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Non-Standard Applications of the IRS 40421 Methodology

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Abstract

This paper shows three non-standard applications of the "relative approach" envisaged by the International Railway Solution IRS 40421: this document imposes some restrictions on the mass and length of interoperable freight trains, but it also provides a methodology for admitting to the traffic trains that exceed these limits. The paper considers the case of a single train, a family of trains with a new brake position and an optimized wagon order.

Keywords: freight trains, longitudinal dynamics, railway operation safety, numerical optimization, accident prevention, train derailments.

1 Introduction

The paper presents several non-standard applications of the International Railway Solution (IRS) 40421 methodology [1] to extract more capacity from the current railway infrastructure in a safe manner. The IRS 40421 describes a methodology, based on the "relative approach", that can be used to bring into service families of freight trains that do not comply with the limits imposed by the same IRS in terms of hauled mass and train length.

The train limits in terms of length and hauled mass are necessary since most freight wagons, [2], are neither equipped with the electro-pneumatic (EP) brake nor with the Digital Automatic Coupler (DAC), which is still in a research phase. Exceeding these limits can lead to train derailments, caused by high in-train compressive forces, and train disruption, caused by high in-train tensile forces. [3] contains a review on the topic of Longitudinal Train Dynamics (LTD) and [4] reports the results of an international benchmark between different LTD simulators.

EP brake and DAC are effective ways to increase the freight train capacity also by increasing the train length and the hauled mass; depending on the reached train length they require investments in wagons and in infrastructures too. A much less impacting technology, in terms of implementation costs, is the radio communication between the traction units (TU): in this way, the venting of the brake pipe occurs from several locations and the braking of wagons is more synchronous and only the TU must be upgraded (reducing the implementation costs). In the recent years, among the different projects in the European Union, two of them have employed the software *TrainDy* for the calculation of Longitudinal Train Dynamics (LTD): in the European Union (EU) Framework Programme 7, with the MARATHON Project, and in the EU Horizon 2020 Programme, with the Shift2Rail Joint Undertaking Marathon2Operation project (www.marathon2operation.eu).

The relative approach envisaged by the IRS 40421 is of general applicability and it is used in this paper for three non-standard applications: a) train with fixed mass and length; b) determination of equivalents limits, in terms of hauled mass and train length, for extended long locomotive brake position; c) train with optimized wagon arrangement. All these applications do not require any investment and they can increase the freight efficiency.

This paper continues the work carried out in [5] and [6] where DAC, EP brake and radio technologies have been explored as effective ways to increase the freight train capacity and uses the *TrainDy* version developed by the Tor Vergata University of Rome.

2 The IRS 40421 "relative approach"

The IRS 40421 provides several limits in terms of train length and hauled mass for interoperable freight trains. Basically, the train length (without TU) is limited to 700m and the hauled mass depends on the brake position: a) up to 800t the train can be in brake position P ("passengers"); beyond this and up to 1200t the TU must be in brake position G ("goods"); beyond this and up to 1600t the TU and 5 wagons must be in brake position G and the remaining in P (this is known as Long Locomotive -LL- braking regime); beyond this and up to 4000t all wagons must be in brake position G (G-braked trains). For P-braked trains (hauled mass up to 1600t) the maximum speed is 120km/h and for G-braked trains it is 100km/h.

For trainsets not matching the characteristics explicitly mentioned by the IRS 40421, there is still the possibility to operate them by following the "relative approach": this approach fulfils the Common Safety Methods (CSM) adopted by the European rules (Commission Implementing Regulation (EU) 2015/1136 of 13 July 2015). The "relative approach" compares a new train family with an accepted train family in terms of Longitudinal Compressive Forces (LCF) and compares the number of potential derailments of these two families. If this number is lower for the new train family, it can circulate safely. The number of potential derailments is calculated by determining the permissible LCF according to specified extrapolation rules based on experimental data. Trainsets respecting the previous limits are examples of accepted train families. The comparison requires the checking of a series of parameters, noting the value in reference and new train family (or system), describing the (statistical) changes from reference to the new system and commenting on them (optionally). An example of parameters to check is given in Table 1.

What to check	**Example/observation**
Train composition	Arrangement of vehicles in terms of mass and length
Brake equipment of vehicles.	Occurrence of empty/load and auto-continuous devices
The means the braking is controlled	Pneumatically, via radio, by wire
Braking regime	P-braked or G-braked trains
Type of wagons	The wagons are the same, but the permissible LCF is different (as it happens for DAC)
Initial braking speed	
Braking mode	Emergency braking or full-service braking, from coasting or acceleration (traction).
Wagon load	Positioning of empty wagons at the train end

Table 1: List of parameters to check during the comparison of train families.

The most important aspect to consider is that the results of such analyses strongly depends on the choice for reference and new system: in order to highlight the effect of the differences between them, these should be limited (i.e. changes must be limited to the parameters that need to be investigated); the cited papers [5] and [6] gives examples of such comparison.

The application of the relative approach described by the IRS 40421 requires the knowledge of statistic distributions for: a) Hauled mass and/or train length; b) Wagons occurrence; c) Payload carried by each wagon; d) Number of consecutive wagons of the same type and load. Moreover, there are two types of parameters which affect the in-train forces: the operational and technical parameters. The operational parameters are the most important for in-train forces and they are under control of Railway Undertakings (RU): the hauled mass, the train length, the train braking position, the train braking scenarios are all examples of operational parameters. The technical parameters have a smaller effect on in-train forces and their specific value is not known in operation: the current braking efficiency of each wagon, the current maximum braking pressure at brake cylinders, the specific value of friction coefficient are all examples of technical parameters whose exact value is not know and influence in-train forces. Strictly speaking, also the braking starting speed, or the track gradient are not exactly known, but the relative approach considers enough employing the same assumption for the reference and new system.

For many RU these values are not available, therefore the relative approach is used by considering the trains admitted to service, in accordance with the limitations given above, as a reference train and a new train family that is as similar as possible to the reference train and differs from it in only a few parameters. Furthermore, there are some cases in which the new system is not well defined in terms of wagons, since it does not still operate, but it is defined in terms of hauled mass and train length: for these circumstances the iterative proportional algorithm can be used.

2.1 The Iterative Proportional (IP) algorithm

This algorithm can be used each time a new train family has to be investigated but there are no data in terms of wagons or payload statistic distributions and only the hauled mass range is known. For these circumstances the train belonging to the reference family of mass *m* can be transformed into a train belonging to the new family of mass *M*; this can be done by the following linear interpolation as:

$$M = M_1 + \frac{M_2 - M_1}{m_2 - m_1}(m - m_1) \tag{1}$$

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

Knowing the mass of each wagon of the reference train (with mass *m*), it is possible to increase the mass of the heaviest wagon(s) up to the maximum mass and repeating this increment until the target mass *M* is reached. In this way, the new trains have the same length, type, and order of wagons of the reference trains but with a less favorable mass distribution, since the differences in wagon mass have been amplified: the new train is an “evolution” of the reference train towards higher hauled masses. Section 3.2 gives an application example of this method.

2.2 A combinatorial algorithm for in-train forces optimization

This section briefly recalls an algorithm like the one used in [9] and based on the one described in [10] for the optimization of the wagon order in order to improve the in-train forces. In many cases, it is not possible to optimize the wagon order for logistical reasons, but with the Digital Automatic Coupler (DAC) this situation can be overcome more easily, resulting in heavier but still safe trains. Having defined $\left.\frac{LCF}{PLCF}\right|_{max}$ and $\left.\frac{LTF}{PLTF}\right|_{max}$ as the maximum ratios of the compressive and tensile forces in the train with their corresponding permissible values, the optimization variable is:

$$z = \max\left(\left.\frac{LCF}{PLCF}\right|_{max}, \left.\frac{LTF}{PLTF}\right|_{max}\right) \tag{2}$$

Trains with a variable *z* less than 1 can be considered as safe against both the risk of derailment (or wagon lifting) and the risk of train disruption. The algorithm requires a first set of *N* random simulations, i.e., the position of the wagons is changed randomly and the best order is taken in accordance with (2); then further *N/2* random simulations are performed, and further *N/2* simulations are performed, changing the best order by permuting the position of n_p wagons. Again, the best wagon order is computed and the improvement in terms of *z* is evaluated: if the difference is less than a given threshold Δ_z, the iterations stop, otherwise they continue with further *N/2* random simulations and further *N/2* simulations where the best order is slightly changed. In this paper, when the number of permutations n_p is bigger than 2, a number of n_p wagons is permuted with the corresponding consecutive wagon; of course, other strategies can be possible.

3 Results

This section describes three applications of the relative approach that do not follow the standard scheme reported in IRS 404-21 but are still consistent with the relative approach method.

3.1 Homogeneous train

When the new system is not a family of trains, but it is just one train since the traffic is homogeneous, the application of the relative approach can be done in different ways: a specific example is here given. The new train has a mass of 3000t, it has a length of 500m (TU included), it employs just one wagon type, and they carry the same load. This new train is accepted by the IRS 40421, but RU in Italy requires a dedicated analysis for such trains. The reference trains considered have the same length, the same wagon type, but they carry a different mass (randomly positioned), still having the same percentage of braked mass (100%).

	Reference	**New (homogeneously loaded)**
Hauled mass	1600t	3000t
Length (with TU)	500m	
Number TU	2 (in front)	1
Wagon tare	36.3t (reference trains have 7 empty wagons)	
Wagon load	98.2 x 10 wagons	130.4 t x 18 wagons
Braking regime	LL	G-braked train
Maximum traction force	550kN	320kN

Table 2: Parameters for reference and new homogeneous train.

Details are given in Table 2 but other choices could have been done; the train operation is an emergency braking from 30 km/h from: a) full acceleration (label TEB) and b) coasting (label EB). The speed of 30 km/h is used since around this speed the trains experience the highest compressive in-train forces during an emergency braking. The new system has the following mitigative factors with respect to the reference train: a) the train brake position, b) the absence of empty wagons and c) the lower maximum traction force (relevant only for TEB operation). The effect of technical parameters is also considered, similarly to what done in [6].

Figure 1 reports the cumulative frequencies of in-train forces in (a) and of the ratio with their permissible values: negative values refer to compressive forces (which may cause wagon derailment), whereas positive values to tensile forces (which may cause train disruption, i.e. the train separation). Each dot refers to a train and represents the worst value of in-train force (the most negative for compressive forces and the most positive for tensile forces); the ratios with permissible values in (b) for compressive forces are computed considering that the highest compressive force occurred on a wagon running on a curve of 190m radius. The permissible in-train compressive forces are computed following the IRS 40421 which provides simple rules based on experimental data extrapolations. The permissible in-train tensile force is assumed equal to 550kN, as done in [8], even if this value slightly changes with the specific type of drawgear and it can be considered conservative: the advantage of the "relative approach" envisaged by the IRS 40421 consists in comparing trains under similar conditions. The legends in (b) report between parentheses the probability intervals (with a confidence of 95%) of derailment and disruption and they are linked to the number of points which overcome "-1" and "+1", respectively.

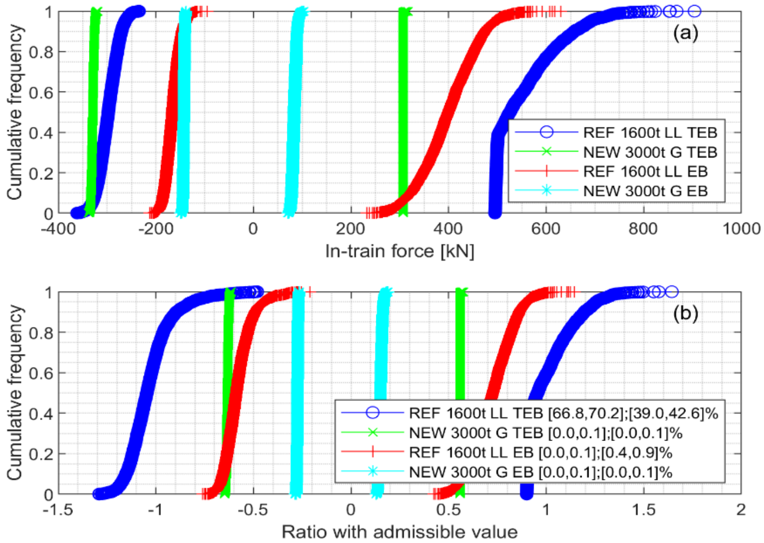

Figure 1: Cumulative frequences of (a) in-train forces; (b) ratio with permissible values.

Figure 1 shows that homogeneous trains are safer than already admitted trains, in terms of in-train forces, since their ratios with permissible values are smaller (in absolute sense) than those of reference trains. The in-train compressive forces, especially for the TEB operation, are most favourable for reference trains, usually; nevertheless, since the new trains wagons are heavier that the reference trains wagons, the ratio of in-train compressive forces is favourable to new trains.

3.2 Extended LL braking regime

The "Long Locomotive" (LL) braking regime is an effective way to increment the train mass without penalizing too much the remaining railway traffic because of a low operational speed. Incrementing the number of G-braked wagons in LL trains from 5 to 7 (7LL) results in an affordable increment of stopping distance and in a reduction of in-train compressive forces: consequently, heavier trains could be assembled with a similar degree of safety of existing trains. A complete study on this topic is far beyond the aims of this paper; the results of the simulations reported below show what could be the guidelines for the future implementation of an extended LL braking regime.

At this aim, two real train families, extracted from the database (label DB is used) of trains used as reference for the simulations in [7], have been simulated. The first consists of LL trains with a mass range of 1550-1600t, the second consists of G trains with a mass range of 1950-2000t, both with a train length in the range of 600-740m (TU included).

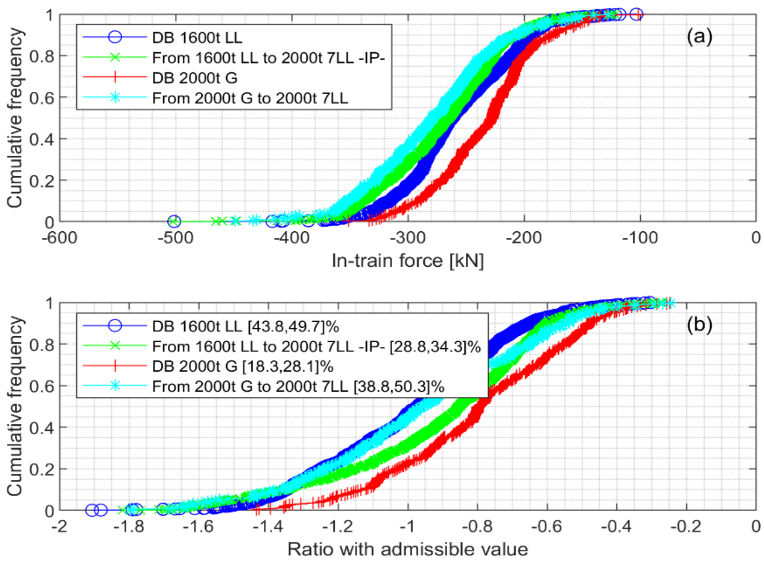

Figure 2: Cumulative frequences of in-train compressive forces in terms of (a) in-train forces; (b) ratio with permissible values.

Figure 2 is like Figure 1, but it reports only the in-train compressive force for four train families for the TEB train operation; beyond those described before (1st and 3rd row in the legend), there are other two train families in 7LL. The real trains in G have been simulated in 7LL (4th row in the legend), whereas the real trains in LL have been modified and operated in 7LL using the described Iterative Proportional (IP) algorithm (2nd row in the legend). A derailment probability range, calculated according to [1], is also included in the legend of part (b): it shows that incrementing the hauled mass of existing trains up to 2000t and running them in 7LL is safer than just switching the G-braked trains to 7LL. In fact, the derailment probability range of the 2nd row is smaller than that of the 1st row showing a higher level of safety of these new possible trains. On the contrary, the derailment probability range of the 4th row exceeds that of the 1st row; finally, as expected, the derailment probability range of the 3rd row is the best of all the others. This means that trains with a mass range of 1950-2000t running in 7LL are safer than existing LL trains if they are similar to these trains, and are risky if they are derived from existing G trains.

In order to better understand the reason for the previous result, the Figure 3 shows some statistics for real train families; in particular, (c) and (d) show the payload frequency for wagons in the centre of the train (from 40% to 60% of the train length), as this is the area where higher in-train compression forces are usually achieved and the use of light wagons in this area increases the ratio between the compression force and the permissible value.

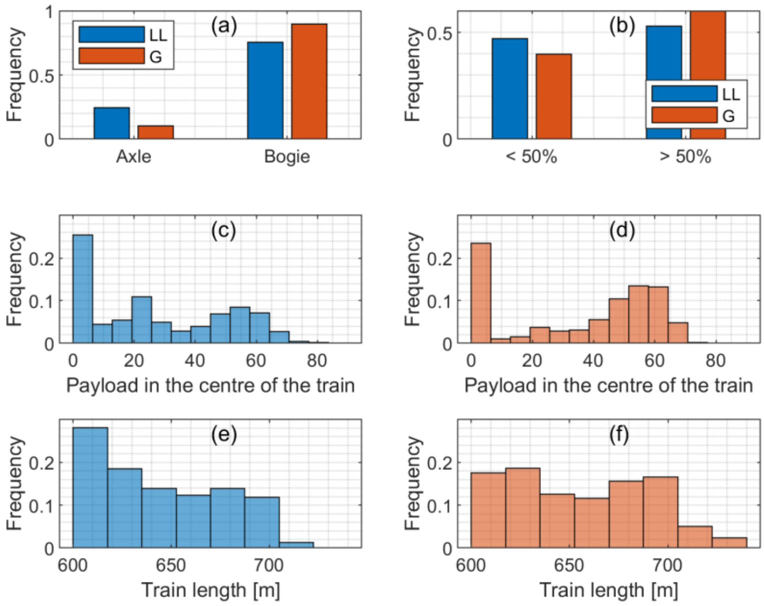

Figure 3: Real train statistics: (a) shows the frequency of bogie and axle wagons; (b) shows the percentage of wagons with a mass less or greater than 50% of the maximum value; (c) and (d) shows the payload frequency for wagons in the centre of the train for LL and G trains respectively; (e) and (f) shows the train length for LL and G trains respectively.

The Figure 3 shows that LL trains usually have a length lower than G trains, therefore when these trains switch to 7LL (see 4th row in the legend of Figure 2) they are more dangerous than shorter trains in 7LL (see 2nd row in the legend of Figure 2). Based on these simulations, trains in 7LL can haul a mass up to 2000t if their length is lower than 650m.

3.3 Train with optimized wagon order

This last section considers the experimental train of the Shift2Rail Marathon2Operation (M2O) project, operated by DB Cargo at the beginning of 2021 [8] on a commercial line and equipped with radio communication between the three TUs. The train is an example of single wagon traffic, and it has a length of 640 m and a mass of 1740t; it was moved by three TUs, uniformly distributed along the train. The algorithm parameters used are N = 26, 52 (52 is the number of cores of the workstation in use), n_p=2, 3 and 4 and $\Delta_z = 10^{-2}$; many other choices could have been made, but this is not the purpose of this paper, nevertheless the simulations were run 10 times to quickly study the dispersion of the results.

Figure 4 shows the results of the optimization method and of 1k and 3k random simulations, i.e., not only the optimization method was repeated 10 times, but also the sets of 1k and 3k simulations were repeated 10 times: 1k is the number of simulations usually performed when the "relative approach" is used. The performed train operation is a full acceleration from zero speed up to 30 km/h followed by an emergency braking. The results from (a) to (d) refer to N = 26, the others to N = 52; (a) and (e) show the (average) best ratio obtained in 10 runs of the optimization method: increasing *N* slightly improves the optimization. (b) and (f) show the average performance of the optimization algorithm with respect to the random permutation: more than 98% of the time (on average), the optimized train has an optimal ratio according to (2) that is better than a random train generation. (c) and (g) show the average number of simulations needed to obtain the optimized wagon order: doubling N roughly doubles the time. Finally, (d) and (h) show the coefficient of variability (given by the ratio between the standard deviation of the number of simulations needed to find the optimal wagon order and its mean value) for the two values of N: the variability of the number of simulations needed to find the optimal solution does not seem to depend on N.

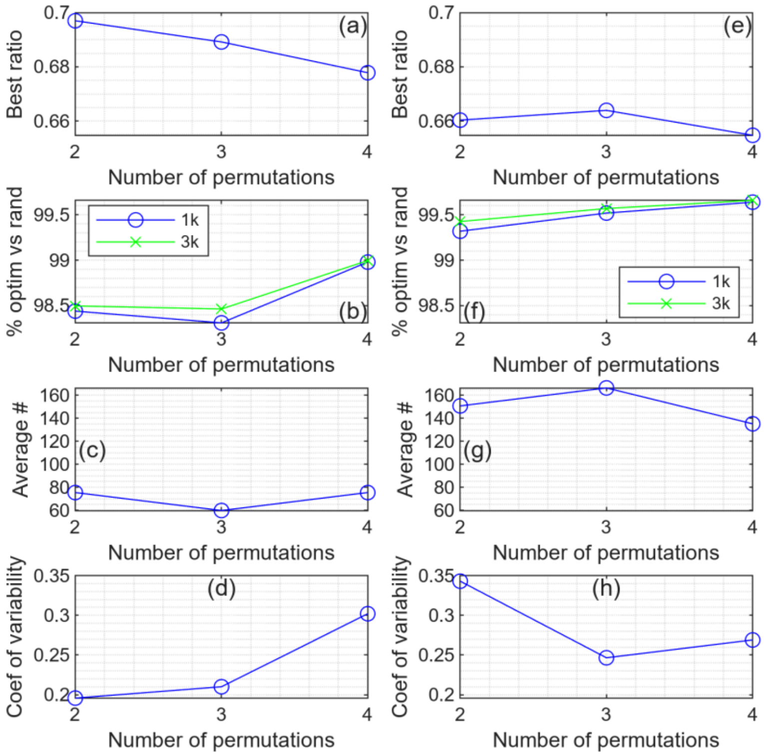

Figure 4: Optimization results: (a)-(d) and (e)-(h) refer to N=26 and N=52, respectively.

The results shown prove that the optimization algorithm can generate the optimal train in terms of in-train forces with 90% less computational resources than a random train generation, and that the optimized train arrangement is better than the random arrangement in more than 98% of cases. Although not discussed further here, for a full application of the "relative approach" it would be necessary to compare the initial train configuration with the optimized one and to show that (considering the technical parameters) the optimized configuration has a lower probability of derailment.

4 Conclusions and Contributions

This paper has shown how to apply the IRS 40421 to three non-standard situations: a) train with fixed mass and length; b) determination of equivalents limits, in terms of hauled mass and train length, for extended long locomotive brake position (7LL); c) train with optimized wagon arrangement. All these applications do not require any investment and they can increase the freight efficiency. Among these applications, the implementation of a new brake position (with 7 wagons if G after the TU and the remaining in P) can put in service new heavier, but still safe, trains. In addition, the example of wagon positioning optimization shows the possibility of quickly optimizing wagon positioning to allow trains with masses and lengths beyond the current limits to be put into service.

References

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

[2] Q. Wu, et al., "Freight train air brake models", International Journal of Rail Transportation, 11, 1, 1-49, 2021. 10.1080/23248378.2021.2006808

[3] C. Cole, M. Spiryagin, Q. Wu and Y. Q. Sun, "Modelling, simulation and applications of longitudinal train dynamics", Vehicle System Dynamics, 55, 10, 1498-1571, 2017.

[4] Q. Wu, et al. "International benchmarking of longitudinal train dynamics simulators: results", Vehicle System Dynamics, 56, 3, 343-365, 2018.

[5] L. Cantone, T. Durand, A. Ottati, G. Russo, R. Tione, "The Digital Automatic Coupler (DAC): An Effective Way to Sustainably Increase the Efficiency of Freight Transport in Europe", *Sustainability*, 14(23):15671, 2022. doi.org/10.3390/su142315671

[6] L. Cantone, "Effective ways to compare two families of freight trains" IOP Conf. Ser.: Mater. Sci. Eng. 1275 012047, 2023. 10.1088/1757-899X/1275/1/012047

[7] L. Cantone, D. Laghi and S. La Rovere, "A statistical study on long freight trains equipped with radio communication within Shift2Rail", IOP Conf. Series: Materials Science and Engineering, 1038, 012034, 2020. 10.1088/1757-899X/1038/1/012034

[8] L. Cantone, "Simulation of freight trains with up to three traction units in radio communication", IOP Conf. Ser.: Mater. Sci. Eng., 1214, 012039, 2022. 10.1088/1757-899X/1214/1/012039

[9] E. Di Gialleonardo, et al., "Freight trains for intermodal transportation: optimisation of payload distribution for reducing longitudinal coupling forces." Vehicle System Dynamics, 61, 2532-2550, 2022.

[10] A. Alazzam, Harold W. Lewis III, “A New Optimization Algorithm For Combinatorial Problems”, International Journal of Advanced Research in Artificial Intelligence, 2, 5, 63-68, 2013.