can be safely operated in nominal mode with DPS considering up to 4 TU and a train length up to 1500 m. "Safely" in this context means with a virtual probability of derailment and train disruption lower than the corresponding probabilities of the trains currently considered safe (see Tab. 6).

- In degraded mode, the risk (both of derailment and disruption) increases considerably. Tab. 7 shows an example of computation of occurrence of degraded mode that makes the DPS train safe as the reference train (always in nominal mode, of course), based on considerations of 12.2. Looking at the results reported in accompanying document, D3p1_TrainDy_Extended_Simulations.pdf, it is possible to compute such occurrence for many other train families. If the actual occurrence of degraded mode is lower than the occurrence computed according to 12.2, the train family is safer than the existing train families.

- Results reported on degraded mode show that it is possible to improve the actual performance of DPS by increasing the gradient of traction reduction and the quickness of venting the brake pipe. Upon the agreement with FR8RAIL II, these modifications can be tested in 2020.

- By means of a different driving strategy, employed in DPS trains, it is also possible to considerably reduce the in-train forces, in degraded mode.

- It is worthwhile to mention that the best results in terms of overall mass and train length are achieved if the wagons are all switched to G (goods) regime, once the overall train is formed. If the original brake regime of the wagons is kept, overall train length and mass has to be limited: see results in D3p1_TrainDy_Extended_Simulations.pdf.

- The performance of LTE technology (used as bridge technology for FRMCS* based on 5G radio) and of 5G technology are proved to be better than the performance of GSM-R in terms of longitudinal or in-train forces, showed in this deliverable. Therefore, it is advised, according to the simulations results, to implement and employ such technologies as soon as possible, in order to optimize the efficiency of freight trains with DPS system and to improve their safety against derailment and disruption risks.

- The simulation work with four TU has to be continued by generating much more different train families that can operate safely. Their economical viability will have to be studied. Simulations results of Fig. 39 show that, differently from what expected, the best solution is not to couple "equal" trains, but to couple trains having a descending length and hauled

mass. Even if it has been not proved yet, by means of further studies and simulations, it is possible to find also other sequences of sub-trains mass and length, to increase the hauled mass of the coupled train.

11. References

[1] Laghi D., La Rovere S., Cantone L. – *D2.2 – M2O TrainDy, Sensitivity Analysis* – 2019, https://www.marathon2operation.eu/web/pdf/D2.2_TrainDy_Sensitivity_Analysis.pdf and https://www.marathon2operation.eu/web/pdf/M2O_D2.2_Extended_results.pdf

[2] Leaflet UIC 544-1, Brakes – Braking performance, 5th edition, June 2013

[3] Leaflet UIC 421, Rules of the consist and braking of international freight trains, 9th edition, January 2012.

[4] L. Cantone, E. Crescentini, R. Verzicco, V. Vullo, "*A numerical model for the analysis of unsteady train braking and releasing manoeuvres*", *Proc. IMechE, Part F: J. Rail and Rapid Transit*, 2009, 223 (F3), 305-317. DOI 10.1243/09544097JRRT240.

[5] DYNAFREIGHT "D3.2 Safety precautions in train configuration and brake application" https://projects.shift2rail.org/download.aspx?id=6b703a20-4e88-475b-8667-6b00ee9ccffe (link viewed on 3rd of February 2020)

[6] L. Cantone, "New Random Trains Generation According to UIC Code 421", International Journal of Mechanical Engineering and Technology, Vol. 9, no. 10, October 2018, pp. 890-899.

12. Appendices

12.1. Appendix A

The complete list of simulations can be found in the document:
D3p1_TrainDy_Extended_Simulations.pdf

12.2. Appendix B: Occurrence of degraded mode

In this section, it is shown an easy method to compute the occurrence of degraded mode that would provide the same level of safety of the new system (with DPS) and the classic system (with TU in front).
The probability of derailment of reference system is P^{ref}:

$$P^{ref} = \sum_{i=1}^{n} p_i P_i, \quad \sum_{i=1}^{n} p_i = 1$$

Where:
- p_i is the occurrence of each train operation, e.g. full service brake, emergency braking, …
- P_i is the probability of derailment with train operation i

Probability of derailment of new system (with degraded mode) - P^{new}:

$$P^{new} = \sum_{i=1}^{n} p_i [(1 - \alpha) P_i^N + \alpha P_i^D]$$

Where:
- α is the occurrence of degraded mode.
- P_i^N is the probability of derailment for train operation i in nominal mode
- P_i^D is the probability of derailment for train operation i in degraded mode

By equating P^{new} and P^{ref} it is possible to compute the occurrence α of degraded mode. If this value is <u>above</u> (i.e. higher than) the estimated or measured occurrence of degraded mode, the train family is <u>safer</u> than the reference system. Currently, α has not been estimated but it is closely linked to the reliability of radio technology: GSM-R, LTE and so on.

12.3. Appendix C: Generator of virtual trains

The algorithm used to generate virtual trains is compliant with [3]. In this appendix, it is quickly reviewed to benefit the interested Reader.
The train consists reported in this deliverable were generated using data from actual trains, operated in Germany. The cumulative probabilities of train mass and wagon type are generated considering the running distance, i.e. a train or a wagon that has a higher running distance counts more of a train or a wagon that performs few kilometres.
Since the wagon database of TrainDy, provided at this aim by DB Systemtechnik, does not contain all the wagons listed in the train database, the wagons that do not exist are substituted by the

wagons that are in TrainDy database, in a proportional way: e.g, if WagA occurs 40%, WagB 30%, WagC 20% and WagD 10% and WagB is not in the TrainDy database, the occurrences of the other wagons are changed proportionally: WagA 57.1%, WagC 28.6% and WagD 14.3%.

When a sub-train with a specified interval of mass and length has to be generated statistically, the overall database, which counts hundred thousands of trains, is interrogated and the trains that fits those requirements are extracted. From these trains, a train mass distribution, a wagon distribution, a group distribution and a load distribution for each wagon are generated. These data are used to randomly create the virtual trains according to the methodology described more in detail in [6], see also the following figure:
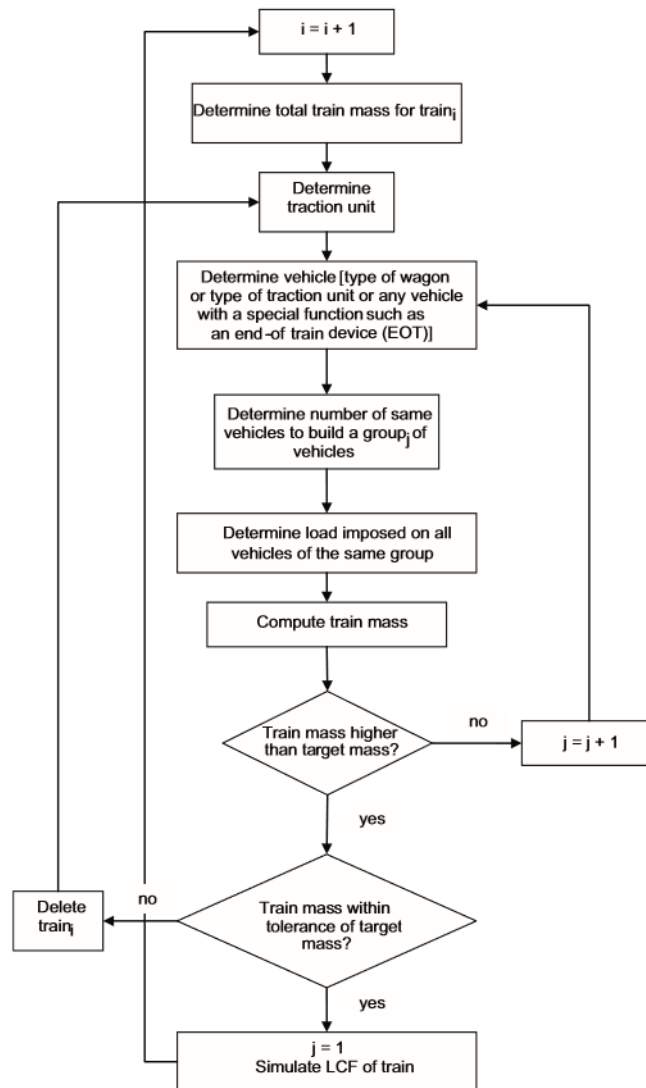
By taking each time a different subset of trains, from the comprehensive database, and by considering the running distance, the generated virtual trains are more similar, in terms of wagon type, load distribution and hauled mass, to those actually existing.