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Marathon2Operation, a Shift2Rail project for radio communication and simulation of train dynamics for distributed power within long trains

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Abstract

The paper reports the main objectives of the European research project Marathon2Operation (M2O). This project aims to define the best train configurations with distributed traction and communication via GSM-R radio technology, compared to longitudinal dynamics and to demonstrate their safety through a safety analysis independently assessed. The analysis involves trains with two up to four traction units. The trains analyzed are randomly composed, considering different types of wagons and different mass distributions along the train, to be representative of the operational reality. The first results of the project allow identifying some families of distributed traction trains (these are coupled trains) that have a behavior of longitudinal dynamics (also considering the degraded operation, i.e. with radio problems) similar to that of some trains currently running.

Keywords: Shift2Rail (S2R); Marathon2Operation (M2O); Distributed Power System (DPS); Freight Trains

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1. Introduction

Shift2Rail (S2R) is the first European rail initiative for research and innovation (R&I) and market-driven solutions aiming to accelerate the integration of new and advanced technologies into innovative rail product solutions. This Horizon 2020 R&I initiative develops the necessary technology to complete the Single European Railway Area (SERA). The development of the European economy is closely linked with efficient mobility both for persons and for cargo. Road mobility, being the dominant modality, has always taken a larger share of the growing needs. A network of high-speed railway lines has been developed across Europe, for passengers. Since the EU is more and more concerned about the external effects of road modality, it has promoted more sustainable solutions for goods transport. Among the more environmentally friendly modalities, inland waterways and railways are the most efficient. However, Railway is serving Europe territories more largely and the EU has implemented a series of corridors constituting a Trans-European network. In the meantime, transport demand has fundamentally changed, and smaller and more frequent shipments are the core of the commercial growth. Confronted with that evolution, extremely favorable to road modality, Railway has developed the combined transport actively and has been focused on interoperability to overcome barriers to seamless border crossings. These efforts are costly and now the railways must face a double challenge: enhance drastically and rapidly its competitiveness and offer the necessary capacity on the rail network. The capacity issue is crucial as the EU target for rail modality in 2050 is to transport 50% of what road modality transports to match the necessary reduction of CO2 and particulates emissions preserving the planet from a dramatic climate change. This issue is even more crucial as it is more and more difficult to create new infrastructure due to decreasing acceptance by populations and since huge maintenance works are necessary on the Network to recover a normal quality level after many years of restricted maintenance. In summary, the challenge is Transport by Rail two to three times more with a much more competitive price in the next 30 years.

To address the above objectives, the EU has launched the European Program Horizon 2020 and within this program has launched the Shift2Rail (S2R) Initiative. S2R has launched several projects and one of these is the Marathon2Operation (M2O) project. The topic of this project is the simulation and the safety analysis of trains with distributed power and braking; the DYNAFREIGHT project, in Visakh V Krishna et al. (2019), has already covered this issue and it has emphasized the need to compute reference values for the admissible longitudinal compressive forces.

In M2O, the topic of admissible longitudinal compressive forces is not addressed directly, but it is handled by following the approach of Leaflet UIC 421 (2012), i.e. utilizing extrapolated curves based on measured (or assumed/computed) limit values for axle and bogie wagons. The UIC TrainDy software, introduced by Cantone (2011), is used to compute the in-train forces of the new types of trains with distributed power and braking. This software has been recently updated through a new module for composite brake blocks type LL described in Cantone and Ottati (2018) and a new module of control valve proposed by Arcidiacono and Cantone (2018), to broaden its application field. Qu et al (2017) and Cole et al. (2017) show the results of a benchmark on Longitudinal Train Dynamics (LTD) and a review of the various modelling techniques used to compute the LTD. As pointed out by Cheli et al. (2017), in-train forces depend on payload distribution; for this reason, the M2O project will consider families of trains and not just single trains and will base its conclusions on a statistic approach. This can lead, in the future, to optimization of mass (payload) distribution as discussed by Arcidiacono et al. (2017)-(2018).

2. Project overview and aims

M2O is a project aiming to take up this challenge or at least to contribute efficiently. Having understood that the timeline is constrained the project will consider the infrastructure as it is but for marginal improvements to resolve some bottlenecks on the network. Having also understood that the demand for more frequent and smaller shipment will remain largely spread over the whole European territory the project will have to provide more competitive solutions for connecting all main parts of European territories between them without reducing the frequency of the connections. To fulfill these objectives, the project will continue: to make the best use of the network as it is; to enhance the efficiency of the various kind of trains (heavy trains and combined transport trains); to organize train couplings with distributed traction online and in a very short time and to run safely these new consists with one driver, piloting all the Traction Units (TU).

This project capitalizes on the results of the FP7 Marathon project where two real experimental demonstrators of around 1500m length and up to 4500T involving each two similar electric TU and two similar diesel TU have safely run on the French Rail Network on 250km performing a series of tests after more than 1000 simulations with TrainDy software. It will capitalize also on the results of the ongoing FFL4E project for which a 550m standard train length but heavily loaded train with Electric TU at both ends has made experimental runs on the German network, in May 2019.

M2O will collaborate with the FR8RAIL II project to define the type of trains that will be used for tests, which will be handled by DB AG with Bombardier traction units and with Faiveley Transport (a Wabtec Company) Distributed Power System (DPS). The configuration of the test trains will involve up to four TU in the consist. The TU will be connected between them by GSM-R devices of FUNKWERK to ensure their remote control by the head driver.

The project will start by analyzing all functions necessary for operating such types of trains. It will define the architecture of the system to operate such a train. It will perform a risk analysis on the functions and the architecture of the system to define all possible failures creating degraded modes and the mitigation solutions, also capitalizing the results of TrainDy simulations.

Once defined the functions and the architecture and adopted the equipment, they will be separately studied to make their hazards analysis; then they are integrated into the system to make it operational. The integration itself will be studied in terms of safety to precise the degraded modes and see what mitigation solutions should be implemented. The integration of the radio in the system, with its interface, will focus the attention, but the level of safety of GSM-R is already validated in the rail industry and largely developed in Europe.

The project will simulate with TrainDy a series of train compositions to cover precisely the test trains envisaged but also the trains up to 1500m with distributed traction to define the field where train compositions and corresponding running speed can be safely utilized on defined network infrastructure. This main part will involve extremely numerous simulations to align the safety probabilistic level on the level currently accepted for standard trains running on the network in all possible operational situations. The whole process will be conducted under the supervision of NIER Ingegneria (a specialized safety company) to validate the system and the mitigating solutions in case of failures.

An Advisory Board will be set up involving ERA, other Railway Undertakings (RUs) and Infrastructure Managers (IMs) to have a European view of the constraints that would allow these trains to run safely in different EU Countries.

For the test trains a very precise analysis of the test trains composition resulting from sensitivity analysis to find the most critical configurations to be tested if they are realistic. Finally, an independent Safety Assessor (TUV Sud) will give its opinion on the process, the hazard analysis, the mitigation solutions, and the possible train, loading configurations and operating constraints necessary to submit a demand of the authorities to run such trains on the national networks.

Our project aims to reduce the capacity occupied per ton carried by 40% on trunk travel. This should be achieved with ultimately two coupled trains of 750m each reaching 1500m length in total. However, the real efficiency supposes that these long trains have to be full in comparison with full standard trains of 740m. For that purpose and to offer the necessary frequency requested by the market, it is compulsory to serve frequently several traffic generation points and then couple the trains for their trunk travel before decoupling them to serve frequently several destinations. The distributed traction and the couplings and de-couplings on-line enable reaching this goal in around five minutes. All these operations need a fully organized management of the drivers necessarily present during the coupling and decoupling operations while the long train may run on the trunk travel with only one driver.

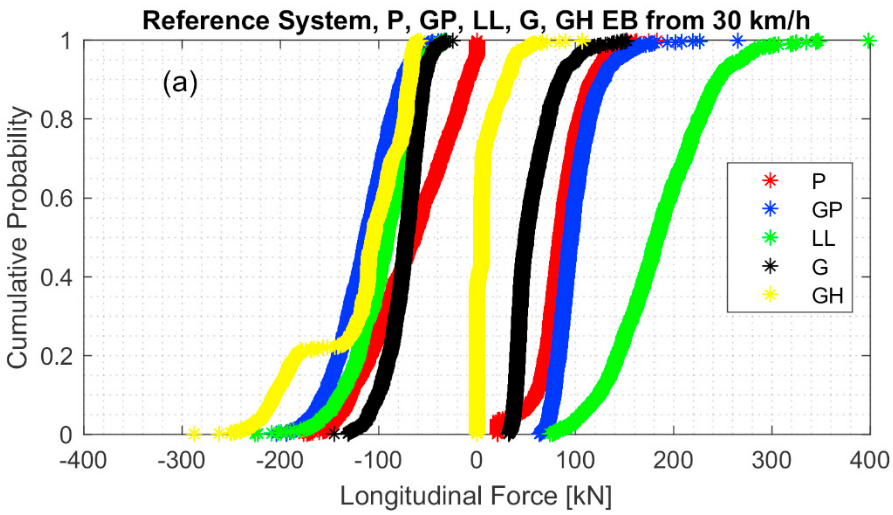
As regards the costs, radio remote control equipment and specific drivers brake valves on a TU should remain light costs and the target is to reduce the cost per ton by around 30%. The on-going digitalization of rail transport should simultaneously reduce the cost of the train preparation and increase the filling coefficient by a better exchange of information on the transport offers and demands. New solutions for last-mile traction and automation of operation in a European network of Hubs and terminals should offer with M2O trains sustainable solutions to progress towards the goals of the EU in terms of more environmentally friendly and safe mobility.

3. Preliminary results

Methodology to assess new trains, based on Longitudinal Train Dynamics considerations, relies on Leaflet UIC 421, hence, on a “relative approach”, i.e. new trains are considered "safe" if their performance, in terms of in-train forces, is like reference trains. Reference trains are the trains already admitted to circulation. The comparison should be performed both in nominal and in degraded modes (considering the likelihood of degraded mode); moreover, comparison in terms of in-train compressive forces is more relevant for safety (e.g. derailment risk), whereas comparison in terms of in-train tensile forces is more relevant for maintenance (e.g. train-disruption risk). Trains showed in this paper are "virtual", i.e. they do not exist in reality, but they are numerically generated employing "probability considerations", based on actual trains. Leaflet UIC 421 approach is followed in this paper and it is not here recalled for brevity's sake; the only "enhancement", to the current version of Leaflet UIC 421, is that trains are generated not only according to mass distribution but also considering bounds for the train length. This means that fixing bounds in terms of train mass and length, from the overall train database are extracted the trains respecting those bounds. From these trains, the cumulative probability of train mass, wagon type, wagon payload and so on are determined. Finally, virtual trains are generated, following the Leaflet UIC 421 methodology, using those cumulative probabilities. In this way, the virtual trains reproduce, at best, the actual running trains.

3.1. Reference system

Following the previous methodology to generate virtual trains, Figure 1 shows the cumulative probabilities of reference trains, assuming cast iron as brake material for each wagon. In this figure, different curves and line-colors refer to the train hauled mass and brake position, see Leaflet UIC 421 (2012): “P” lower than 800t; “GP” between 800t and 1200t; “LL” between 1200t and 1600t; “G” between 1600t and 2500t; “GH” above 2500t (train brake position is “G”). Latter family of trains is made of wagons almost uniformly loaded, whose hauled mass arrives up to 5500t, see Fig. 2, where the mass distributions of all families are shown. Fig. 1 (a) refers to an emergency braking manoeuvre (target air pressure in brake pipe is zero) from the speed of 30 km/h; (b) refers to an acceleration from zero speed with maximum power, followed by an emergency braking when the train has reached 30 km/h: this is the riskiest condition for in-train compressive forces. In Fig. 1 and similar figures of this paper, negative and positive values are used for in-train compressive and tensile forces, respectively; for each train, the maximum 2m in-train tensile force and the minimum 10m in-train compressive forces are reported on the graph. Each family consists of 1000 virtual trains.



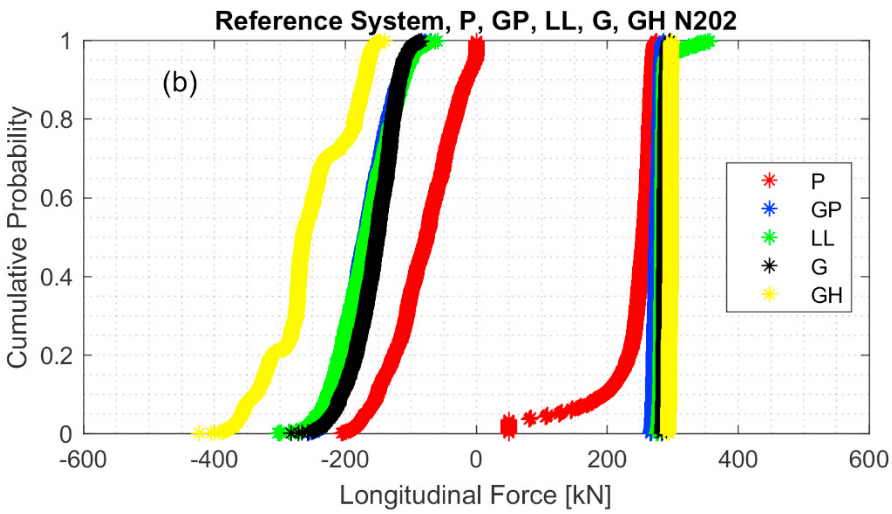


Fig. 1 (a) Emergency braking; (b) traction followed by emergency braking.

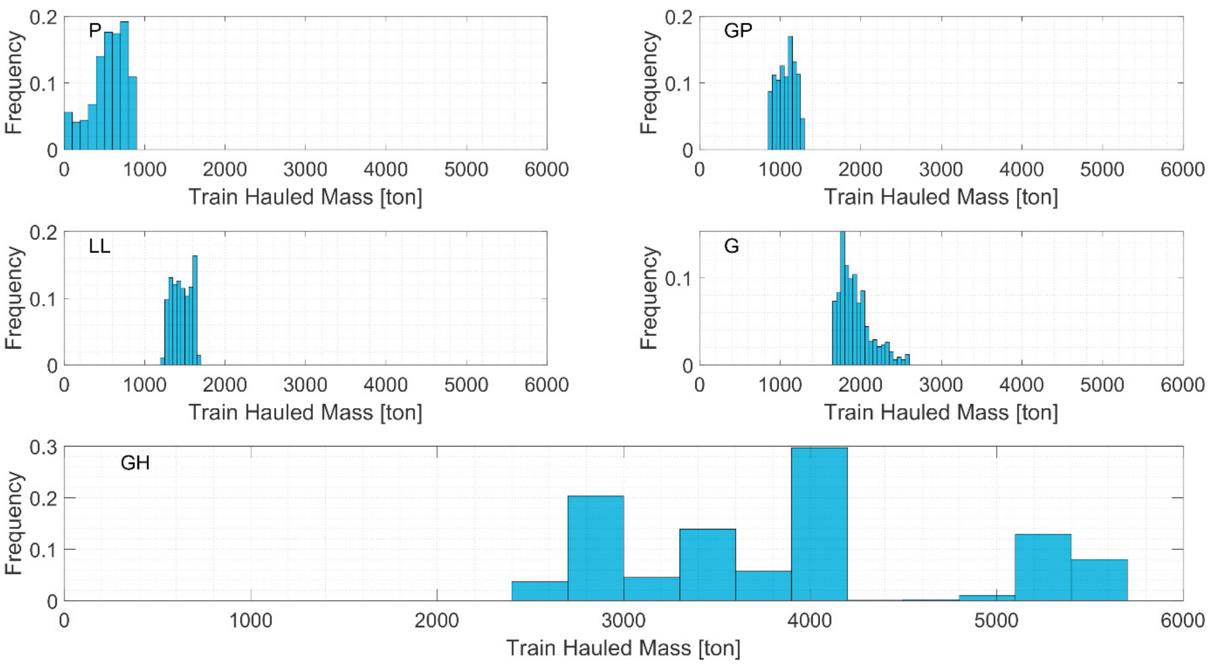


Fig. 2 Mass Distribution, Reference System, Different brake positions.

3.2. Trains with two traction units

Two families of trains, moved by two traction units (TU), are here shown having overall train length (traction units included): lower than 740m and 1000m, respectively. These trains are formed by coupling two types of trains following Table 1. Coupled the trains, all wagons are set in brake position “G”; moreover, the first train is always heavier and longer than the second train: this configuration is "convenient" for in-train forces.

The cumulative probabilities of in-train forces are displayed in Fig. 3 and Fig. 4 for 740m and 1000m of maximum train length, respectively. Meaning of the legend is:

- Emergency Braking (EB) from 30km/h.

- Full acceleration up to 30km/h starting from rest, with full power from all TU. When the first TU has reached 30km/h, all TU continue to apply full power for 2s. Then the first TU applies an emergency braking and reduces the traction force with a gradient of 300kN/s. After 2s, the other TUs reduce the traction force with the same gradient and apply as well an emergency braking until rest. Label N202 is used for this manoeuvre.
- D202 is the label used for a train operation like above but considering that the Distributed Power System (DPS) is not working appropriately, because of a GSM-R communication loss or other reasons. In this train operation, as for N202, the TUs perform a full acceleration up to 30km/h starting from rest. When the first TU has reached 30km/h, all TUs continue to apply full power for 2s. Then the first TU applies an emergency braking and reduces the traction force with a gradient of 300kN/s. Since DPS "failure", other TUs reduce the traction force after 3s with 300kN/s gradient. At the same time, they monitor the pressure in brake pipe (BP): when a pressure of 4.8bar is detected, TU performs a first-time braking (target of 4.5bar in BP); when it detects a pressure of 4.3bar, it performs a service braking (target of 4bar in BP) and when it detects a pressure of 3.8bar, it performs a full-service braking (target of 3.5bar in BP).
- D204 is the label used for a train operation where DPS experiences a "failure" like above. The initial scenario is an emergency braking performed by leading TU. Because of DPS failure, after 3s the other TUs start to detect a pressure drop in BP. If the pressure in BP is 4.8bar, it performs a first-time braking (i.e. target pressure in brake pipe of 4.5bar) and it continues as before for the others pressure drops (i.e. when a pressure of 4.3bar is detected in brake pipe by the DPS, the guided TU performs a service braking with target pressure of 4bar).

Table 1 Mass and length of the coupled trains.

Max Train Length [m]	Train 1		Train 2	
	Length [m]	Mass [t]	Length [m]	Mass [t]
740	380-420	1200-1600	280-320	800-1200
1000	560-600	1200-1600	360-400	800-1200

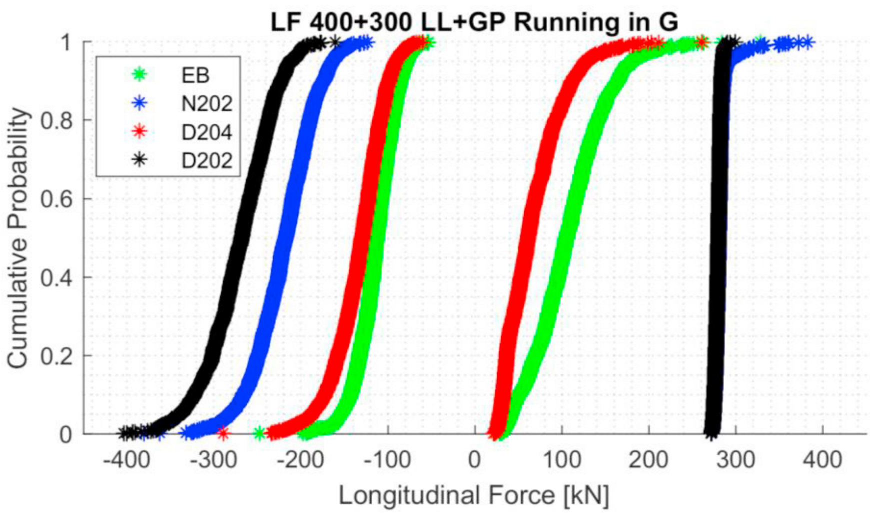


Fig. 3 Cumulative probability of in-train forces for trains with a maximum length of 740m.

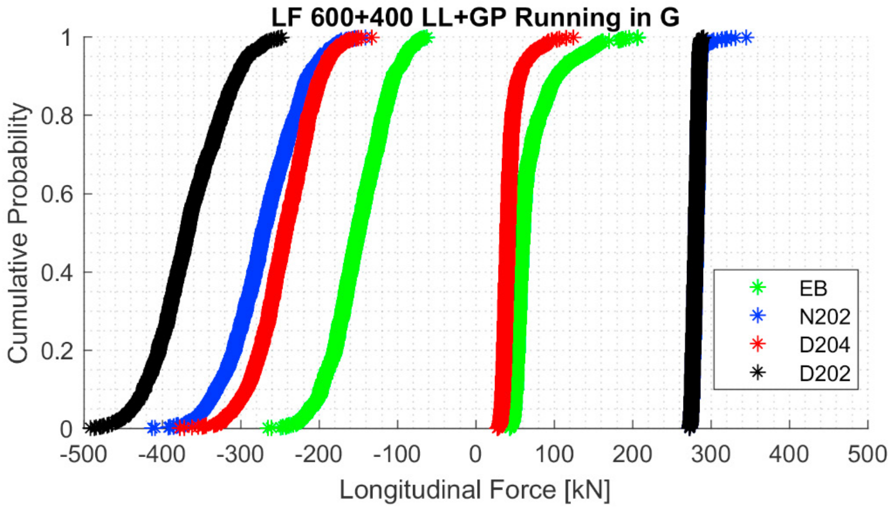


Fig. 4 Cumulative probability of in-train forces for trains with a maximum length of 1000m.

Results from Fig. 3 shows that in-train forces of coupled trains are similar to those of reference trains both in nominal (EB and N202) and in degraded (D202 D204) modes; hence these configurations are possible candidates for longer and heavier trains with two TU. Fig. 4 suggests that these coupled trains could require an infrastructure with higher radii of curvature. As it is well known, in-train compressive forces are more dangerous when they occur on a curve, depending on the curve radius, the type (2-axles or bogie wagons), the payload of adjacent wagons and other factors, such as the radii of the buffers, the torsional stiffness of the wagons, the track irregularities. At this stage of project development, these aspects have been considered in a very simplified way considering a unique limiting value of 400kN for in-train compressive forces taken from Leaflet UIC 421, as discussed in section 3.4.

3.3. Trains with four traction units

Fig. 5 shows the in-train forces for trains created by coupling four trains originally running in brake position GP and having hauled mass between 800t and 1200t; as before, coupled trains run in brake position G.

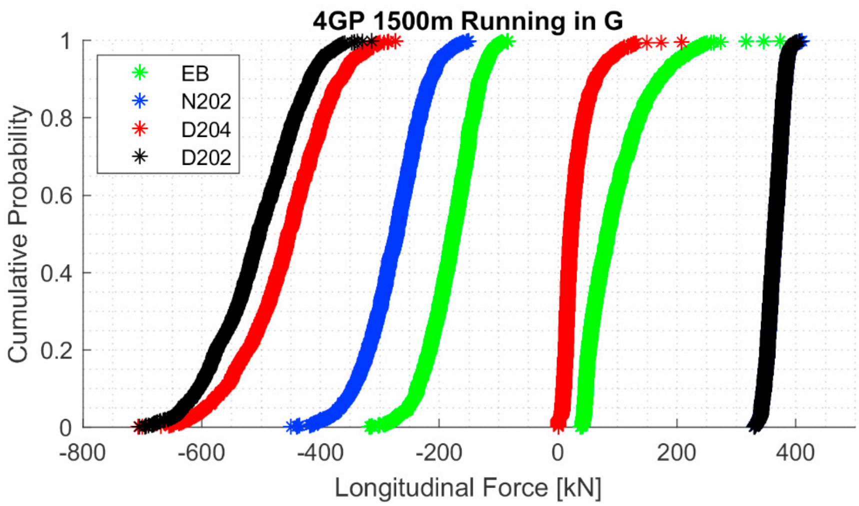


Fig. 5 Cumulative probability for in-train forces of trains with four TU.

Differently from previous trains, these long and heavy trains experience high in-train compressive forces in degraded modes. These forces can be diminished by considering a different scenario of possible degraded mode, i.e. not all guided TU do not brake, but this is beyond the scope of the paper since it requires a deeper insight on the specifications of the DPS.

3.4. Comparison with the reference system

As shown by previous results, among classical trains, the most dangerous in terms of in-train compressive forces is the GH train (hauled mass between 2500t and 5500t and wagons loaded with very similar payloads). At this early stage, this train is taken as representative of the reference system.

New, coupled, trains have been computed with 2 TU up to 4 TU. For coupled trains with 2 TU, *suitable* train compositions have been found. Suitable means that in nominal mode the train is safer than the reference trains, i.e. the probability to overcome the limit of 400kN for reference trains is bigger than for coupled trains. The limit of 400kN is taken from leaflet UIC 421 as a common value to compare reference trains with coupled trains. In the future, different limits will be assumed for different types of wagons, different payloads, track radii and position on the track. This very rough simplification is in the spirit to highlight the effect of degraded mode on the safety of coupled trains.

For coupled trains with up to 4 TU, suitable train compositions have not been found, yet. Anyway, most promising coupled trains with up to 4 TU are here reported showing that there is no big difference in respect to the reference trains, in nominal mode.

Table 2 reports a synthesis of some of the simulations carried out, so far. For each train family (1000 randomly generated trains), the maximum compressive (negative values) and tensile in-train forces computed by *TrainDy* are listed: these values are the extreme points of the curves reported from Fig. 1 to Fig. 5. To ease the understanding of this table the following legend is given:

1. 4GP is a coupled train made of 4 sub-trains originally running in GP (hauled mass in the interval 800-1200t). When the trains are coupled the coupled train runs in G: all coupled trains run in G. The length of the coupled train is 1500m, i.e. average length of sub-trains is 375m. If there is no further specification it means that the train is performing an emergency braking from 30km/h; otherwise, the train operation is specified. This convention is applied to all *coupled* trains.
2. 330x3 LL is a coupled train made of 3 sub-trains originally running in LL (hauled mass in the interval 1200-1600t). The length of the coupled train is 1000m, i.e. average length of sub-trains is 333m.
3. 600-400 LL-GP is a coupled train made of 2 sub-trains: the first 600m length originally running in LL and the second 400m length originally running in GP. Hauled mass of this family of trains is *lower* than the hauled mass of the previous family of trains.
4. 400-300 LL-GP is a coupled train made of 2 sub-trains: the first 400m length (loco not included) originally running in LL and the second 300m length (loco not included) originally running in GP. Hauled mass of this family of trains is *similar* to the hauled mass of the previous family of trains.
5. EB P, EB GP, … are the reference trains performing an emergency braking (EB) and running in P, GP, … braking regime.
6. N202 P, N202 GP, … are the same trains' families performing the train operation N202.

Table 2 Synthesis table of in-train forces.

Type of train and manoeuvre	Max in-train compressive force	Max in-train tensile force	Probability of overcoming 400kN [%]
4GP	-317.56	373.59	0.049
4GP N202	-449.40	410.76	1.842
4GP D204	-706.52	937.28	78.241
4GP D202	-705.08	3216.28	94.517

333x3 LL	-319.47	209.77	0.076
333x3 LL N202	-484.43	443.49	8.850
333x3 LL D204	-518.68	94.49	19.934
333x3 LL D202	-653.07	7221.91	92.310
600-400 LL-GP	-265.45	207.08	0.032
600-400 LL-GP N202	-412.65	345.25	0.224
600-400 LL-GP D204	-377.71	124.27	0.063
600-400 LL-GP D202	-491.91	290.26	23.142
400-300 LL-GP	-247.09	328.43	0.000
400-300 LL-GP N202	-380.23	382.29	0.063
400-300 LL-GP D204	-289.22	260.96	0.016
400-300 LL-GP D202	-403.61	299.32	0.172
EB P	-176.26	183.05	0.021
EB GP	-203.90	265.17	0.007
EB LL	-225.56	398.21	0.003
EB G	-145.03	152.49	0.000
EB GH	-287.60	107.47	0.046
N202 P	-206.43	275.07	0.034
N202 GP	-257.72	286.21	0.035
N202 LL	-303.66	356.33	0.047
N202 G	-282.84	295.39	0.031
N202 GH	-423.43	298.30	0.255

From the previous table, the best (coupled) trains' family, considering in-train compressive forces, is the 400-300 LL-GP, which has a probability to overcome 400kN lower than the reference GH trains' family. Anyway, when comparing the probability to overcome 400kN for reference and coupled trains it is important to consider the likelihood of degraded mode.

Naming α this probability, it is possible to compute the likelihood of degraded mode that makes equal the two probabilities to overcome 400kN for reference and coupled trains: $P_R = (1-\alpha)P_N + \alpha P_D$

Where:

- P_R is the probability to overcome 400kN for reference train;
- P_N and P_D are the same probability for nominal and degraded mode (respectively) of the coupled train.

Therefore:

$$\alpha = \frac{(P_R - P_N)}{(P_D - P_N)} \qquad (1)$$

As an example, comparing Reference and 600 LL 400 GP, we obtain:

$$\alpha^{EB}_{600\ \mathrm{LL400\ GP}} = \frac{(0.046 - 0.032)}{(0.063 - 0.032)} = 0.452 = 45.2\% \tag{2}$$

$$\alpha^{N202}_{600\ \mathrm{LL400\ GP}} = \frac{(0.255 - 0.224)}{(23.142 - 0.224)} = 0.00135 = 0.135\% \tag{3}$$

Above probabilities, also 0.135%, imply a very un-stable GSM-R communication, which is not the case, therefore the likelihood of overcoming 400kN for 600 LL 400 GP has to be considered lower than for the reference family of trains.

Since 400-300 LL-GP is the best (coupled) trains' family, it is interesting to compute the probability that a random train from a different family is more dangerous (in terms of in-train compressive forces) than a random train taken from 400-300 LL-GP trains' family. Table 3 reports this probability and the comparison is carried out considering the same train operations: if the probability is bigger than 50% means that the trains' family is more dangerous than the 400-300 LL-GP trains' family.

The above table shows that all families are more dangerous than 400-300 LL-GP trains' family, as expected. This result implies a careful consideration for the employment of these new trains' family in the existing traffic. Anyway, the above computation has been conducted considering all possible values of in-train compressive forces, whereas it can be narrowed to an interval where the in-train forces are greater than a specific (dangerous) threshold.

Table 3 Probability to overcome the 400-300 LL-GP trains' family.

Type of train and manoeuvre	The probability that a random train is more dangerous than corresponding 400-300 LL-GP
600-400 LL-GP	79.72
600-400 LL-GP N202	81.01
600-400 LL-GP D204	98.73
600-400 LL-GP D202	94.00
4GP	92.85
4GP N202	82.11
4GP D204	99.96
4GP D202	99.84

4. Conclusions

The paper summarizes the main goals of the Marathon2Operation (M2O) Project and their impact on freight transportation in Europe. At this aim, the paper reports the first candidate trainsets, for different train lengths and amount of Traction Units (TU), running with a similar safety level of already circulating trains. All new coupled trains family run in brake position G and they are built, statistically, according to the model described in Cantone (2019). Actual trains, running on German Railway Network, are the basic input for statistic generator tool of trainsets; consequently, the results represent the actual performance of trains, concerning longitudinal train dynamics. The coupled trainsets are compared against the reference family of trains, for both nominal and degraded modes (not applicable to reference family trains). This comparison shows that a coupled train formed by two trains of 400m and 300m length, respectively, and with overall hauled mass up to 2800t is safer than currently circulating trains (homogeneously loaded).

In the future, a systematic sensitivity analysis is envisaged and more trainsets will be studied, e.g. with leading TU in front and guided TU at the end of trainset

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