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An Innovative Framework for the Simulation of Longitudinal Dynamics for Long Freight Trains

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Abstract

In the current logistic landscape, freight train transportation is becoming a pivotal element for fast, environmentally friendly operations. The current push toward enhancing productivity, reducing costs and achieve *green* operations require to maximize trains length and hauled mass. However, these goals introduce challenges to trains running safety due to the increase of longitudinal forces during braking and traction manoeuvres they cause. To address these critical concerns, an investigation on the longitudinal dynamics of heavy freight trains becomes fundamental.
This paper introduces a new software framework designed to simulate and assess the longitudinal dynamics of various freight trains. The software employs a self-assembly logic, thus enabling the construction of entire trainsets with minimal input data from the user on component characteristics.
The versatility of this tool is fundamental for optimization purposes, where changes to variables such as the wagon number, train payload distribution and braking characteristics are essential. By presenting this innovative software suite, this work aims at contributing to advance the understanding of freight train dynamics.
The software suite is then utilized to solve an optimization problem regarding the best positioning of a second locomotive on long freight trains: its results are found to be in accordance with the current literature.

Keywords: longitudinal dynamics, freight trains, optimization, longitudinal compressive forces, longitudinal tensile forces, double traction

1 Introduction

The environmental and logistical significance of railway transportation is pivotal in the current freight landscape in Europe. Rail transportation has the potential to dramatically decrease the footprint of logistics and enhance the throughput of goods. To achieve this goal, a better utilization of the available infrastructure is required, in turn demanding for the introduction of longer, heavier freight trains. However, heavier trains often require the presence of a second locomotive to deliver the required tractive effort. The placement of a second locomotive is not a straightforward task, since it influences the tensile and compressive forces acting on the whole length of the trainset and can, in certain limit scenarios, even cause couplers to fail or vehicles to derail [1]. Moreover, longer trains may pose higher stresses on their drivers, thus requiring additional training and technological aid [2].

A set of optimal solutions for the placement of the second locomotive can be obtained using longitudinal simulation of train dynamics [3]. These tools allow to predict the maximum compressive and tensile forces developed by the couplers during operations. An example of the application of this procedure can be found in [4]: here, statistically significant populations of freight trains are tested during braking manoeuvres, finding that that the best position for a second locomotive to minimize longitudinal compressive and tensile forces is roughly at two thirds of the trainsets. A similar approach is followed in [5]: a statistically significant set of trains, each having a different payload distribution, is generated and the order of vehicles is optimized with the aim of minimizing longitudinal forces during a brake application manoeuvre. However, fewer studies have been made regarding the investigation of the best locomotive position for reducing in-train forces during an acceleration manoeuvre.
Several software for longitudinal train dynamics analysis have been developed [6,7]: however, the approach highlighted in [8] is followed in this work. A library of several sub-models which can be assembled to create the model of a trainset is created. This library allows the generation of a statistically significant set of trains, which are then used to assess the best placement of a second locomotive along their length in order to minimize in-train forces.

2 Methodology

The methodology used for this work is based on the simulation of longitudinal dynamic of a freight train via a Simulink toolbox. Simulink simplifies the visual representation of system components and their interactions through its user-friendly graphical interface. The main objectives of the simulation are to model the braking and traction systems, the connection between wagon as well as the exchange traction and braking force. The wheel-rail interaction and the adherence are also introduced in the model.

A fundamental aspect of the system design is its modularity, meaning the customization and adaptability of the model. To achieve this, the use of a comprehensive input file containing all the necessary information for the composition of the model is accomplished. A trainset model is then created and assembled starting from a library of sub-models: each of them represents a specific component of the train, being it a coupler, a locomotive or a wagon. This approach facilitates iteration and optimization of the model, enabling more efficient design and better understanding of system dynamics. Moreover, it allows the future implementation of *Hardware in the Loop* or HiL components within the simulation environment. This feature broadens the application range of this methodology and allows for more precise results by accurately replicating the authentic behaviour of specific components.

A general representation of the model layout is given in Figure 1. The assembly process followed in this work, as well as a description of the main components, is given in the following paragraphs.

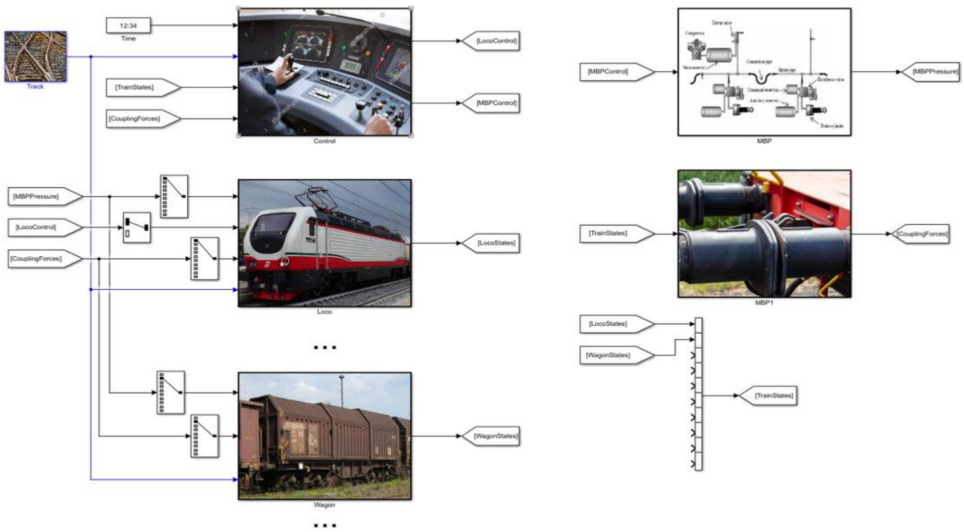

Figure 1: General architecture of the Simulink model.

2.1 Self-assembling model

The creation and assembly of the various sub-models which compose the trainset model are performed by means of automatic programming through MATLAB scripts. This aims at providing enhanced flexibility, control, and reproducibility, as well as an easy reconfiguration of the sub-models when assembling trainset with different characteristics. Moreover, this approach facilitates iteration and optimization of the model.

The convoy is implemented using a struct data structure, which will contain all the information related to each vehicle within the convoy. This structure includes essential data such as mass, inertia, geometry, suspensions, and other relevant features. Through an automated process, this input file is processed to assemble the corresponding Simulink model, while allowing customization of various system blocks. The approach of using a single input file offers numerous advantages in terms of flexibility and ease of model customization. Users can easily modify system parameters and configurations by simply updating the input file, without the need to make direct changes to the Simulink model. This greatly simplifies the process of adapting the system to specific requirements or variations.

2.2 Locomotive: architecture of the sub-model

The locomotive model is developed using the MATLAB-Simulink environment and all the vehicle characteristics are listed in the input file. A generalized architecture of the locomotive speed control model, used to evaluate the traction and braking forces of the total vehicle has been showed in Figure 2.

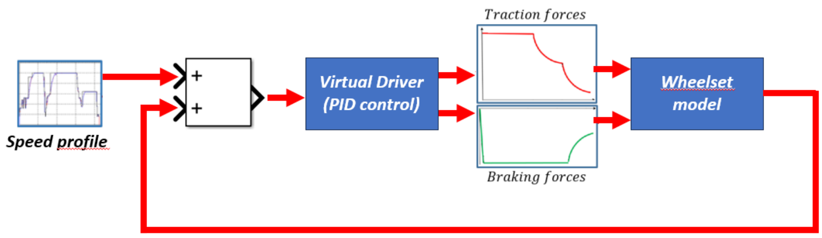

Figure 2: Locomotive speed control architecture.

More in detail, the locomotive dynamic algorithm is fundamentally based on a specific velocity mission profile (alternatively, the mission profile can be calculated within the model considering the vehicle timetable) and, through the comparison with the current velocity of the vehicle, a virtual driver model based on a PID control regulates the traction or braking requests in order to respect the imposed velocity mission profile. The calculation of the train motion takes into account both traction and braking forces and various resistant loads.

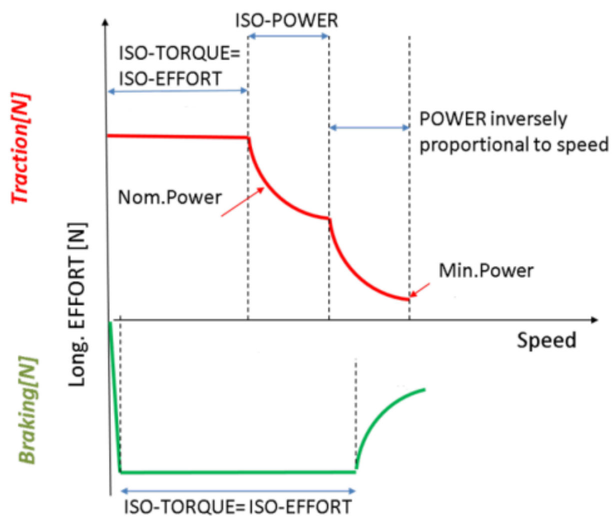

Figure 3: Vehicle traction and braking curve.

The traction creep forces are calculated for each wheelset independently using the classic Polach tangential model [9] that combines numerical efficiency and precision. More in detail, starting from the vertical load on each wheelset (in the 1D model the vertical load on each wheelset is calculated starting from the total locomotive mass which is then distributed over the four wheelset equally as in static conditions) it is possible to use the Hertz Theory [10] to evaluate the size of the contact patch semi-axis as function of the wheel and rail material and geometrical characteristics.

At the current stage of the modelling process, starting from the output of the Hertz model and the angular and longitudinal velocities of each wheelset it is possible to evaluate the creep forces on each wheel-rail contact patch as function of the tangential stress gradient, according to Polach theory, as shown in Equation 1.

$$F = -\frac{2Qf}{\pi}\left(\frac{\varepsilon}{1+\varepsilon^2} + \tan^{-1}\varepsilon\right) \tag{1}$$

where Q is the vertical load, f is the friction coefficient and ε is the gradient of the tangential stress in the area of adhesion and it has been calculated as follow:

$$\varepsilon = \frac{2}{3}\frac{C\pi a^2 b}{Qf} \cdot s \tag{2}$$

with a and b that represents the semi-axis of the contact patch, s which is the creep and C which represents the proportionality coefficient characterising the contact elasticity.

Furthermore, traction and braking efforts are exchanged between vehicle and track at the wheel/rail interface, and it is fundamental to consider the available adherence, which depends on different parameters, such as the vehicle speed. From the other side, starting from the real traction curve of each electric motor it is possible to evaluate the traction torque applied on the wheelset axle and then by also knowing the creep force it is possible to evaluate the angular acceleration and velocity (by means of the time integration block in Simulink) of each wheelset. The longitudinal dynamic equilibrium of the resistance, traction, braking and coupling forces are then used to compute the total forces acting on the locomotive, which can be in turn divided by the mass (that is the equivalent inertia mass and includes also the contribution of rotating masses as wheelsets, motors and transmission systems) to obtain its instantaneous acceleration. Finally, by using time integration Simulink blocks it is even possible to evaluate the longitudinal velocity and the position along the prescribed track of the vehicle.

2.3 Wagons: architecture of the sub-model

From the point of view of the wagons sub-model architecture, each wagon characteristics are listed in the input file. Furthermore, each wagon sub-model, based on its position along the input track and velocity, can compute all the resistance values (gradient resistance, curve resistance, aerodynamic and friction losses, …).
The dynamic equilibrium of the resistance, braking and coupling forces are then used to compute the total forces acting on the vehicle, which can be in turn divided by the mass to obtain its instantaneous acceleration and hence its subsequent speed and position. A reference diagram of all the forces acting on each wagon is depicted in Figure 4.

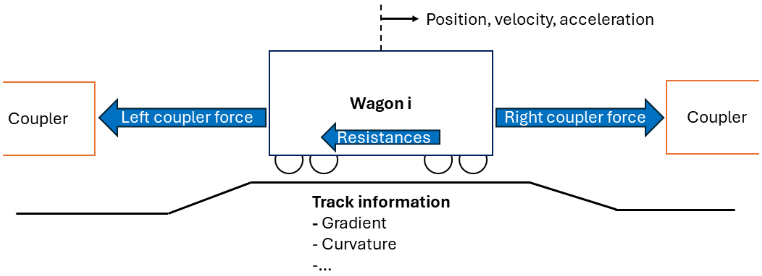

Figure 4: Forces acting on a single wagon.

The payload carried by each wagon can be adjusted based on the input file: it contains a vector containing percentages of the maximum payload capacity of the whole train. Each wagon block then computes its own total adhesive mass, which is used for all dynamic computations. This approach allows to deal with simulations involving several identical vehicles with different payloads, a typical situation in railway operations. At the current stage of the modelling process, a relatively simplified braking system has been implemented in each wagon model. At first, the dynamics of the braking pipe is solved off-line on a separate, dedicated solver. The time series of the brake cylinders' pressures is then used to compute the braking force on each vehicle.

2.4 Couplers: architecture of the sub-model

The coupling system introduced in the Simulink model reproduces the complete rheological behaviour of the typical freight train buffers and hook: a general scheme of the coupling elements is represented in Figure 5. Each coupler sub-model takes the relative displacement and velocity of its adjacent vehicles and uses these data to compute the coupling force acting on them.

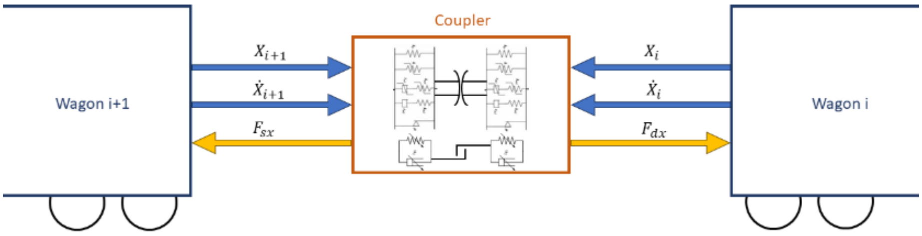

Figure 5: General scheme of the couplers.

The force generated by the coupler is computed as the sum of the forces developed by the two buffers and the central hook. The hook is modelled as a nonlinear spring in parallel with a nonlinear dampener. The general scheme of the two buffers is based on the work of Cheli and Melzi in [11]: here, the buffer is modelled as the sum described in Equation 3:

$$F_b = F_p + F_s + F_{m,1} + F_{m,2} + F_f \qquad (3)$$

In this equation, the term F_p represents the contribution of the buffer's linear spring, the two terms $F_{m,1}$ and $F_{m,2}$ consider the effects of two Maxwell elements, the term F_p represents the buffer's preload and the term F_f represents the contribution of the internal buffer friction. This model allows to better reproduce the buffer's dynamic behaviour. Finally, the effects of preload or slack can also be added to the couplers.

Case study

Due to its versatility, the proposed methodology can be employed in different scenarios. The scope of this work is to use it to optimize the position of the second locomotive on long freight trains in order to minimize traction force in acceleration.
To do so, a set of 500 trainset having different characteristics is generated. Each trainset is composed by two E402B locomotives (commonly employed in Italian railways for freight transport) and several SGMNSS railcar, each of them having a random payload so that the trainset reaches either the maximum allowed mass (2500 t) or the maximum allowed length (750 m). This dataset can therefore be assumed as a statistical representation of the possible spectrum of trainsets which will normally circulate on European railways. The following tables recall the main parameters of both locomotives and SGMNSS cars.

Variable	**Value**	**Unit of Measurement**
Mass	88080	Kg
Length	19.42	m
Maximum speed	220	Km/h
Maximum traction effort	265	kN

Table 1: principal characteristics of the E402B Locomotive.

Variable	Value	Unit of Measurement
Maximum payload	73500	Kg
Tare mass	16500	kg
Length	17.25	m

Table 2: principal characteristics of the SGMNSS Wagon.

For the first iteration of the simulation cycle, both locomotives are placed at the train head. The Simulink model of each trainset is generated and is commanded to start from a standstill with an acceleration of 0.1 m/s^2 for a time of 40 seconds. After each simulation, the maximum tensile and compressive force acting on the whole trainset are recorded and used as a baseline.

Then, for each of the 500 trainsets comprising the dataset, a set of different simulations is generated: on each of them the second locomotive is moved along the convoy until it is at the very bottom of it, the whole train acting in a push-pull configuration. A representation of the iterative process can be appreciated in Figure 6.

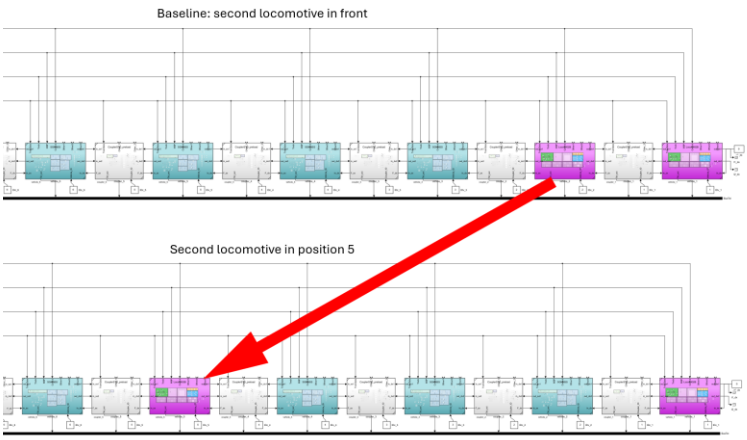

Figure 6: A detail on the second locomotive placement iterative process.

For each configuration, the parameters $f_{max,i}$ and $f_{min,i}$ are then computed as follows:

$$f_{max,i} = \frac{F_{max,i}}{F_{max,2}} \tag{4}$$

$$f_{min,i} = -\frac{F_{min,i}}{F_{max,2}} \tag{5}$$

Where $F_{max,i}$ is the maximum tensile force recorded in the simulation having the second locomotive in the i-th position, $F_{min,i}$ is the maximum compressive recorded in the simulation having the second locomotive in the i-th position and $F_{max,2}$ is the maximum tensile forces recorded in the simulation having the second locomotive immediately after the first one, i.e. in the second position. This allows both the maximum and minimum forces to be scaled with respect to a single value, which is in turn representative of the traction effort required to move every trainset. Moreover, the sum of $f_{max,i}$ and $f_{min,i}$ can be used to obtain an estimation of the total amount of forces being applied to the trainset.

Results

Figure 7 represents the behaviour of the indexes $f_{max,i}$ and $f_{min,i}$ with respect to the position of the second locomotive along the trainset. It is possible to appreciate how all the trainset exhibit a similar behaviour, but a better insight into the variation of the force ratios can be analysed by averaging the results of the 500 simulation sets and computing their standard deviation.

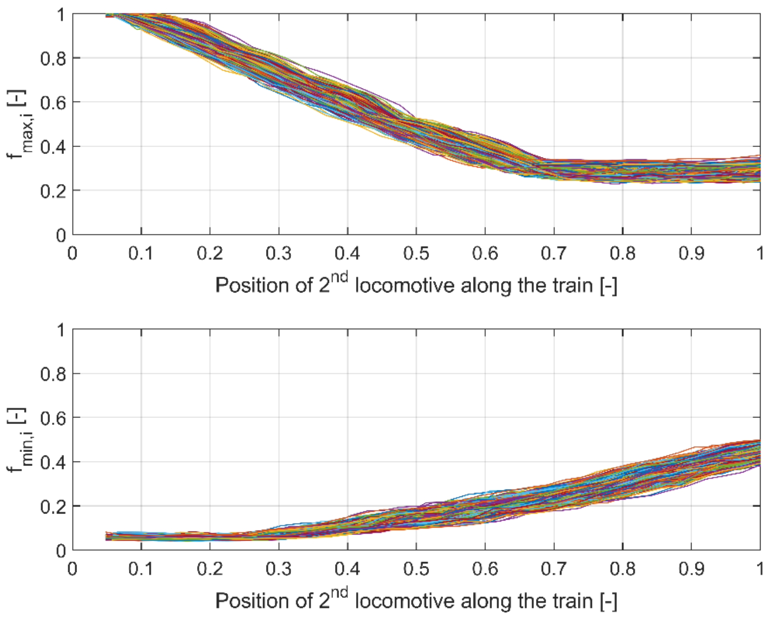

Figure 7: Behaviour of the maximum and minimum force ratio for the trainset under analysis.

The average value of the indexes $f_{max,i}$ and $f_{min,i}$ depicted in Figure 8 reveal a clear trend: the tensile force ratio reaches a plateau value of 0.3 when the locomotive is approximately ad two thirds of the train; after this position, it slightly increases again. The compressive force ratio instead steadily increases with the position of the second locomotive, reaching a maximum when the locomotive is at the back of the train. Its maximum value is 0.45, therefore lower than the maximum tensile force ratio. However, larger compressive forces pose a derailment threat for long freight trains: a minimization of both compressive and tensile forces is therefore the best possible scenario.

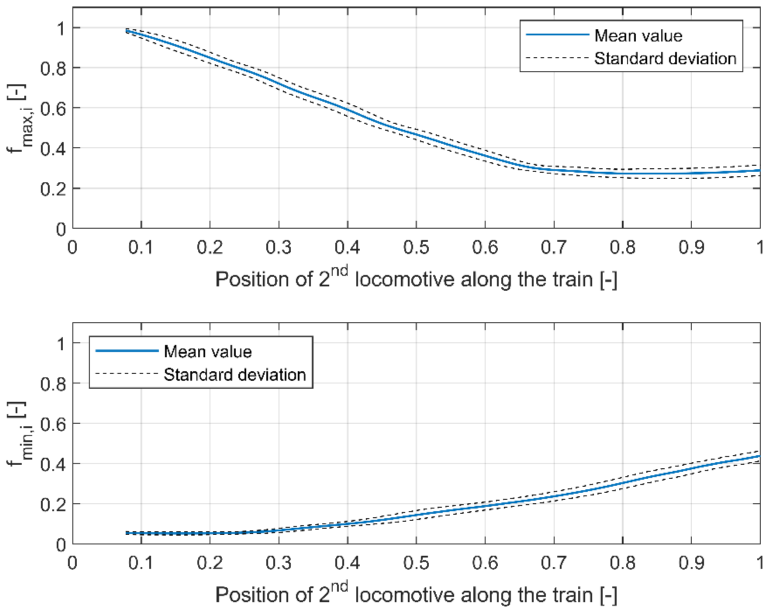

Figure 8: Mean force ratios and their standard deviation.

In order to obtain a single index which represents both the behaviour compressive and tensile forces, the value of indexes $f_{max,i} + f_{min,i}$ is plotted against the position of the second locomotive. Figure 9 represents its behaviour. Its minimum value is found when the second locomotive is at two thirds of the train: here, it is possible to minimize both tensile and compressive forces acting on the couplers, relieving the highest number of coupler and ensuring a smooth train starting.
Moreover, this value is coherent with the best placement for the second locomotive found in [1, 2, 4]: this generalises the optimality of this trainset architecture.

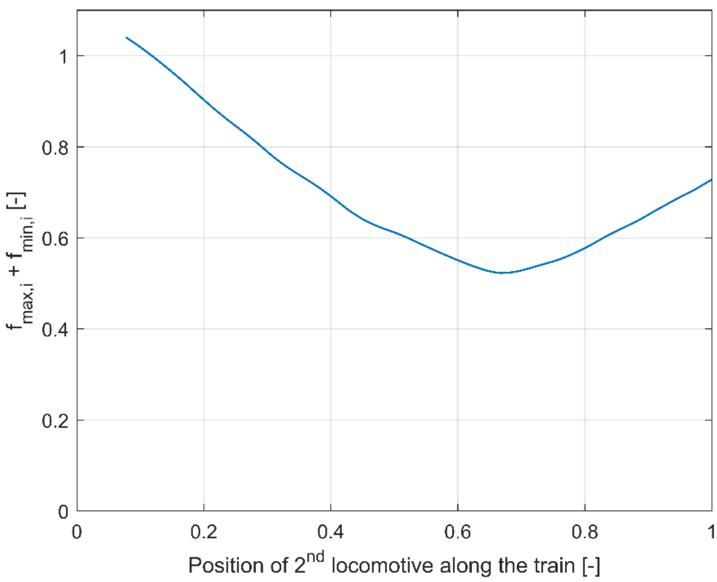

Figure 9: Sum of the two force ratios.

Conclusions

In this work, an innovative methodology for the simulation of longitudinal train dynamics of freight trains is introduced. This framework is based on the Simulink environment and can generate and simulate several trainset configurations. This methodology is used to investigate the behaviour of a statistically significant population of freight trains, with the goal of assessing the best position of a second locomotive to minimize coupling forces during acceleration. A set of indexes for the description of the maximum tensile and compressive force ratios acting on the trainsets are derived and uses with the aim of finding the best-case scenario. After analysing the results for the whole population, the best position for the second locomotive is found to be at two thirds of the trainset. This result is coherent with the literature examples which address the issue of minimizing coupling forces during braking manoeuvres, thus extending its generality.

References

[1] Cole, C.: Longitudinal Train Dynamics, Taylor and Francis, 2006

[2] Van Der Meulen, D.: Development of Train Handling Techniques for 200 Car Trains on the Ermelo-Richards Bay Line, 4th IHHA Railway Conference, Brisbane, Australia, 11-15 September 1989, Page 574-578

[3] Wu Q. and Spiryagin M. and Cole C. (2016): Longitudinal train dynamics: an overview, Vehicle System Dynamics, 54:12, 1688-1714

[4] Krishna, V. and Jobstfinke, D. and Melzi, S. and Berg, M.: An integrated numerical framework to investigate the running safety of overlong freight trains, Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit, Vol. 235(1) 47–60 (2021)

[5] Di Gialleonardo, E. and Melzi, S. and Trevisi, D. (2022): Freight trains for intermodal transportation: optimisation of payload distribution for reducing longitudinal coupling forces, Vehicle System Dynamics

[6] Spiryagin, M. and Wu, Q. and Cole, C. (2017) International benchmarking of longitudinal train dynamics simulators: benchmarking questions, Vehicle System Dynamics, 55:4, 450-463,

[7] Wu, Q. and Spiryagin, M. and Cole, C. and Chang, C. and Guo, G. and Sakalo, A. and Wei, W. and Zhao, X. and Burgelman, N. and Wiersma, P. and Chollet, H. and Sebes, M. and Shamdani, A. and Melzi, S. and Cheli, F. and Di Gialleonardo, E. and Bosso, N. and Zampieri, N. and Luo, S. and Wu, H. and Kaza, G. (2018) International benchmarking of longitudinal train dynamics simulators: results, Vehicle System Dynamics, 56:3, 343-365

[8] Pugi L, Malvezzi M, Allotta B, Banchi L, Presciani P.: A parametric library for the simulation of a Union Internationale des Chemins de Fer (UIC) pneumatic braking system. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2004;218(2):117-132.

[9] Polach, O.: A Fast Wheel-Rail Forces Calculation Computer Code. Proc. Of the 16° IAVSD Symposium, Pretoria, August 1999, Vehicle System Dynamics Supplement 33 (1999), pp. 728-739 (era 1)

[10] Hertz. H.: The contact of elastic solids, Journal fur Die Reine und Angewandte Mathematik 92 (1881) 156-171

[11] Cheli, F. and Melzi, S.: Experimental characterization and modelling of a side buffer for freight trains, Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit 1(F6):1-12 (2010)