REPORT CEF UBS

Increasing hauled mass by mitigation factors

Abstract

TrainDy simulations showing several mitigation factors useful to increase the hauled mass. Placement of light wagons; number of wagons in G for Extended Long Locomotive; effect of railway infrastructure (i.e. radius of curvature): are analyzed in this report together with the employment (or not) of articulated wagons

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Summary

1 Introduction and status of the art

This work is linked to SNCF study, [1], where the feasibility and the safety of trains with 3 consecutive not braking wagons in P (randomly placed along the train) has been assessed, by means of TrainDy simulations and application of IRS 40421 [2] methodology. According to this study, assuming hauled mass trains between 1600 and 2500 t (minimum 32 t/wagon) in regime LL and hauled mass trains between 2500 and 4000 t (minimum 40 t/wagon) in regime LL can be considered as a reference, it is possible to admit to the traffic trainsets having these characteristics:

- Hauled mass between 1600 and 2500 t (minimum 32 t/wagon) in regime LL with a maximum of 3 consecutive unbraked wagons, without articulated wagons. These trains are labelled as REF1, in this report.
- Hauled mass between 2500 and 4000 t (minimum 40 t/wagon) in regime LL with a maximum of 3 consecutive unbraked wagons, without articulated wagons. These trains are labelled as REF2, in this report.

The aim of this study is to investigate the risk for derailment when wagons lighter than 32 t are in a wagon rake > 1600 t and wagons lighter than 40 t are in a wagon rake > 2500 t, all in P-braked trains.
The scenarios in which the risk for derailment is requested to be studied, by means of TrainDy simulations, are the following (the number corresponding to the order of preference):

Scenario	**Minimum weight limit in tons (for trains > 1600/2500 t respectively)**	**Wagons forbidden (in trains > 1600 t)**	**Sequence rules (for trains > 1600/2500 t respectively)**
Reference	32/40	Articulated / permanently coupled* wagons	None
3	32/40	None	None
2	None	Articulated / permanently coupled* wagons	Wagons below 32/40 t at the end of the train
1	None	None	Wagons below 32/40 t at the end of the train

*In German “kurzgekuppelte Wagen”

Previous table is solved by results of § 4.1 and 4.2, where scenarios 3 and 1 of previous table are simulated, respectively.
In addition to the beforementioned scenario analysis, the following tasks have been requested to be analyzed:

Task No.	Tasks to be performed
1	A check is needed to identify how much the current [1600 t -2500 t] wagon rake weight limit, from which wagons may not weigh less than 32 t, could be increased in case the Long Locomotive contained 6 or 7 wagons instead of 5 (in brake position G), so that the abovementioned restrictions in the scenarios’ table are still not necessary.
2	A check is needed to identify how much the current [2500 t-4000 t] wagon rake weight limit, from which wagons may not weigh less than 40 t, could be increased

	in case the Long Locomotive contained 6 or 7 wagons instead of 5 (in brake position G).

Scenarios of previous table are analyzed in §4.3

As an alternative approach, it shall in addition be analysed:

Task No.	Tasks to be performed
3	A check is needed to identify how much the [1600 t -2500 t] wagon rake weight limit (from which wagons must weigh at least 32 t) can be increased if the minimum allowed curve radius is also increased (as a function of dependency)
4	A check is needed to identify how much the [2500 t-4000 t] wagon rake weight limit (from which wagons must weigh at least 40 t) can be increased if the minimum allowed curve radius is also increased (as a function of dependency)

Scenarios of previous table are analyzed in §4.4

Special analysis is requested to be done about the influence of articulated wagons in the train in terms of risk for derailment compared to other wagon types, the aim being to identify whether it is justified to apply special restrictions about allowance of articulated wagons in P-trains >1600 t. Thereby articulated wagons can be:

i. loaded
ii. empty
iii. partly loaded (load/container on one side of the wagon only), so that the first and second bogie are loaded considerably more than the third (based on an example of a typical intermodal wagon with three bogies and six axles)

The analysis about articulated wagons is subjected to sufficient technical data delivered about admissible LCF (Longitudinal Compressive Forces) for such wagons.
The following assumptions will be used in the analysis:

- Trains can be up to 740 m long
- Simulation is based on cast iron brake pads as reference
- Analysis considers LCF as well as LTF (Longitudinal Tensile Forces)
- One type of locomotive will be used in the simulation – as a relative approach is used, this can be regarded sufficient
- The simulation assumes the existence of articulated wagons in the trains. These are treated as bogie wagons at longer lengths - corresponding to the actual length of articulated wagons.

Therefore, the present study enlarges the field of application of [1] to:

- articulated wagons
- extended long locomotive, i.e. more than 5 wagons in G follow the leading traction unit(s),
- infrastructure considerations (the effect of the track horizontal radius of curvature on the probability of derailment is investigated).

Moreover, differently from [1], the TrainDy wagons database of DB Systemtechnik has been employed in this study.

Simulations have been carried out by UIC TrainDy software, the same used to perform the numerical calculations of UIC LongT project and the Shift 2 Rail "Marathon 2 Operation" (M2O) project ([3] and [5]).

The trains analyzed in this report are randomly generated in agreement with the IRS 40421 flowchart [2], adding further requirements in terms of minimum mass and wagon types allowed in the trainsets. The trainsets are compared in terms of the IRS 40421 "relative approach", where a safe reference train family is compared to a new (possibly un-safe) train family.

The main topic of the report is to describe the effect of several mitigation factors on the in-train forces, in order to safely increase the freight efficiency and its green footprint. This document is divided as follows:

- ✓ §2 describes the methodology of the study and its assumptions.
- ✓ §3 reports the statistics of the wagons employed.
- ✓ §4 reports the main results of this study.
- ✓ Appendix A compares the in-train forces of trainsets allowed by IRS 40421 versus those of trainsets used as reference in this study (coming from [1]);
- ✓ Appendix B shows the performance of trains in the range 1600-2500 t with only articulated wagons, where empty wagons are allowed.

2 Description of the methodology

2.1 Generation of virtual trainsets

As stated before, the trainsets of this study are generated in agreement with the IRS 40421 flowchart, which requires the knowledge of the following four quantities:

- Train mass distribution.
- Occurrence of each wagon within the train consist.
- Occurrence of group wagons
- Payload of each wagon.

Above quantities were assumed since they were not available; they would have been available if a database of running trains would have been used, but in that case the number of wagons used would have been much less and the number of real trains having specific mass and length characteristics would have been small (depending on the selected train mass and length). In this way, the results are not linked to a specific railway traffic and, at the same time, they follow the spirit of the "relative approach".

The wagon payload distribution has been assumed varying linearly (from its minimum to its maximum allowed values), but with the constraint that one type of wagon having an average payload is able to fill a trainset, having average hauled mass and average train length. This large variety of payload variation allows the explorations of extreme scenarios (in terms of wagon hauled mass); therefore, it is conservative for Longitudinal Forces.

The occurrence of wagons group has been neglected, therefore a single wagon traffic is assumed.

The occurrence of each wagon in the trainset has been computed considering, for each wagon, how many of them are required to fill a trainset with average hauled mass and average train length; then associating to each wagon its relative frequency (implicitly imposing that each trainset is made of a large variety of wagons).

Train mass distribution within the hauled mass range is uniform, to properly consider the effects of the tails of the distribution.

By the previous assumptions, the generation of virtual trainsets is quite fast and it allows constraints in terms of wagon types and wagon mass. However, in a relative approach it is important to keep the same assumptions for the generation of the compared trains families.

2.2 Train operations

In other to emphasize the in-train forces, the following train operations are used:

- Full acceleration (i.e. with full power) from zero speed to 30 km/h followed by an emergency braking
- Emergency braking from 30 km/ h and train in coasting conditions. The label EB is used

Other train operations are not used since the emergency braking provides higher in-train forces with respect to full service braking for Long Locomotive braking regime. Among these two train operations, the first one is the most dangerous in terms of in-train forces since the couplings have to absorb not only the same kinetic energy (30 km/h as starting speed is common) but also the initial deformation energy stored in the draw gears because of the initial acceleration.

In a relative approach, it is important to compare the trains families keeping the same train operation and the chosen train operation must be relevant for the in-train forces.

Of course, these two types of train operations are quite rare to occur, nevertheless they represent train operations capable to emphasize the in-train forces. The starting speed of 30 km/h is used as it is customary for these types of studies: according to the trainset, the highest in-train forces are reached when the emergency braking is initiated within the speed interval of 20-40 km /h. In the spirit of relative approach, described in IRS 40421, it is important to keep the same train operation for reference and new system.

2.3 Permissible Longitudinal Forces

The Permissible Longitudinal Compressive Forces (PLCF) are computed in agreement with the extrapolation rules set in IRS 40421; the exception for articulated wagons is described in the next section. The PLCF is a function of wagon type, payload, track radius, buffer type.

For the Longitudinal Tensile Forces (LTF), the IRS 40421 does not provide indications and the value of 550 kN is used for the PLTF, as done in the M2O Project [3]. This values does not cause any train disruption (by itself), but it is capable to start a mechanical fatigue process that after several applications bring to train disruption.

This study computes the in-train forces considering that the train moves on a straight track, then (in a post processing) the permissible forces are computed considering the minimum track radius. The ratios between LCF and PLCF are computed assuming that the highest LCF (in module) force is experienced among two consecutive wagons running on a curve of minimum track radius. This approach is conservative, since it is not likely that the highest LCF of the train is experienced when the wagons are negotiating a curve with the minimum track radius.

Lastly, considering that the linear extrapolations of IRS 40421 are conservative [4], it is clear that the probabilities of virtual derailment displayed in the next sections do not represent the rate of current derailments and they must not be evaluated in an absolute way, but in a relative way: i.e. only the comparison matters.

2.4 Permissible Longitudinal Compressive Forces for articulated wagons

The Permissible Longitudinal Compressive Force of articulated wagons is computed on the basis of IRS 40421 extrapolation for bogie wagons and the following conservative assumption: the payload is divided between the two parts, loading at maximum possible (according to a maximum mass per axle of 22.5 t) one of the two parts and considering as payload, for the IRS 40421 extrapolation, the remaining payload. In formulas:

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

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

$$L_L = L - L_H$$

L_L is used as wagon payload for the extrapolation rules of IRS 40421.

This condition is clearly conservative and reduces the Permissible Longitudinal Compressive Force associated to the articulated wagon. This is so far the best assumption that can be used by TrainDy software for articulated wagons. However, the hypothesis of applying the extrapolation rules of IRS 40421 for bogie wagons to articulated wagons still remains. In the absence of specific values concerning the permissible LCF for articulated wagons, the assumption used should be checked by means of 3D simulations or experimental tests (see also conclusions of the study).

3 Statistics of DB SYSTEMTECHNIK TrainDy Wagon Database

The database of TrainDy wagons provided by DB Sysemtechnik consists of 181 wagons; Figure 1 reports a pie chart with the percentages of Axle wagons (2 or 3 axles per wagon), Bogie wagons (with 2 or 3 bogies, 4 and 6 axles respectively) and articulated wagons (with 3 or 4 bogies and 6 or 8 axles, respectively).

Figure 1 also reports the histograms of wagon length and tare per each wagon type.

The simulations use the Traction Unit BR187 at the beginning of the train, in single traction mode. Data for BR187 are the same used for UIC LongT and M2O projects ([3] and [5]). The track is straight is without any slope.

The large variety of wagons used in the simulations tends to explore the extreme scenarios of Longitudinal Forces variations.

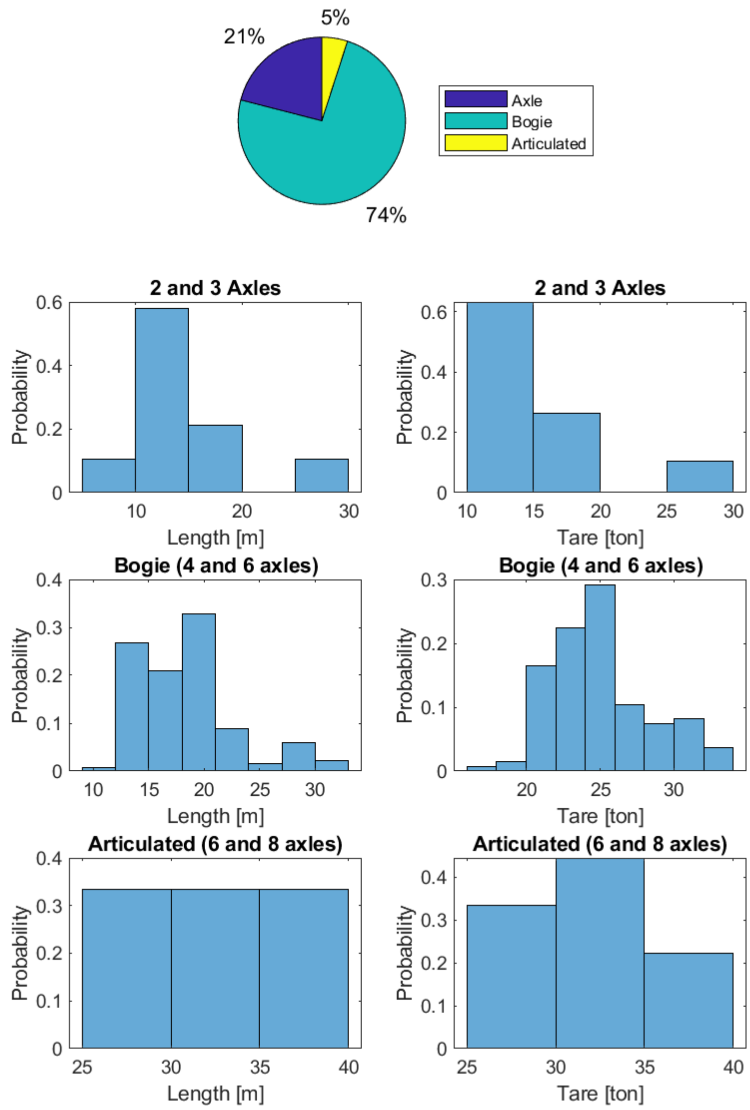

Figure 1 Statistics of the DB Systemtechnik TrainDy wagons used for the simulations

4 Results of the project

4.1 Employment of articulated wagons

4.1.1 REF1 trains

Figure 2 reports the Longitudinal Forces (LF) of REF1 trains and trains with articulated wagons (still with a minimum mass of 32 t), for an EB from 30 km/h after an acceleration. In the top part of the figure, longitudinal forces are displayed (negative values refer to compressive forces); whereas the bottom part of the figure displays the ratio between the longitudinal forces and the corresponding permissible values: legend shows, among brackets, the probability of virtual derailment and that of virtual train disruption, respectively. Each train is represented by a point associated to the highest value (in module) of in-train force or of the ratio between in-train force and the permissible counterpart (i.e. PLCF and PLTF). For LCF, the curve on the left part corresponds to the system that can be considered as the most risky. A train derailment occurs when the ratio LCF/PLCF is lower than -1; a train disruption occurs when the ratio LTF/PLTF is bigger than $+1$. The radius of curvature used to compute the PLCF is 190 m.

Results are quite similar in terms of forces, there are higher differences in terms of probability of virtual derailment and the trains with articulated wagons are unsafer than the REF1 trains.

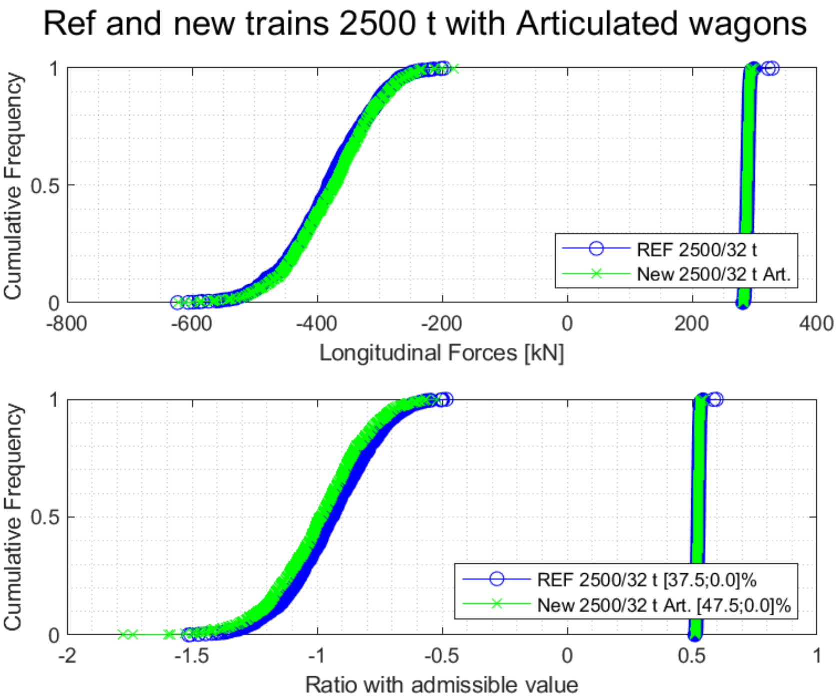

Figure 2 Comparison of longitudinal forces for REF trains and trains having articulated wagons (minimum mass is still 32 t). EB from acceleration

This result is confirmed by Figure 3, which refers to an EB from 30 km/h when train is in coasting conditions.

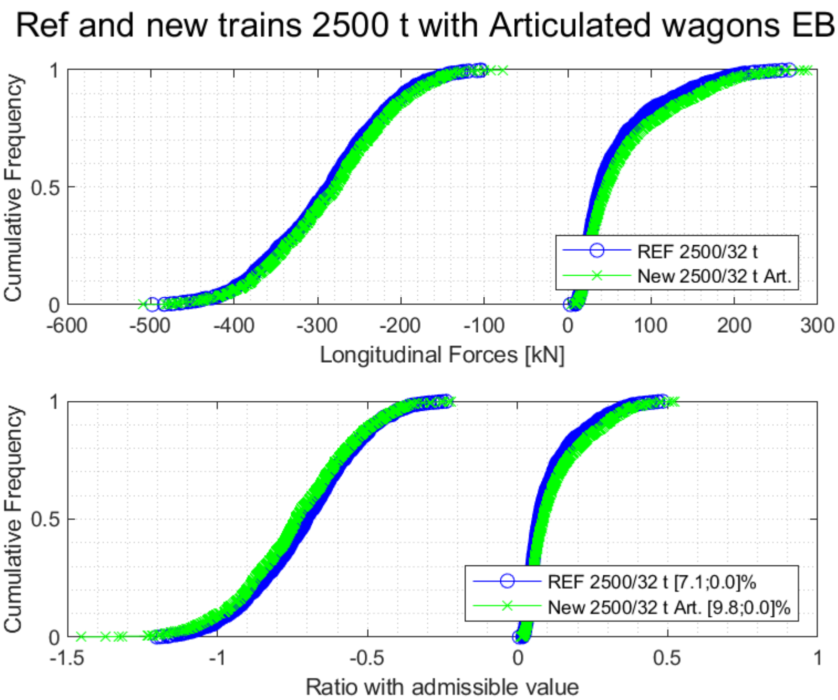

Figure 3 Comparison of longitudinal forces for REF trains and trains having articulated wagons (minimum mass is still 32 t). EB from coasting

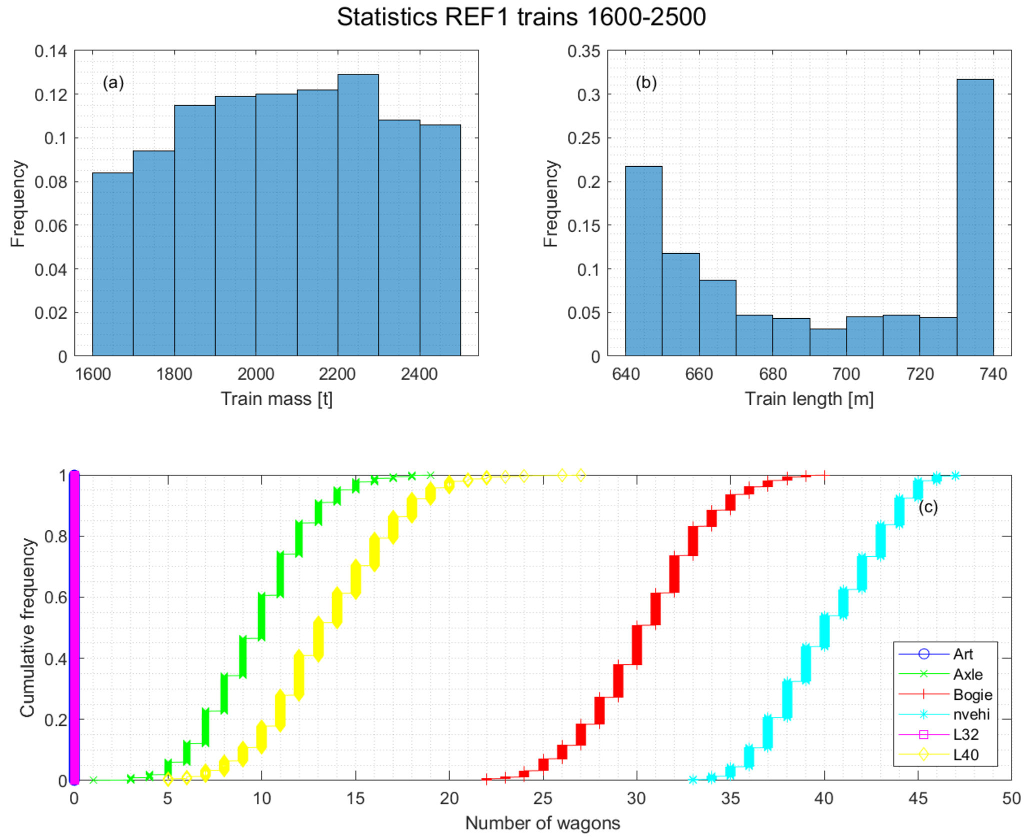

Figure 4 Statistics of New trains having mass below 2500 t, articulated wagons and minimum wagon mass of 32 t.

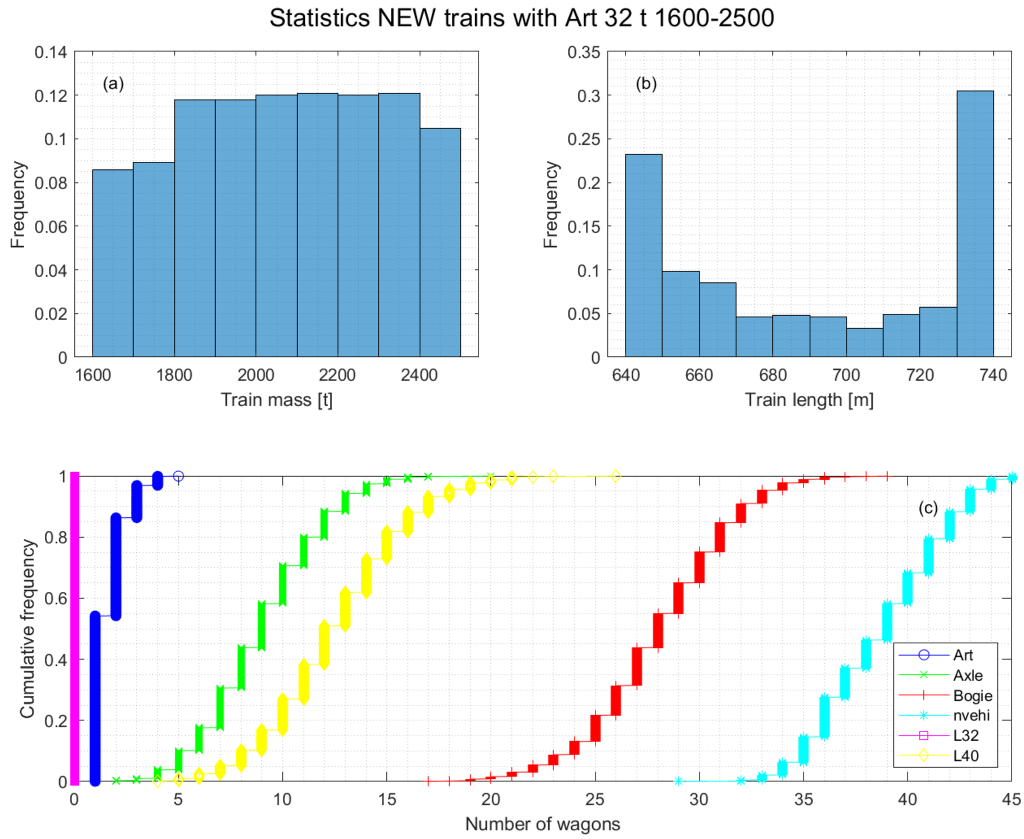

Figure 5 Statistics of New trains having mass below 4000 t, articulated wagons and minimum wagon mass of 40 t.

Figure 4 reports the statistics of REF 1 trains: (a) reports the train mass distribution (it is almost uniform); (b) shows the train length distribution having a peak toward high train length; (c) reports the cumulative frequency of axle, bogie and articulated wagons (the figure (c) labels are Axle, Bogie and Art, respectively) used in the generic train; moreover, it reports the number of wagons for each train (label nvehi) and the number of wagons having mass below 32 (label L32) and 40 t (label L40), for each train. Comparing Figure 4 (c) and Figure 5 (c) shows that the presence of articulated wagons reduces the number of wagons within the train, since articulated wagons are usually longer than axle or bogie wagons.

The counterpart of Figure 4 is given by Figure 5: they looks very similar except for the the presence of articulated wagons.

4.1.2 REF2 trains

Figure 6 reports the LF of REF2 trains and trains with articulated wagons (still with a minimum mass of 40 t), for an EB from 30 km/h after an acceleration. Results are quite similar, even if the trains with articulated wagons are a little safer than the REF2 trains. This result is confirmed by Figure 7, which refers to an EB from 30 km/h when train is in coasting conditions.

It is worthwhile to note that, within this mass range, just very few trains use articulated wagons, in reality. Therefore, these results deal with a traffic which still does not exist.

For REF2 trains, the presence of articulated wagons is a little beneficial; this result is confirmed also by next results. The presence of articulated wagons reduces the number of axle wagons and this is beneficial for the reduction of ratio LCF/PLCF. Figure 8 reports the statistics of REF2 trains whereas Figure 9 reports the statistics of the corresponding new trains: except for the employment of articulated wagons and the slight reduction of axle wagons, the statistics are similar to Figure 8.

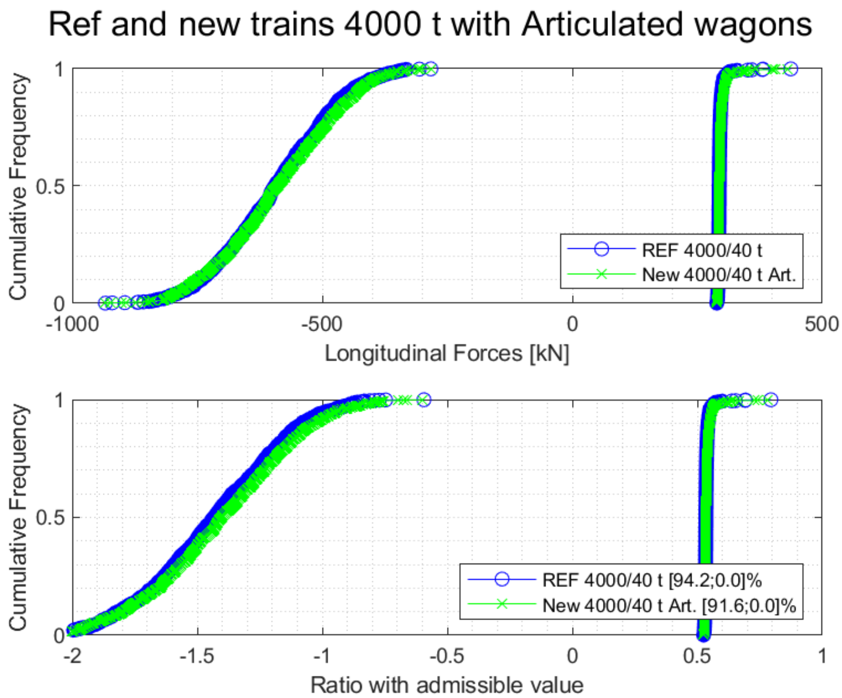

Figure 6 Comparison of longitudinal forces for REF2 trains and trains having articulated wagons (minimum mass is still 40 t). EB from acceleration

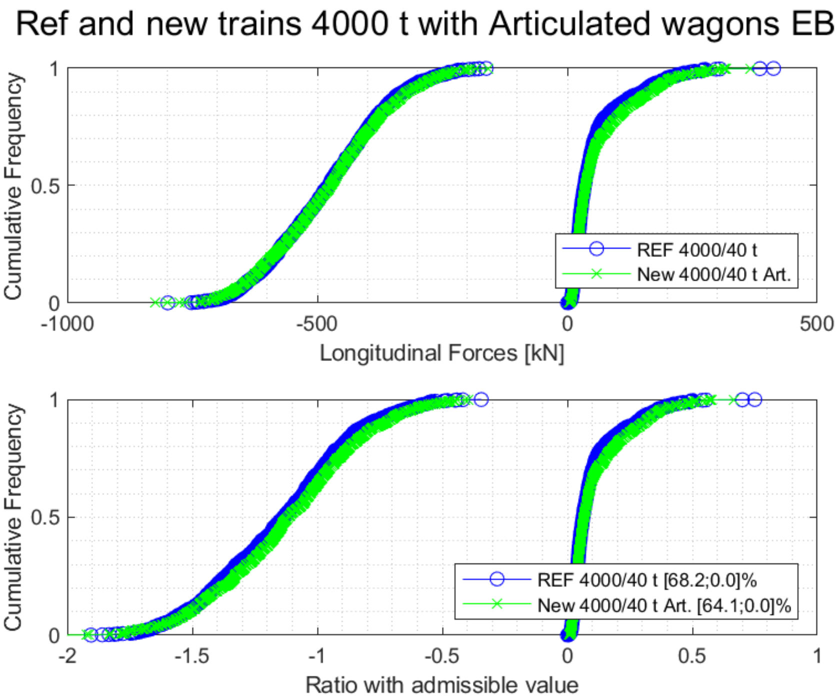

Figure 7 Comparison of longitudinal forces for REF2 trains and trains having articulated wagons (minimum mass is still 40 t). EB from coasting

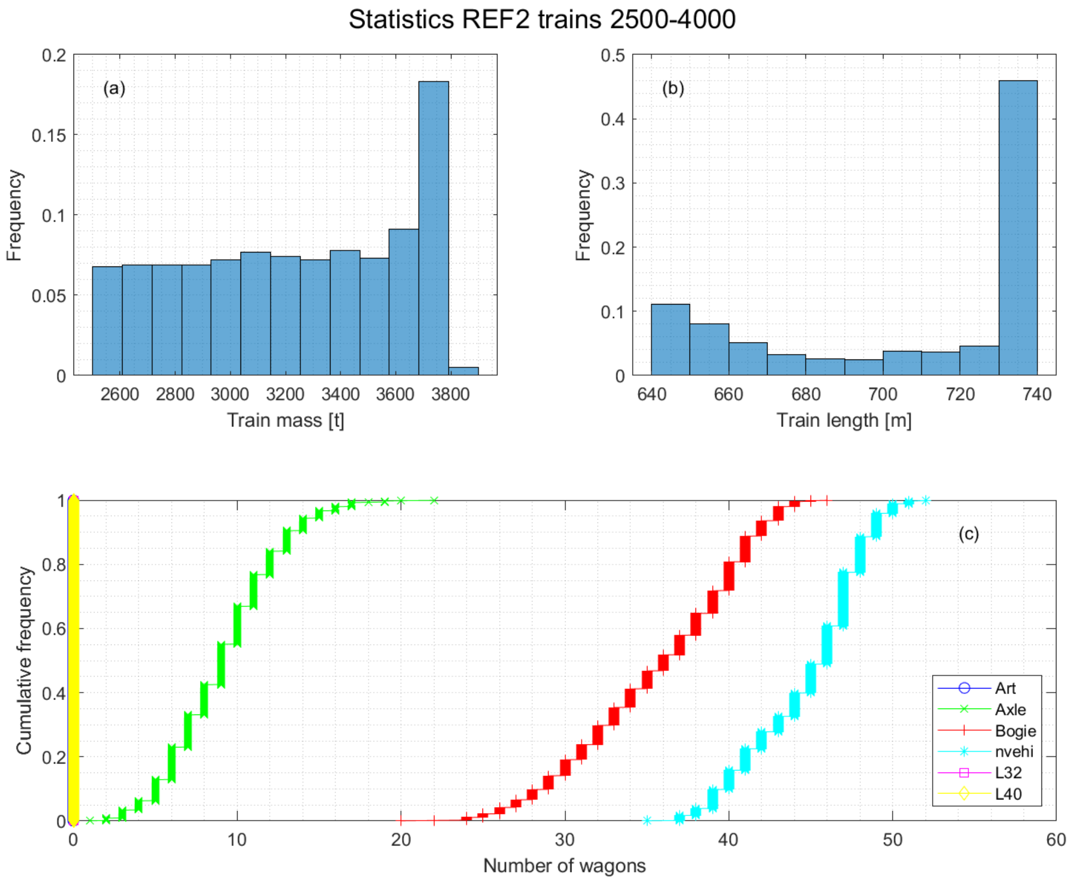

Figure 8 Statistics of REF2 trains having mass below 4000 t, no articulated wagons and minimum wagon mass of 40 t.

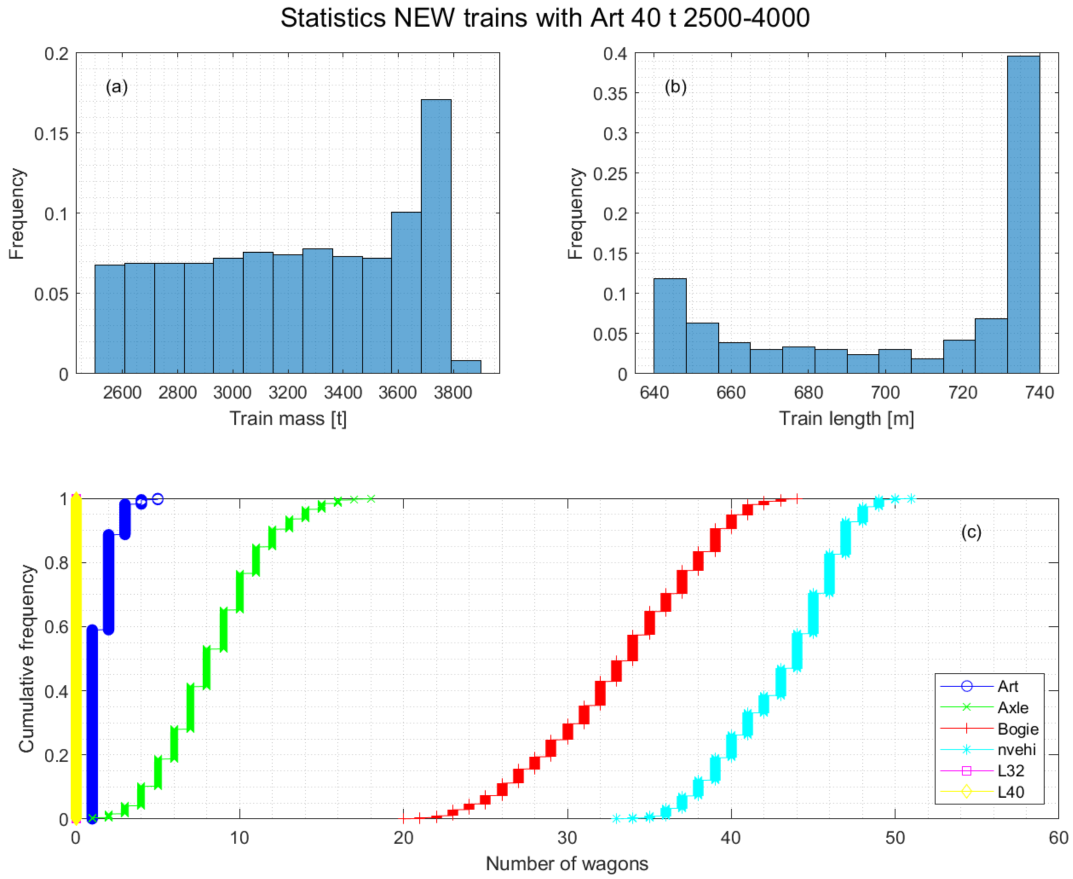

Figure 9 Statistics of New trains having mass below 4000 t, articulated wagons and minimum wagon mass of 40 t.

Looking at the LCF showed so far, it is clear that the level of safety of REF1 and REF2 is not the same: REF1 trains are safer than REF2 trains: see for example Figure 2 and Figure 6.

However, it has to be emphasized that the trainsets used are virtual and they reproduce somehow the worst scenarios since: a) the train mass distribution is "uniform"; b) the train length is towards the limits (640-740 m); c) there is a large variety of wagons used and the payload distributions vary from the minimum allowed value to its maximum; d) the train operations simulated are not likely to occur; e) the calculation of virtual derailment ratio is conservative.

4.2 Best position of light wagons

4.2.1 REF1 trains

An effective way to employ articulated wagons and accept wagons in tare conditions is to move the wagons having a mass below 32 t in the back (see label B32) of the train, as Figure 10 shows: moving them in the front (see label F32) is not convenient. These new trains are safe also if EB is commanded from coasting conditions, as Figure 11 proves. Figure 12 reports the statistics of these new trains having light wagons (wagon mass is below 32 t) moved: the statistics are the same for B32 and for F32 since just the wagons positions are changed. Comparing the train statistics (Figure 4 and Figure 12) no major differences appear, except the possibility to employ articulated and light wagons.

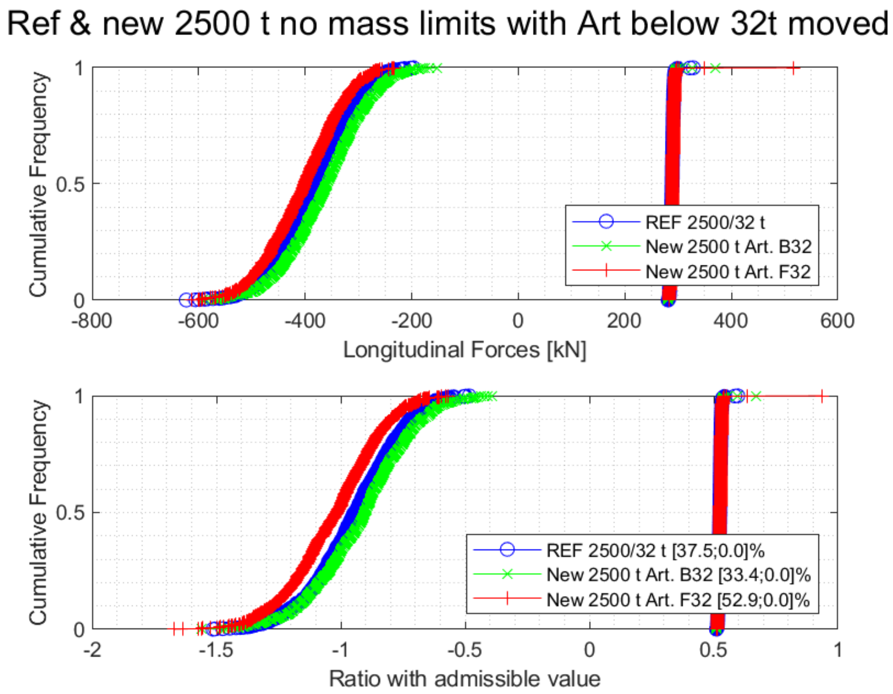

Figure 10 Comparison of longitudinal forces for REF trains and trains having articulated wagons. Wagons with mass below 32 t moved in front or back. EB from acceleration

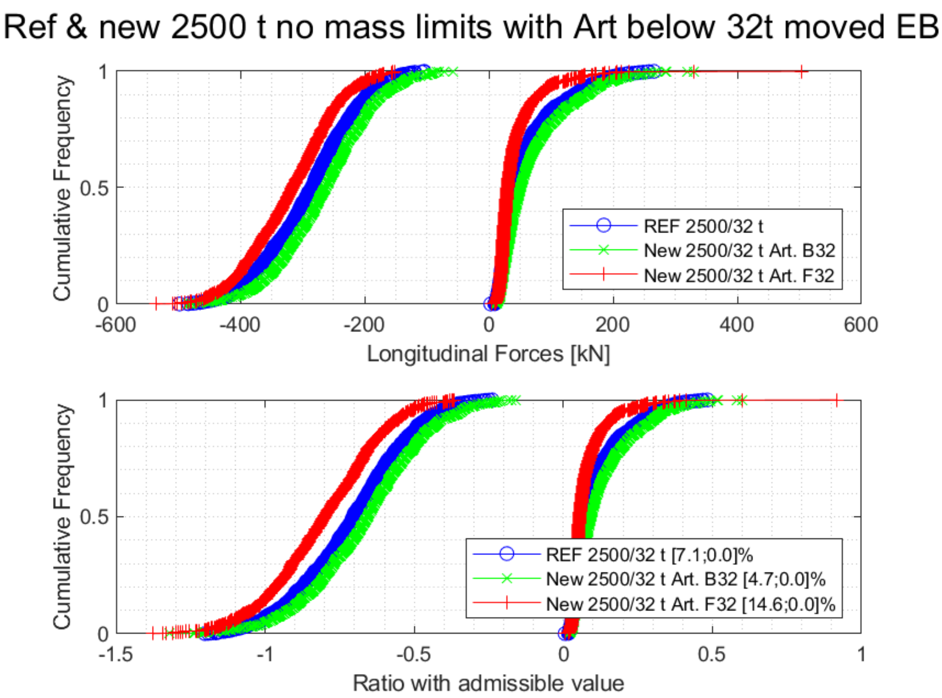

Figure 11 Comparison of longitudinal forces for REF trains and trains having articulated wagons. Wagons with mass below 32 t moved in front or back. EB from coasting

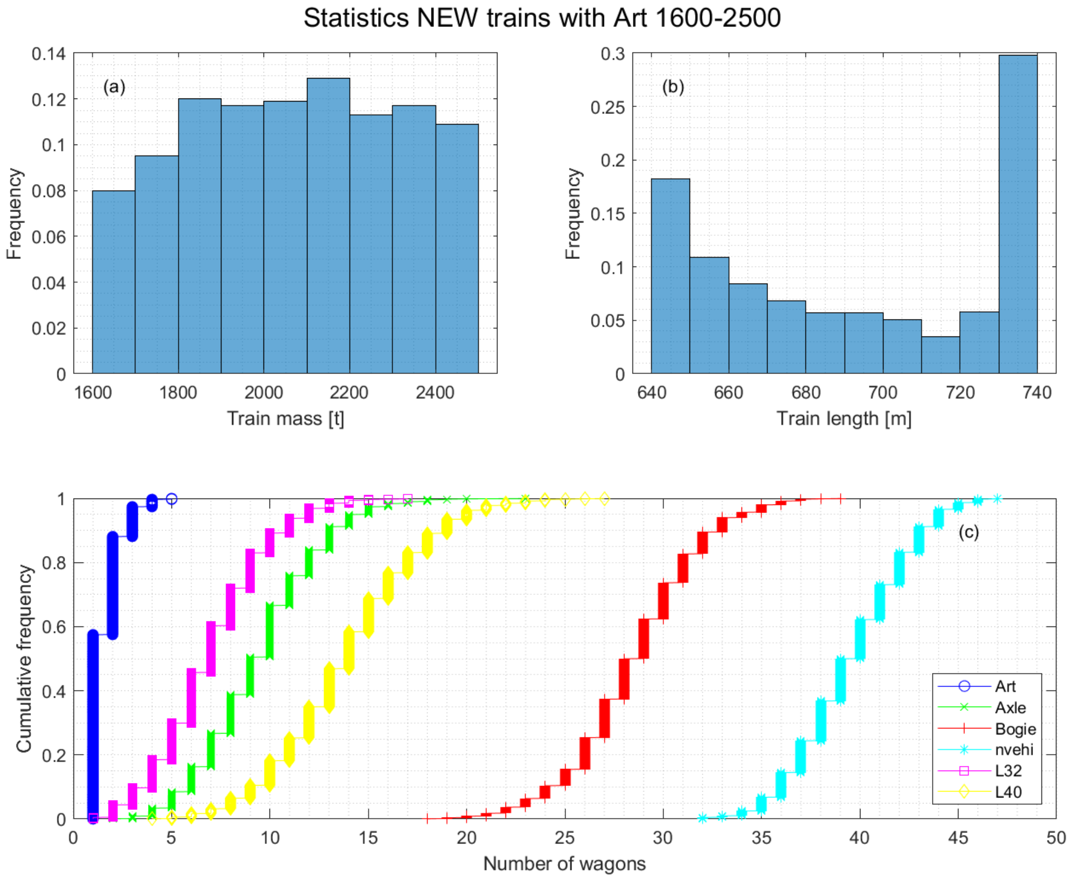

Figure 12 Statistics of new trains with articulated wagons and having wagons with mass below 32 t moved.

It shows that it is better to place empty wagons at the end of the train and this matches with the experience of Railway Undertakings.

4.2.2 REF2 trains

This section confirms the results of previous section: in this case, the wagons with mass below 40 t are moved in front (F40) or in the back (B40) of the train. Figure 13 refers to EB from acceleration whereas Figure 14 refers to EB from coasting; as before, it is better to put light wagons in the back of the train, even if, in this case, moving them in the front is still better than REF2. As shown before in §4.1.2, articulated wagons are capable to reduce the LCF of these types of trains. Figure 15 reports the statistics of these new trains having light wagons moved. Comparing Figure 9 and Figure 15 no major differences appear, except the possibility to employ articulated and light wagons; as before, the presence of articulated wagons has reduced the number of axle wagons and this has been beneficial for the reduction of LCF/PLCF.

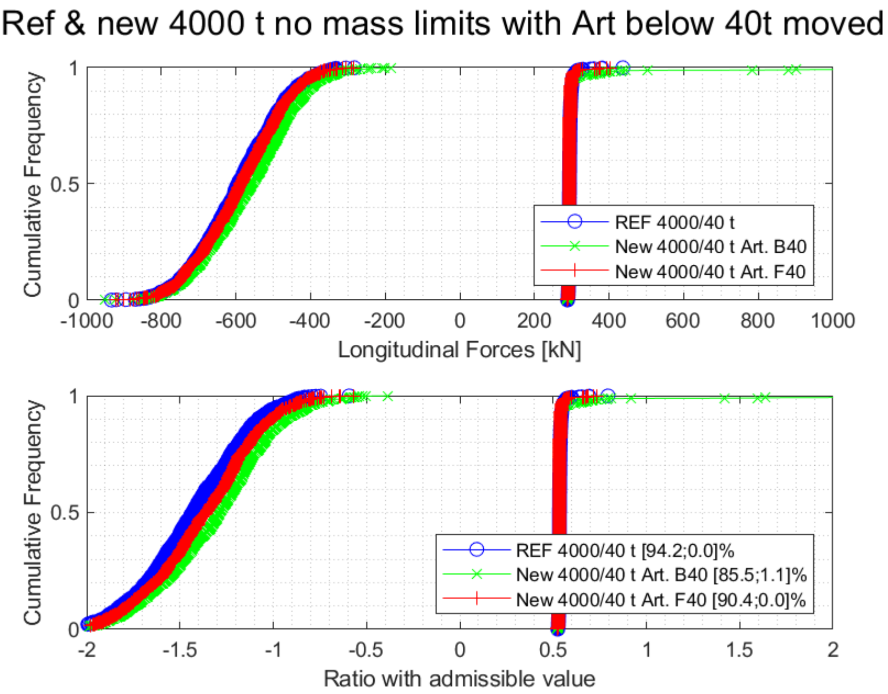

Figure 13 Comparison of longitudinal forces for REF2 trains and trains having articulated wagons. Wagons with mass below 40 t moved in front or back. EB from acceleration

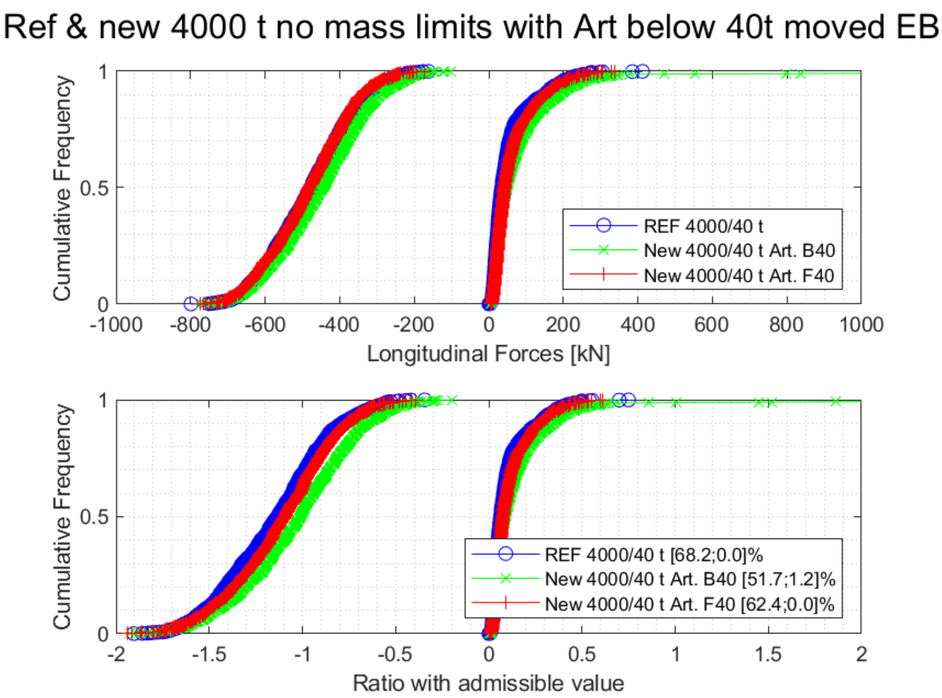

Figure 14 Comparison of longitudinal forces for REF2 trains and trains having articulated wagons. Wagons with mass below 40 t moved in front or back. EB from coasting

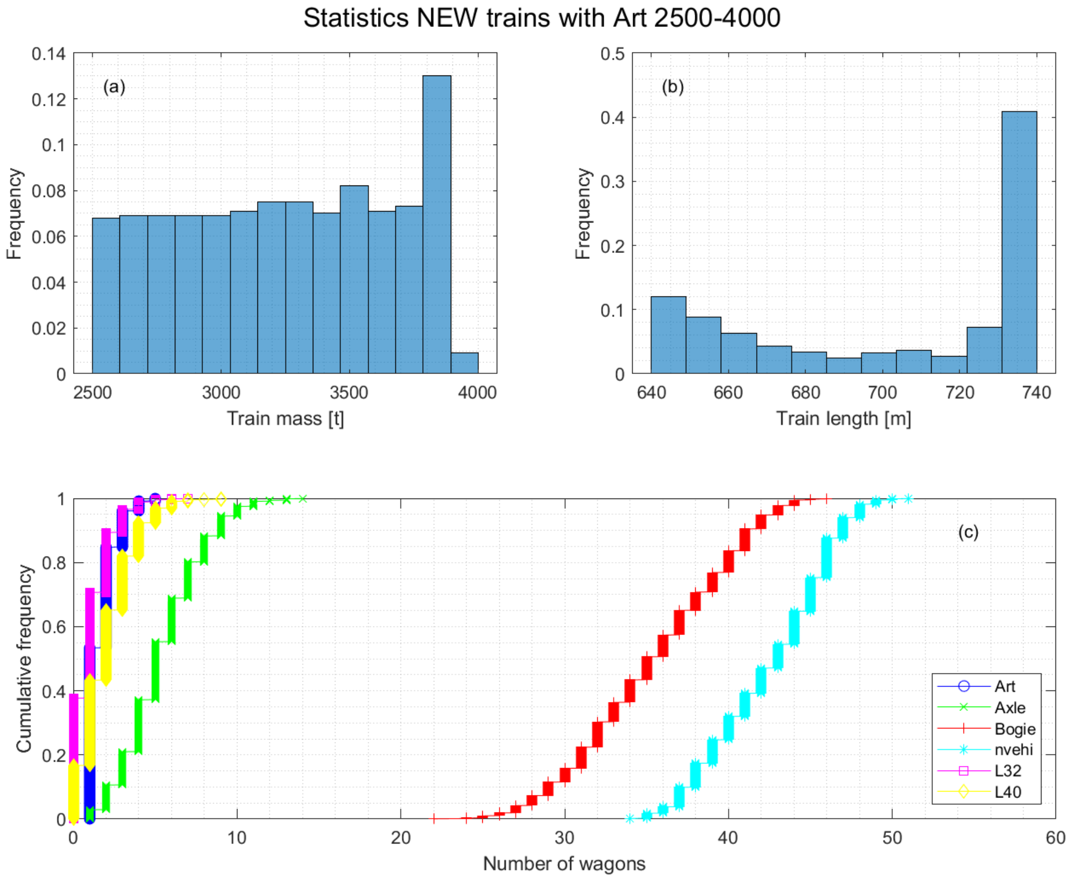

Figure 15 Statistics of new trains with articulated wagons and having wagons with mass below 40 t moved.

4.3 Effect of extra wagons in G for Extended Long Locomotive (ELL)

According to IRS 40421, trains having mass below 1600 t can run in Long Locomotive (i.e. first 5 wagons after the traction unit(s) in G and the others in P) without any limitation in terms of wagon type and wagon mass.

This section investigates the benefits of an extended long locomotive having 6 or 7 wagons in G after the traction unit, with articulated wagons. The section is divided in two subsections:

a) the first does not consider any minimum wagon mass and it considers trains having minimum hauled mass of 1600 t
b) the second considers wagons having a minimum mass of 32 t and it considers trains having minimum hauled mass of 2500 t.

4.3.1 Minimum hauled mass 1600 t, empty wagons allowed

Figure 16 reports the LF of REF trains along with those of ligher trains: a) hauled mass between 1600 and 2100 t with 5 or 6 wagons in G; b) hauled mass between 1600 and 2300 t with 5 or 7 wagons in G. Simulations with 5 wagons in G are reported to highlight the effects of a different number of wagons in G: The only difference among “New 2100/0 t 6 in G Art” and “New 2100/0 t 5 in G Art” is just the number of wagons in G (the same for the other train family). On the contrary, comparying “REF 1600/32 t No Art” and “New 2100/0 t 6 in G Art”, the differences are in the range of hauled mass, the presence of articulated wagons, the number of wagons in G, the minimum allowed mass and consequently the payload distribution along the train and the order of the wagons.

Results show that these new trains are safer than REF1 trains for both EB from acceleration and EB from coasting: considering only one type of manoeuvre would have provided higher masses (e.g. 2400 t instead of 2300 t), therefore the showed results are conservative.

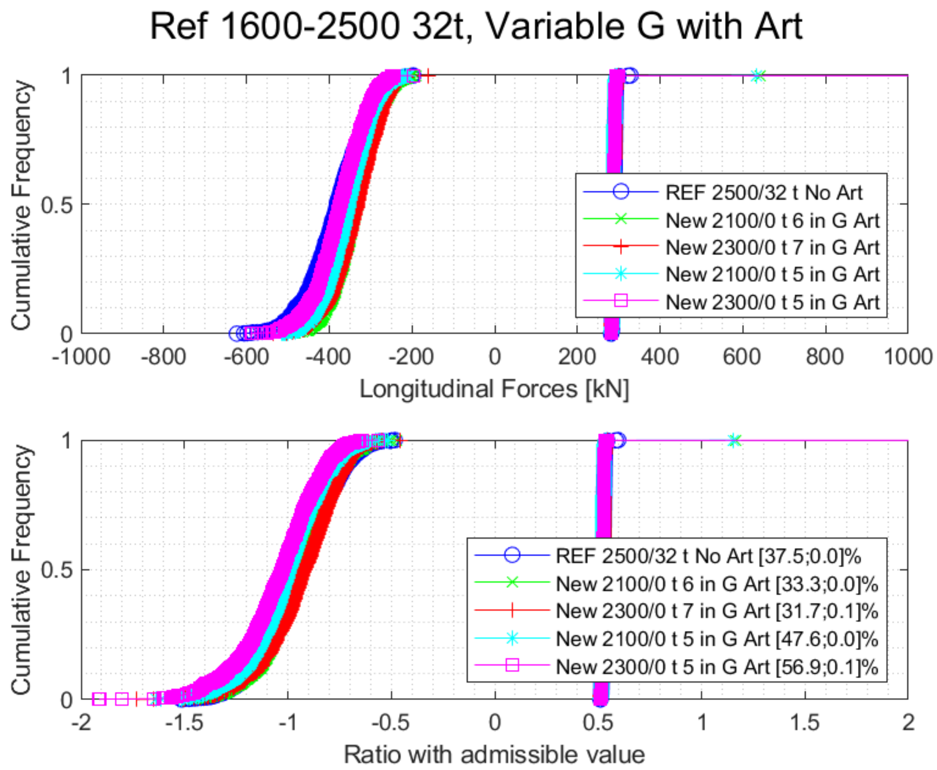

Figure 16 Comparison of longitudinal forces for REF trains and trains having articulated wagons with 6 and 7 wagons in G. Corresponding results with 5 wagons in G are also displayed.

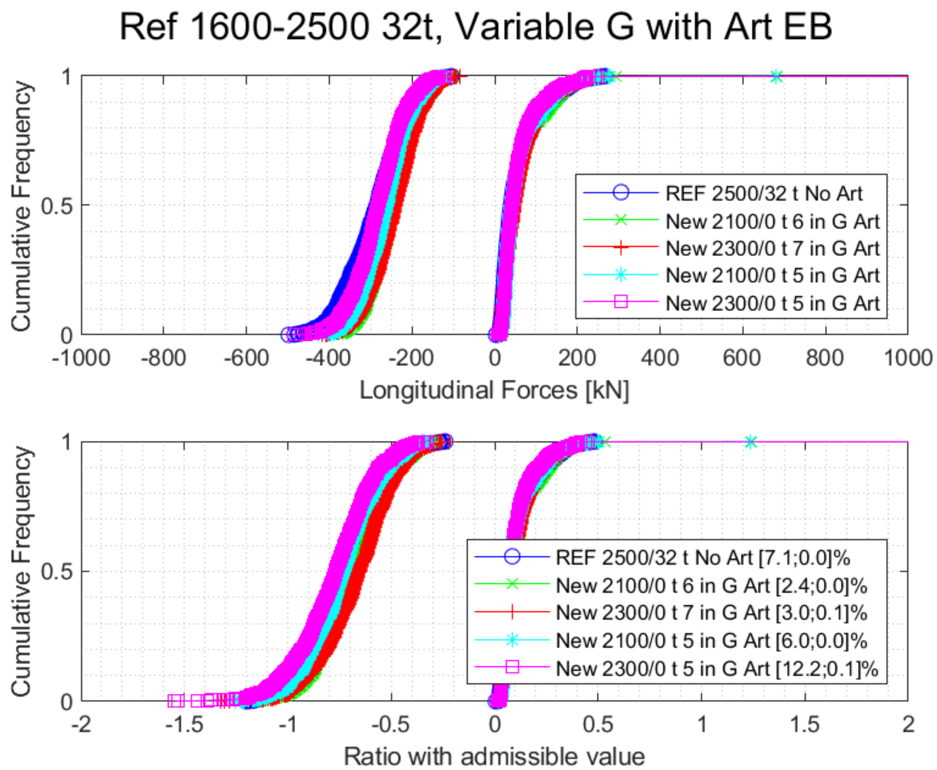

Figure 17 As figure before but with EB from coasting.

The trains having mass between 1600 and 2100 t with articulaterd wagons and with tare wagons are safer than REF1 only if the number of wagons in G is 6 and not if it is 5. The same for the mass interval 1600-2300 t.

4.3.2 Minimum hauled mass 2500 t, minimum wagon mass 32 t

Trains of this section are a sort of extension of REF1 trains where a limit of 32 t on wagon mass exists. Differently from REF1 trains, articulated wagons are allowed in these new trains.

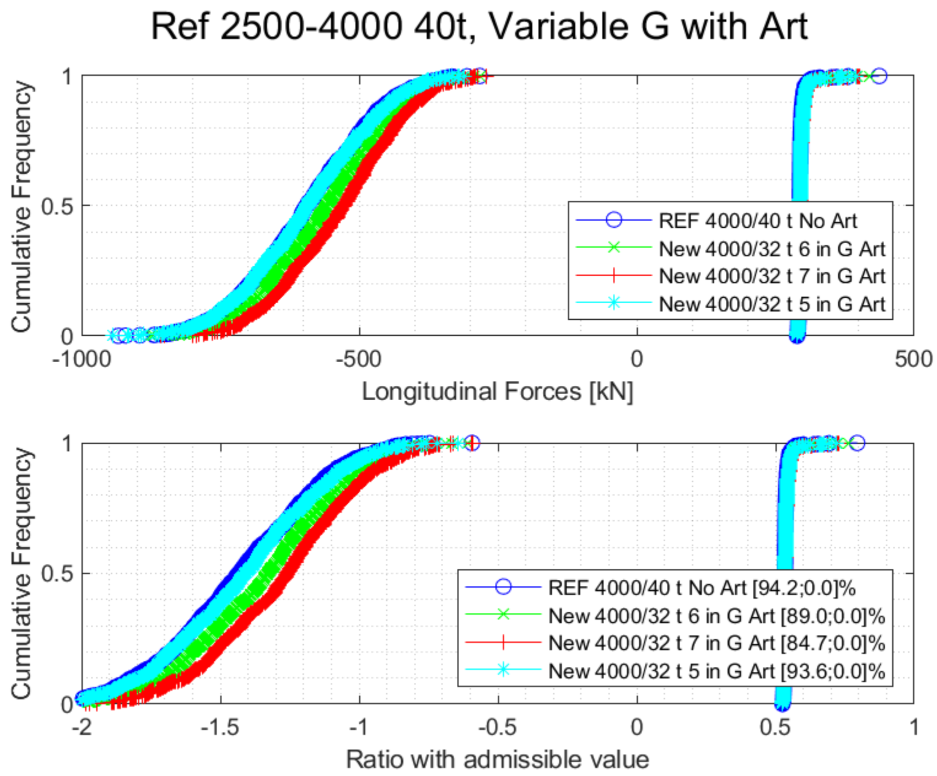

Figure 18 Comparison of longitudinal forces for REF trains and trains having articulated wagons with 6 and 7 wagons in G. Corresponding results with 5 wagons in G are also displayed.

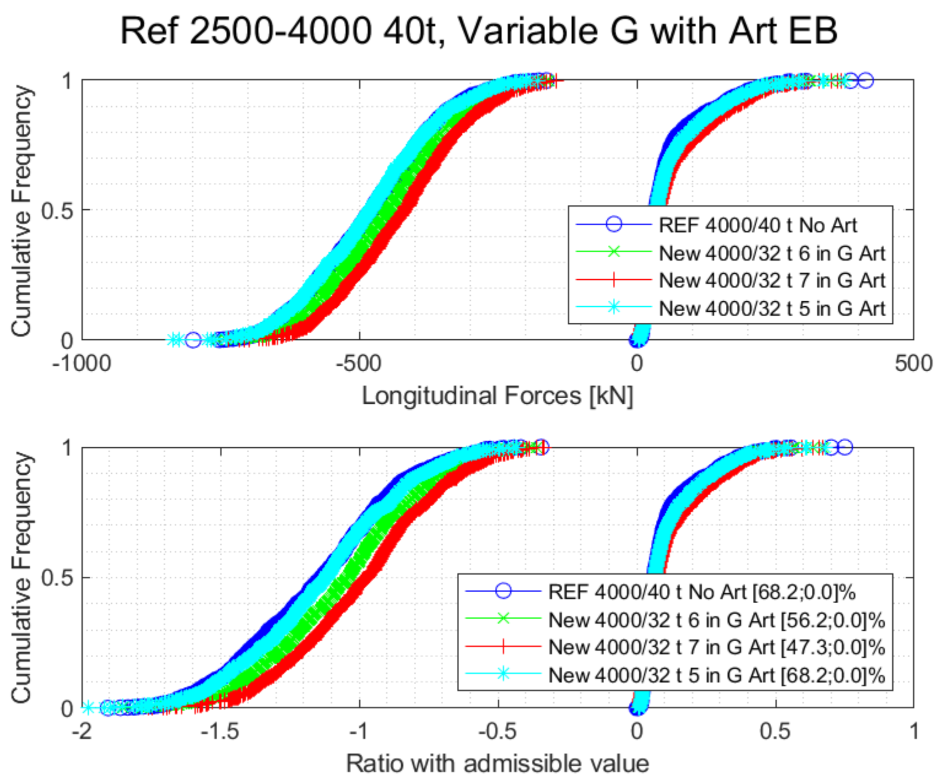

Figure 19 As figure before but with EB from coasting.

Figure 18 reports the LF of REF2 trains along with those trains having up to 7 wagons in G and minimum wagon mass of 32 t (articulated wagons are allowed). Results show that these new trains are safer than REF2 trains for both EB from acceleration and EB from coasting. As in §4.1.2 and 4.2.2, the presence of articulated wagons is beneficial for LCF, since it reduces the number of axle wagons in the consist.

The results show that trains having a mass between 2500 and 4000 t with articulated wagons and minimum mass of 32 t and 5 wagons in G are as safe as trains having the same mass interval but with a minimum mass of 40 t and no articulated wagons.

4.3.3 Effect on stopping distance

The increment of wagons in G has a little impact on the train stopping distance. Figure 20 reports the cumulative frequency of the stopping distance for an emergency braking from 100 km/h in coasting conditions: even with more wagons in G, since the trains have an higher percentage of braked mass, the stopping distance is a little shorter than that of REF1 trains: this means that the number of wagons in G is not the only item to consider, but also the train percentage of braked weight must be considered (obviously).

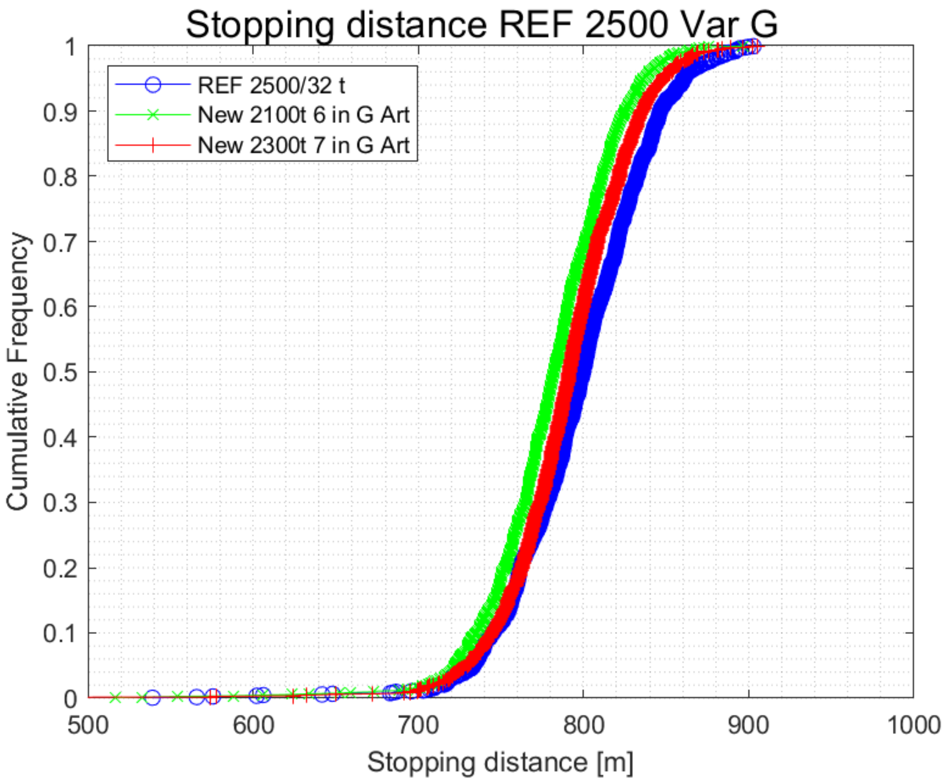

Figure 20 Cumulative frequency of stopping distance, REF and variable number of Wgons in G.

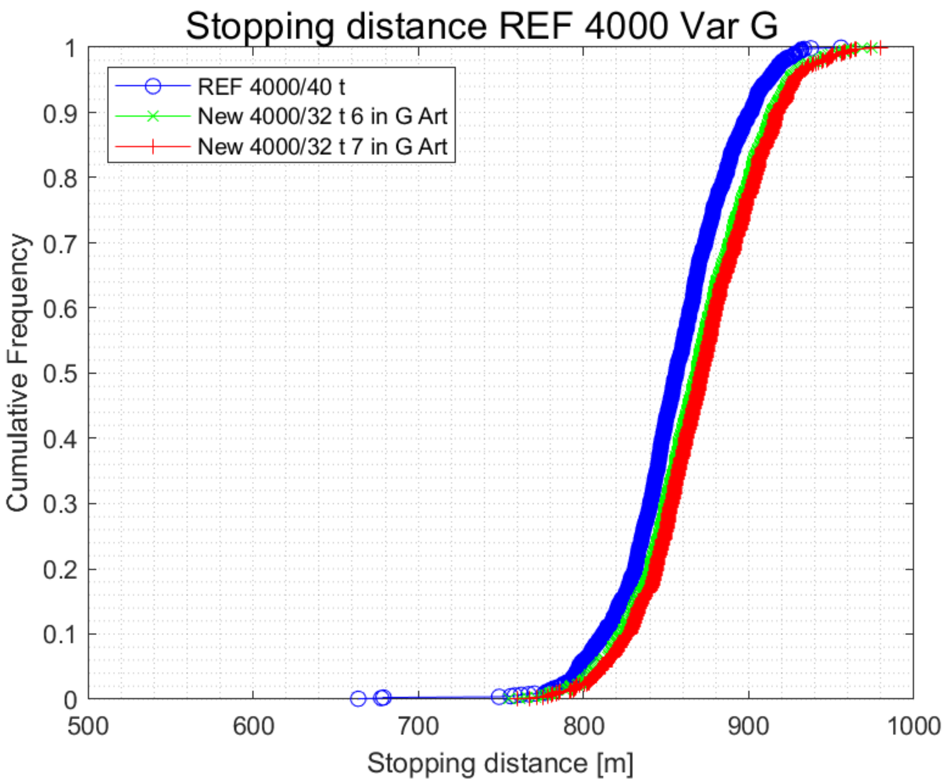

Figure 21 Cumulative frequency of stopping distance, REF2 and variable number of Wagons in G.

Figure 21 refers to REF2 trains and it shows that increasing the number of wagons in G causes (a little) higher stopping distances, since the train families are more similar in terms of mass and length and therefore also the braked weights of wagons in P are similar: in this case, the increase of wagons in G expands the stopping distance.

Results showed in this section prove that, for the simulated trainsets, Extended Long Locomotive (with 6 or even 7 wagons in G) is not a big source for stopping distance variation, especially for trains with hauled mass up to 2500, rather it reduces the LCF, considerably.

4.4 Effect of infrastructure

Up to now, the radius of curvature used to compute PLCF has always been 190 m. In this section, the probability of derailment is given as function of the minimum radius of curvature for different trainsets. The common feature of these trainsets is that they employ articulated wagons, with no constraint in terms of minimum mass, and that the number of wagons in G is 5.

The extrapolation rules in IRS 40421 are the basis for this comparison.

4.4.1 Variation of track radius and REF1 trains

Figure 22 reports the variation of the probability of derailment with the minimum track radius of curvature; this probability is reported for REF1 trains and for several new trains having articulated wagons, empty wagons allowed and minimum hauled mass equal to 1600 t. This figure shows that trains having hauled mass between 1600 and 2500 t with empty and articulated wagons are as safe as the REF1 trains (at 190 m of minimum track radius) if the minimum radius of curvature is bigger than 220 m, if EB after acceleration is considered: the vertical and dashed lines help the visualization. In case of EB commanded from coasting, to have a probability of derailment similar to that of REF1 train, the radius of curvature should be still 220 m at least (see

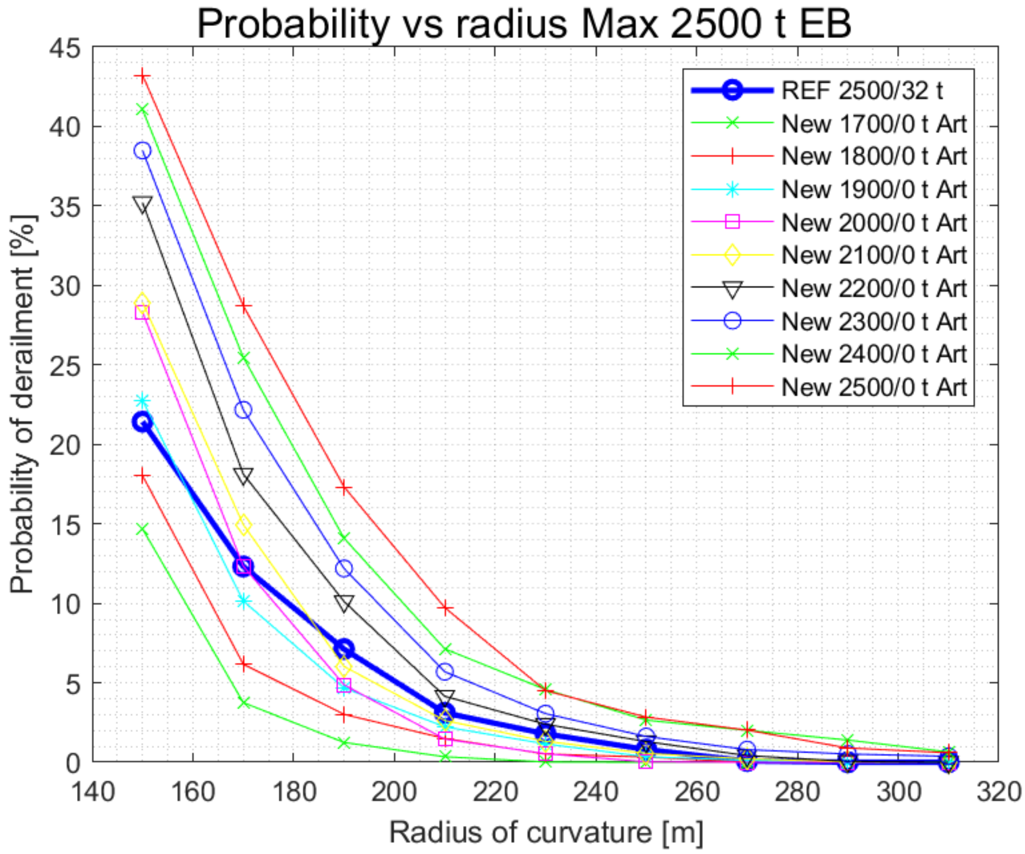

Figure 23).

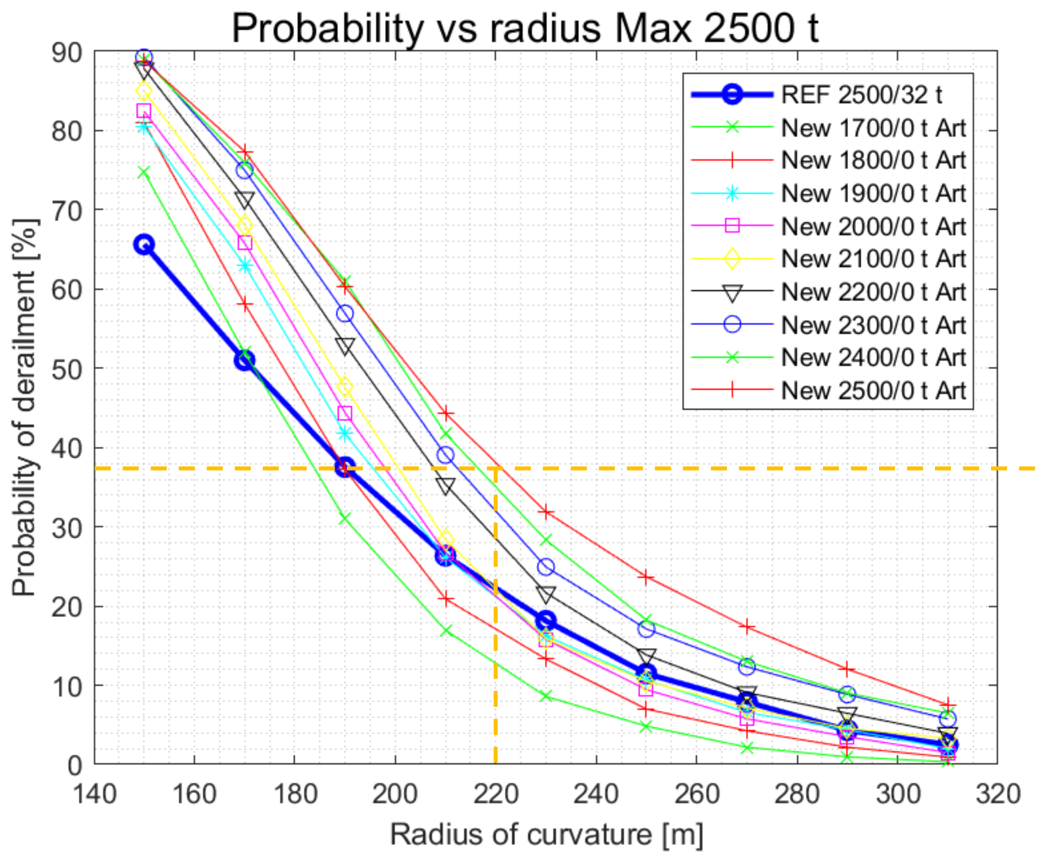

Figure 22 Derailment probability variation with radius of curvature. New trains have a minimum hauled mass of 1600 t, no minimum wagon mass and 5 wagons in G. EB from acceleration.

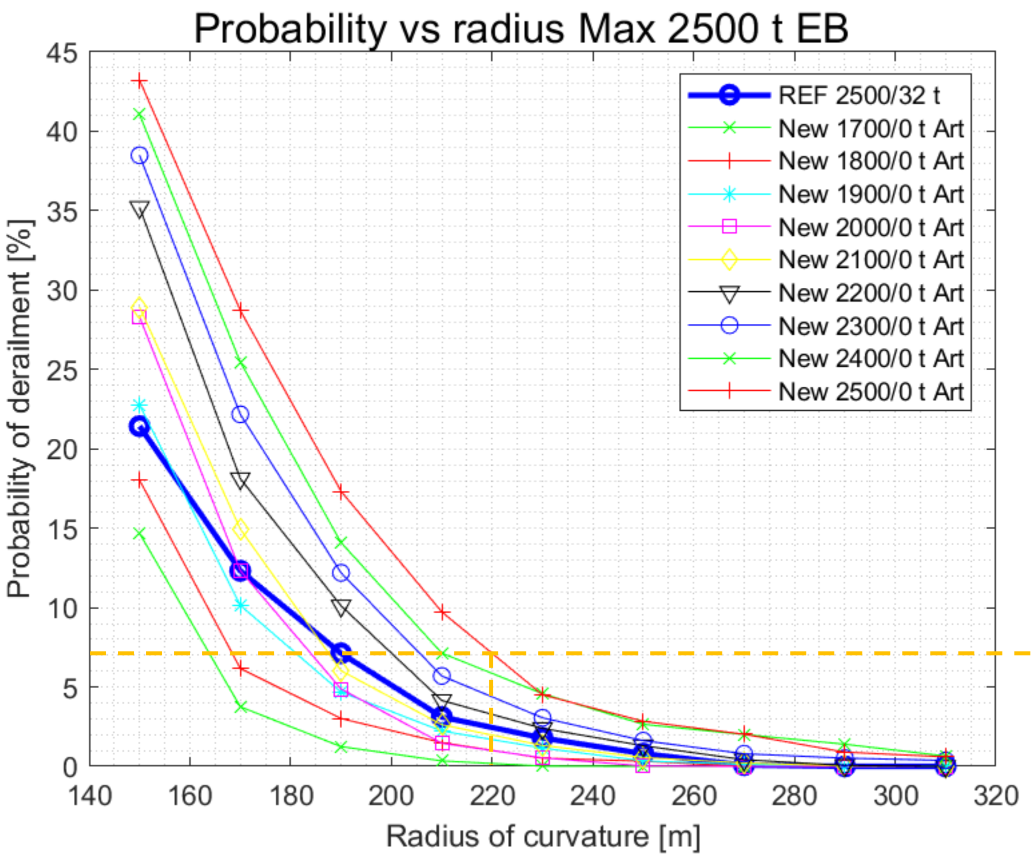

Figure 23 Derailment probability variation with radius of curvature. New trains have a minimum hauled mass of 1600 t, no minimum wagon mass and 5 wagons in G. EB from coasting.

4.4.2 Variation of track radius and REF2 trains

Figure 24 reports the variation of the probability of derailment with the minimum track radius of curvature for an EB after acceleration.

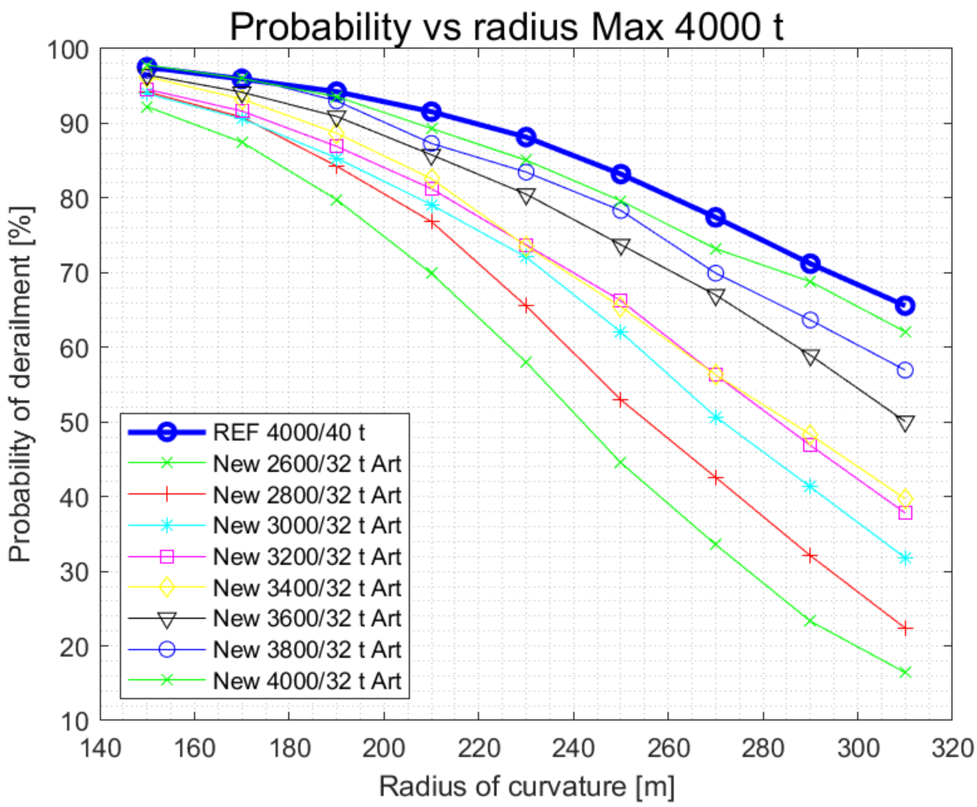

Figure 24 Derailment probability variation with radius of curvature. New trains have a minimum hauled mass of 2500 t, minimum wagon mass is 32 t and 5 wagons in G. EB from acceleration.

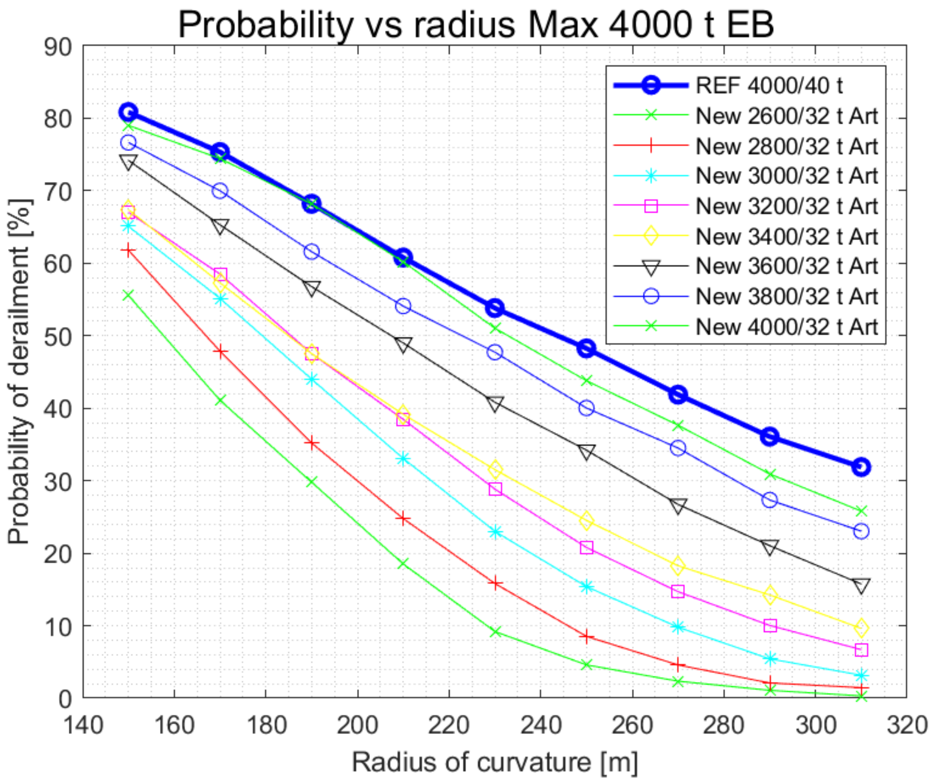

Figure 25 Derailment probability variation with radius of curvature. New trains have a minimum hauled mass of 1600 t, no minimum wagon mass and 5 wagons in G. EB from coasting.

The probability reported in Figure 24 refers to REF2 trains and to several new trains having minimum wagon mass of 32 t and minimum hauled mass equal to 2500 t. This figure shows that these new trains are safer than REF2 trains for all radii of curvature: these results are coherent with previous results (see Figure 18 and Figure 19). The same considerations apply to an EB from coasting conditions: see Figure 25.

5 Conclusions

The results showed in this report refer to very dangerous operative conditions (emergency braking from coasting or from acceleration), normally not encoutered during the daily operations: for this reason the virtual probability of derailment are very high (they are virtual probability of derailment since they are based on virtual trains) and the simulation conditions are conservative (see §2.3).

Therefore, it is possible to say that the following train families (in LL braking regime) are safer than[1] REF1 (Table 1) and REF2 (Table 2) and can be operated, assuming REF1 and REF2 can be considered as reference systems:

Table 1 Train families safer than REF1

Trains with only articulated wagons, without any mass limitation, in the mass range 1600-2200t (see Appendix B)
Trains in the 1600-2500 t mass range with mixed articulated, bogie and axle wagons, without any mass limitation, **but** with the wagons lighter than 32 t moved at the end of the train (§4.2.1)
Trains in the 1600-2100 t mass range with mixed articulated, bogie and axle wagons, without any mass limitation or wagon ordering, **but** with the first six wagons after the traction unit(s) in "G" (freight) position (§4.3.1)
Trains in the 1600-2300 t mass range with mixed articulated, bogie and axle wagons, without any mass limitation or wagon ordering, **but** with the first seven wagons after the traction unit(s) in "G" (freight) position (§4.3.1)
Trains in the 1600-2500 t mass range with mixed articulated, bogie and axle wagons, without any mass limitation or wagon ordering, **if** the track radius is bigger than 220m (§4.4.1)

Table 2 Train families safer than REF2

Trains in the 2500-4000 t mass range with mixed articulated, bogie and axle wagons, with minimum mass of 40 t and any wagon ordering (§4.1.2). If the wagons lighter than 40 t are moved at the end of the train, the level of safety is higher (§4.2.2)
Trains in the 2500-4000 t mass range with mixed articulated, bogie and axle wagons, without any mass limitation or wagon ordering, **but** with the first six wagons after the traction unit(s) in "G" (freight) position (§4.3.2)
Trains in the 2500-4000 t mass range with mixed articulated, bogie and axle wagons, with minimum mass of 32 t and any wagon ordering on every type of infrastructure (§4.3.2).

The following additional conclusions are also relevant:

- In the 1600-2500 t mass range, with minimum mass of 32 t, the use of articulated wagons cannot be validated (see Figure 2 and Figure 3).
- Trains currently admitted by IRS 40421 (1200-1600t/0t, all wagons accepted) are safer than REF1 (1600-2500t/32t no Articulated) trains (see Appendix A)
- REF1 (1600-2500t/32t no Articulated) trains are safer than REF2 (2500-4000t/40t no Articulated) trains.

[1] REF1: Hauled mass between 1600 and 2500 t (minimum 32 t/wagon) with a maximum of 3 consecutive unbraked wagons, without articulated wagons. REF2: Hauled mass between 2500 and 4000 t (minimum 40 t/wagon) with a maximum of 3 consecutive unbraked wagons, without articulated wagons.

The permissible LCF of articulated wagons is based on the extrapolation rules of IRS 40421 valid for bogie wagons: these extrapolation rules are based on ERRI reports (B177.1 and B177.5) and on UIC 530-2 specifications, which also apply to articulated wagons.

As a matter of fact, in agreement with UIC 572, articulated wagons have to satisfy UIC 530-2 and UIC 432 on running stability.

Moreover, UIC B12/RP76 (year 2009) reports that articulated wagons have been safely used since 1987 in a number > 7500 wagons and for more than 7 billion of km. Therefore, these types of wagons can be considered as safe as bogie wagons, considering the return of experience.

Nevertheless, the extrapolation of permissible longitudinal compressive force (LCF) to articulated wagons is an hypothesys and it is the best possible approach within the application field of TrainDy software.

As reported in IRS 40421, the permissible LCF can be obtained by

- tests or
- calculation with Multibody Dynamics Software; or
- extrapolations established on the basis of an equivalent wagon; or
- any method based on an approved scientific and/or technical expert report.

Therefore, to overcome such assumptions on articulated wagons, it is possible to perform the following studies:

- A new *TrainDy* study that considers the mass range of [1200-1600] t in the LL regime, where all types of wagons are allowed, as a new reference system: thus, the same assumption made on the articulated wagons of the reference trains is replicated in the new train families. Consequently, because of the relative approach, the new results are accepted.
- A new study aims to evaluate a more accurate PLCF value for articulated wagons with Multibody Dynamics software and a few full-scale tests to verify the simulations. The results of this study could also improve the way *TrainDy* software handles articulated wagons.
- An experimental pilot testing phase with articulated wagons to gradually validate the safe operation of the train scenarios listed in Table 1 and Table 2 above.

6 References

[1] B177.4/RP 5 "CEF-PSA UBS action project: first TrainDy report".

[2] IRS 40421, *Rules for the consist and braking of international freight trains*, 1st edition, December 2021.

[3] Cantone L, Toubol A 2020 *D3.1 – M2O LTD Simulations Report*, https://www.marathon2operation.eu/web/pdf/M2O_D3.1_LTD_simulations_report_final.pdf

[4] V Krishna , M Berg and S Stichel, "Tolerable longitudinal forces for freight trains in tight S-curves using threedimensional multi-body simulations", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2020;234(5):454-467, 10.1177/0954409719841794

[5] Cantone L, Toubol A, et al 2020 *D3.3 – Test Demonstrators with DPS, LTD simulation report*, https://www.marathon2operation.eu/web/pdf/D3p3%20Test%20Demonstrators%20with%20DPS,%20LTD%20simulation%20report.pdf

Appendix A Safety of reference system

This appendix checks the safety of REF1 train family (hauled mass between 1600 and 2500, with minimum wagon mass of 32 t and three consecutive wagons not braking, without articulated wagons) against the train family with hauled mass between 1200 and 1600 t, train length between 540 and 740 m, with empty and articulated wagons allowed. Both train families are in braking regime long locomotive. Differently from other results displayed in this document, REF1 trains have a length between 540 m and 740 m, in this section, to allow a proper comparison against trains allowed by IRS 40421.

Figure 26 reports the statistics of trains which are safe according to IRS 40421. Even if the mass distribution should be uniform, it does not look like; on the contrary, length distribution looks more uniform. Part (c) of the figure reports the cumulative frequency of axle, bogie and articulated wagons; moreover, it reports the number of wagons for each train and the number of wagons having mass below 32 (L32) and 40 t (L40).

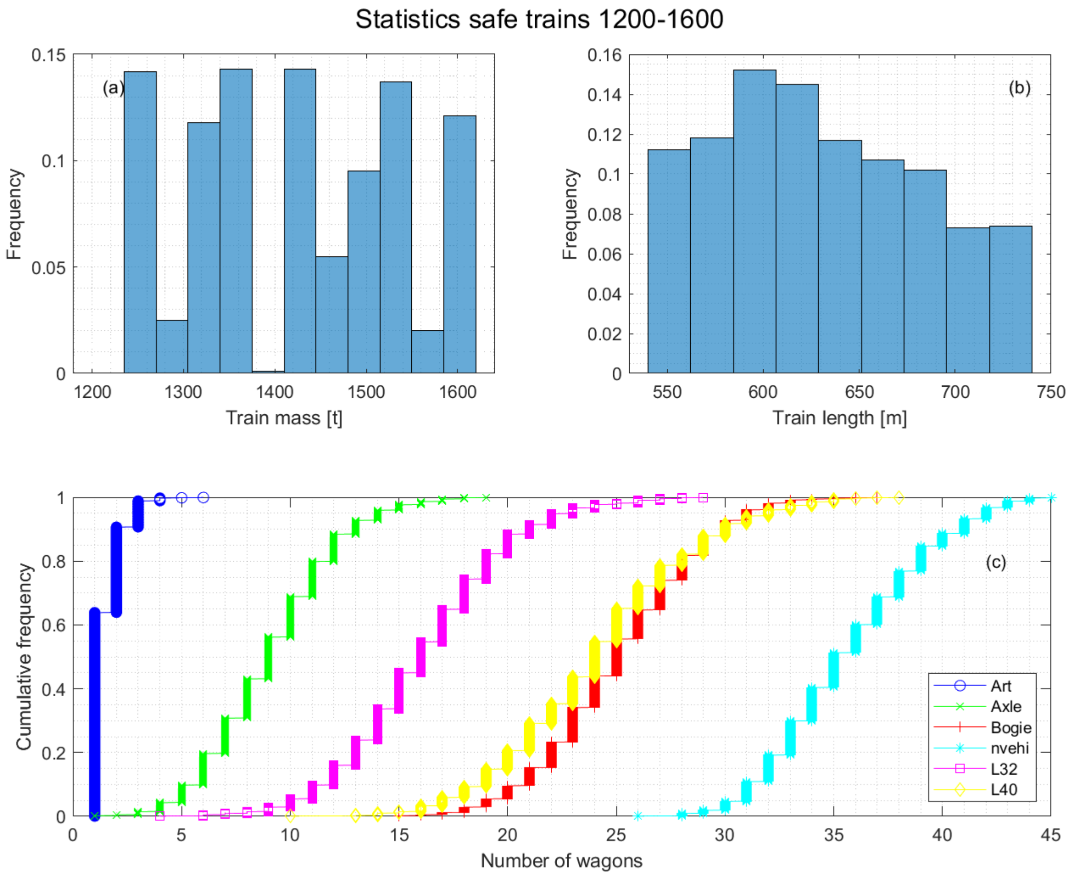

Figure 26 Statistics of trains respecting current limitations of IRS 40421.

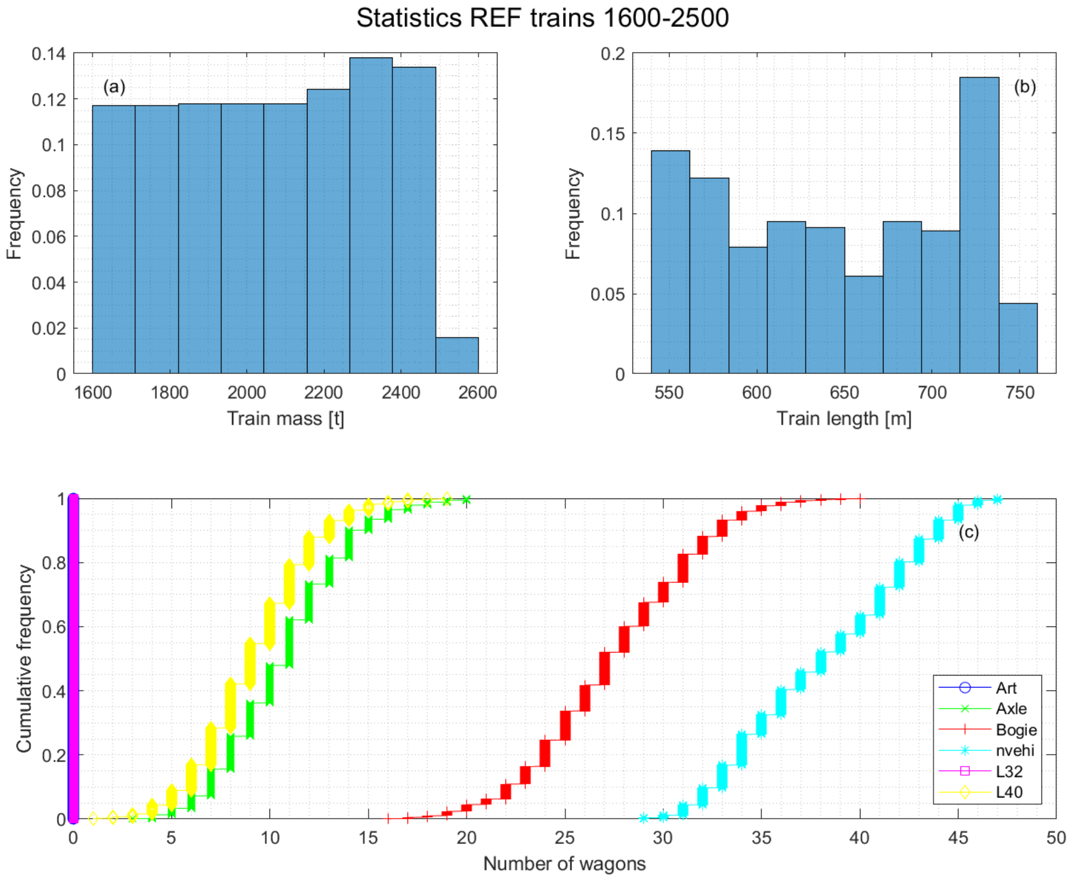

Figure 27 Statistics of REF trains.

Figure 27 reports the statistics of REF1 trains (as Figure 26, for IRS 40421 trains). REF1 trains do not contain articulated wagons and wagons with mass below 32 t, as confirmed by part (c) of the figure. Comparison of Figure 26 and Figure 27 shows that REF1 trains are longer than IRS 40421 trains and this partially explains the different level of safety (in terms of derailment probability) of Figure 28.

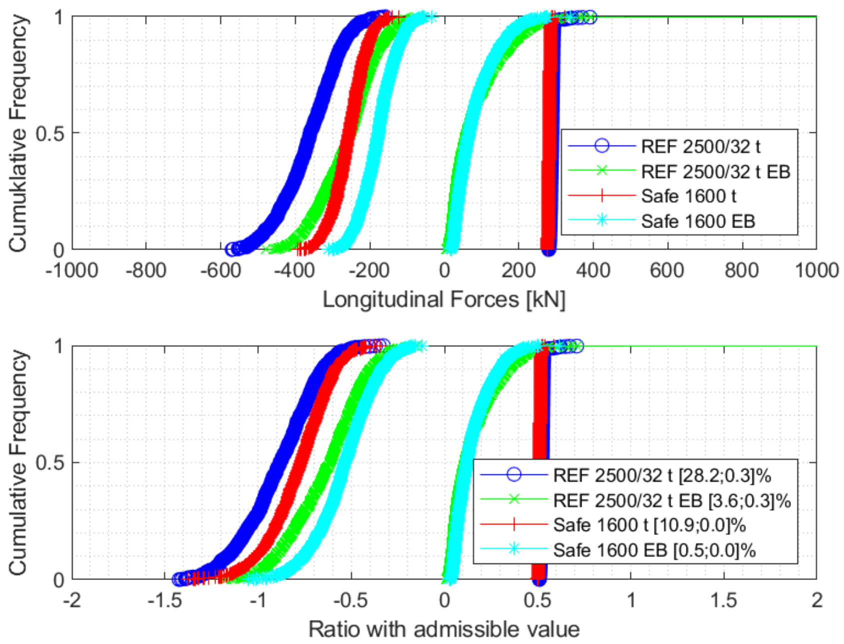

Figure 28 Comparison of longitudinal forces for trains accepted by IRS 40421 and reference trains (REF) of this study.

Figure 28 reports the comparison among the longitudinal force in REF1 trains and in IRS 40421 trains. In the figure, legends having “EB” refer to emergency braking from coasting conditions, otherwise the emergency braking is from acceleration, which is usually more dangerous in terms of longitudinal forces. In the top part of the figure, longitudinal forces are displayed (negative values refer to compressive forces); whereas the bottom part of the figure displays the ratio between the longitudinal forces and the corresponding permissible values: legend shows, among brackets, the probability of virtual derailment and that of virtual train disruption, respectively. The figure shows the benefits of mitigation in terms of minimum mass allowd in REF1 trains: the differences in terms of longitudinal forces are bigger than those in terms of ratios.

Finally, to prove that the numerosity of 1000 trains is suitable to describe the train statistics, the mean value of longitudinal compressive forces and the ratio between the standard deviation and the mean value is computed with 500 trains only taken from the 1000 original trains; the concept of moving statistics is used. (a) reports the average ratio between longitudinal compressive force and permissible longitudinal compressive force (PLCF) considering a moving window of 500 trains from the 1000 generated. The same concept applies to (c) which reports the ratii between the mean and standard deviation of the ratio LCF/PLCF; (b) and (d) reports the histograms of the errors with respect to 1000 trains.

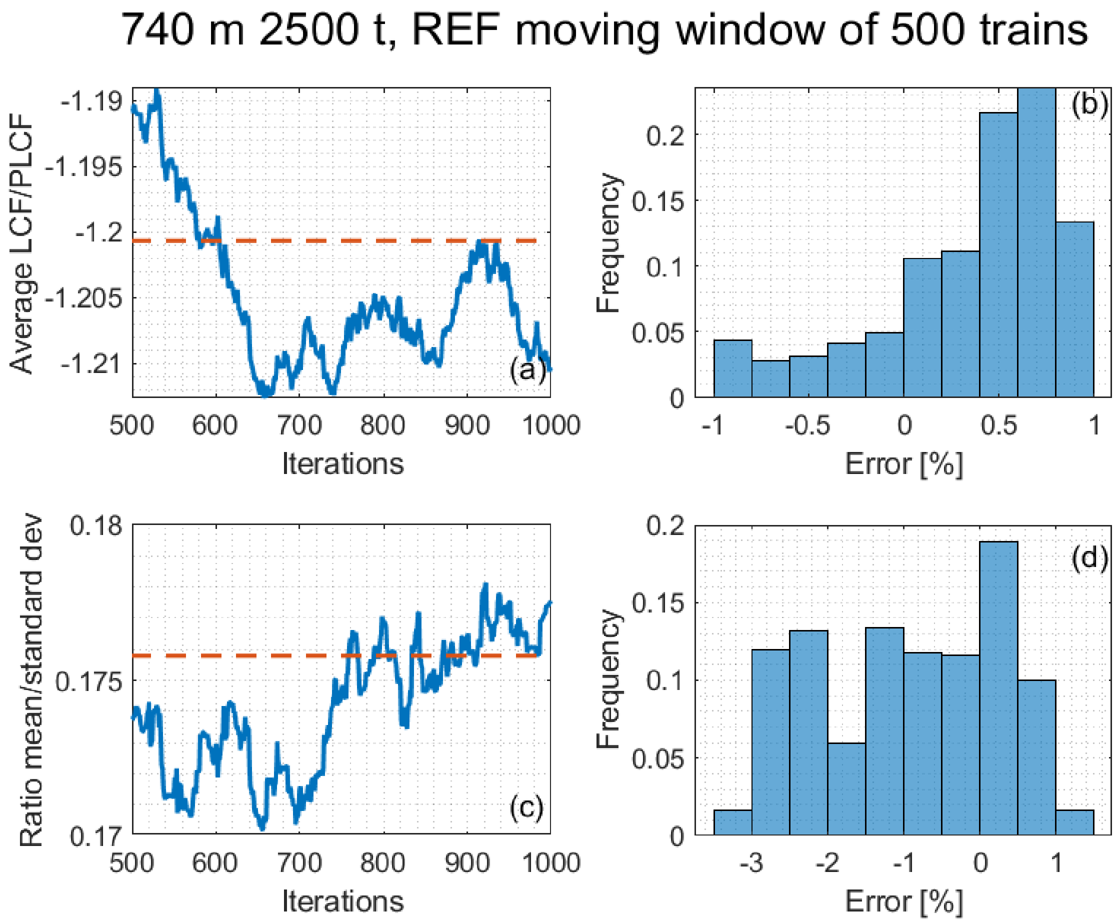

Figure 29 Moving statistics with 500 trains (a) Worst ratio of longitudinal compressive force and permissible longitudinal compressive force; (b) histogram of the error with respect to 1000 trains; (c) ratio of mean longitudinal compressive force and and standard deviation, red line refers to 1000 trains; (d) histogram of the error with respect to 1000 trains.

Appendix B Only articulated wagons

This section deals with trainsets with only articulated wagons having 6 axles. These new trainsets are compared agaings REF1, where it is more likely to actually use articulated wagons.

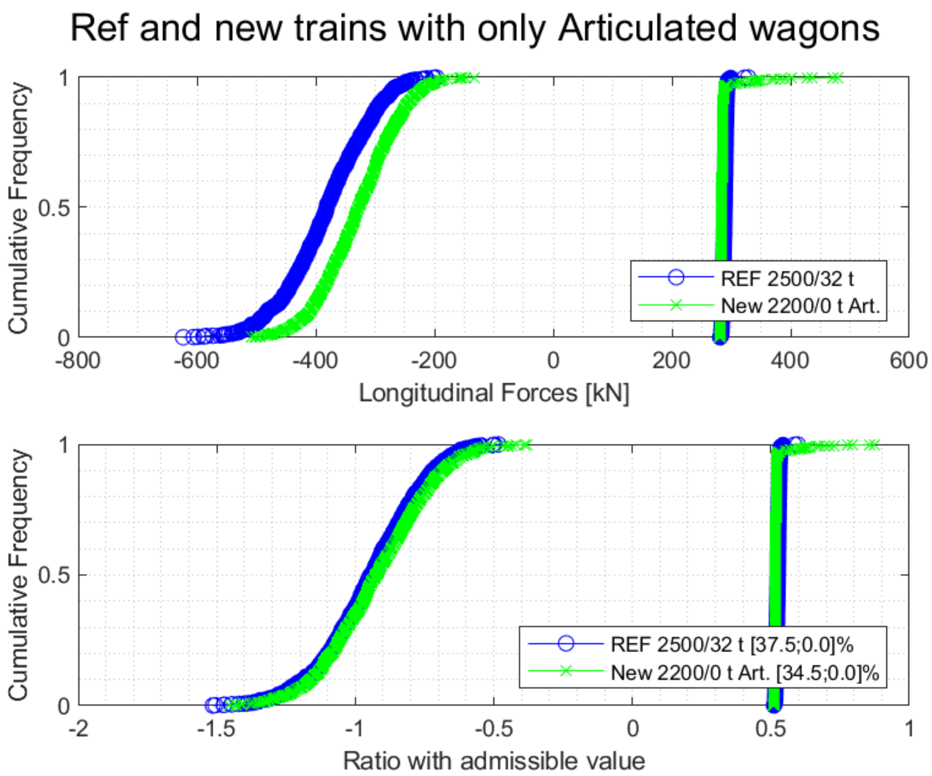

Figure 30 Comparison of longitudinal forces for REF1 trains and trains having only articulated wagons (empty wagons are allowed). EB from acceleration.

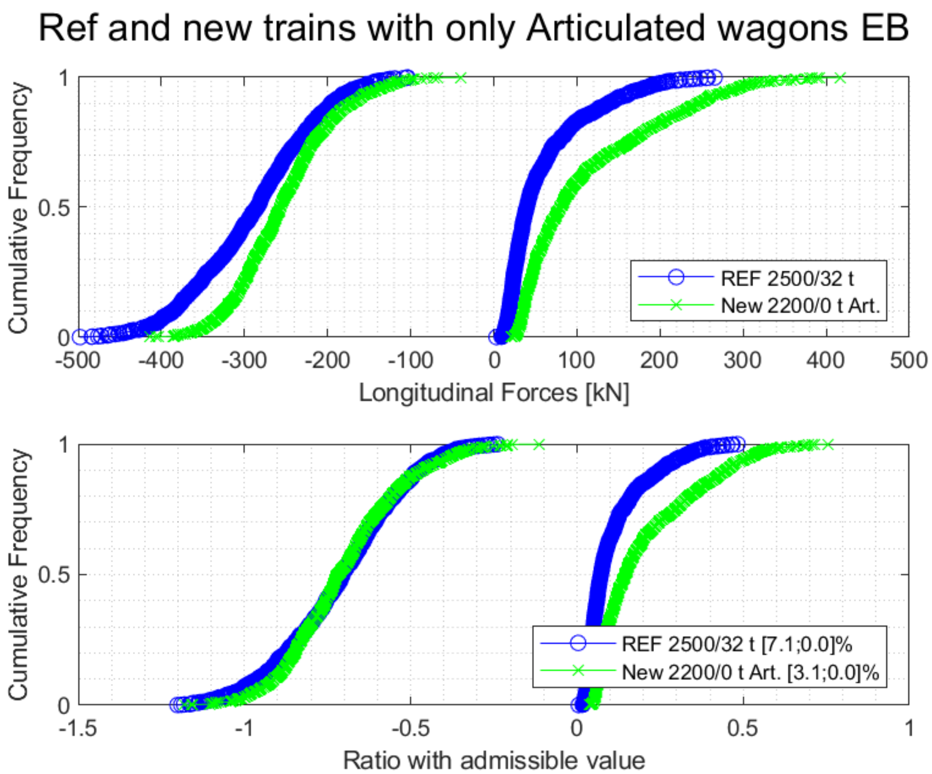

Figure 31 Comparison of longitudinal forces for REF1 trains and trains having only articulated wagons (empty wagons are allowed). EB from coasting.

Figure 30 refers to EB after acceleration a whereas Figure 31 to EB from coasting conditions: in both cases the reference trainsets are REF1. Above results show that trainsets with only articulated wagons have at least the same level of safety of REF1 trainsets if the mass is limited to 2200 t. Of course, the only assumption of this result is about the way the Permissible Longitudinal Compressive Forces are computed (see §2.4). Anyway the figures confirm that the employed assumption is conservative, since the longitudinal compressive forces displayed in the top part of each figure are more dangerous for REF1 than for new trains, wherease the ratios between LCF and PLCF are more similar (bottom part of each figure).