Study of longitudinal dynamics in the case of a train which does not have all the vehicles with active brake

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Abstract. The paper represents a small part of the studies conducted by the authors in the field of longitudinal dynamic phenomena developed in the body of the braked train. The aim of the study in this paper is to evaluate the effect of train composition on the maximum longitudinal forces magnitude and distribution along the train. The particular cases considered are those of trains that have vehicles running with isolated brake (i.e. not able to brake). For the simulations, a freight train consisting of 20 identical vehicles was originally used, followed by a classical train - locomotive and identical wagons, the total number of vehicles remaining the same. For each train formation, there are several scenarios regarding the positioning of the vehicles without brake in its body, scenarios that take into account the national regulations in force or the possible failures in service. A special case is represented by a possible failure of the locomotive braking system and the train movement under these conditions to a point where the problem can be remedied.

1. Introduction

With the arrival of the first railway vehicles and their coupling to form trains, there has been a need to realize and develop a braking system that can stop the train at a fixed point, reduce running speed and allow imposed speeds to be maintained on the slopes without endangering the traffic safety. The problem has been solved by using the indirect brake with compressed air as the basic brake on these vehicles, which is known in the literature as the UIC (International Union of Railways) type brake.

The development of rail transport has led to the modification of this brake system so that it can meet the high-speed traffic requirements for passengers’ transport - the brake acting as a fast-acting brake or the P-type brake, but also for very high tonnage, in the case of freight transport and at a slightly lower speed than in the previous case - known as slow-running brake or the M-type brake. It should be noted that the P-mode or M-mode functioning of the braking system is achieved by switching the mode switch of the single installation from one position to another (e.g., from P in M).

At present, worldwide, the existence of a basic brake on each railway vehicle is regulated by the U.I.C. leaflet no. 540 [1] this being the indirect air brake, which, by its operating mode, is an automatic brake. This brake system, although relatively simple in terms of construction, can safely stop the train, especially if accidental breakage occurs. However, during the braking process there is a sequence of mechanical, pneumatic and thermal phenomena at the level of each vehicle in the train, carried out with different intensities [2]. A major disadvantage of this braking process is given by the delay time until the braking action is encountered at the level of each vehicle in the train composition and an increase of the pressure in each brake cylinder is requested, resulting in the generation of the braking force.
This time delay between the initiation of braking of consecutive vehicles of the train leads to the formation of longitudinal dynamic forces, resulting in damaging the passengers' comfort, the integrity of the transported goods and, sometimes, even the traffic safety.

Air distributors are equipments of the brake installation, which control the value of the pressure in the brake cylinders according to the pressure drop in the train general pipe, thus the size of the braking force for each vehicle in the train. Therefore, at a certain instant, in the body of the train the vehicles in the first half started to brake while the vehicles behind the train still have no braking force or have just begun to develop it. This aspect leads to collisions between vehicles in the train body and thus to dynamic longitudinal forces. Another aspect that cannot be neglected is the length of the train, which influences, on the one hand, the length of the general pipe, with implications regarding the delay time in the development of the braking force and, on the other hand, it contributes to the increase of the towed mass with influences on the maximum values of the longitudinal forces. The effect of delaying the development of braking forces on longitudinal dynamic behavior on freight trains is approached by Nasr and Mohammadi in paper [3], concerns developed later in [4].

The occurrence, development and extinction of longitudinal dynamic phenomena occur at the level of draw-gear devices existing on each railway vehicle and without which a train cannot be composed and maintained. Problems about the modeling and study of these devices are the subjects of works such as [5, 6, 7]. Due to these longitudinal forces, in the operation of railway vehicles, breaks of the traction devices are noticed, which were attributed to the large traction forces occurring during the start-up period.

Through this work, as a continuation of studies in the field of longitudinal dynamics, we propose to analytically analyze whether the isolation of the brake for a certain number of vehicles from the composition of the freight trains leads to a supplementary load of the forces on the traction devices against the normal loads due to braking.

2. Theoretical considerations
In order to establish the mechanical model of the railway vehicle that is part of the train, based on which the motion equations for each vehicle will be written and solved, it should be mentioned that the Romanian Railways vehicles are equipped with buffer and draw-gear devices, manual coupling with screw and traction hook type, and the buffers to mitigate the collision. This aspect is somewhat different to the global study model, where vehicles are equipped with automatic couplings. A study of the mathematical models of the buffer and draw-gear devices used throughout the world was conducted and presented by Q. Wu, C. Cole et al. in the paper [5].

2.1. Collision devices
Ever since the Ringfeder® ring friction springs were introduced in 1900, they have proven to be a solution in absorbing the shocks between two masses in relative motion. These types of springs (see figure 1) are widely used in areas such as: railway transport, aeronautics, rolling mills, vibration isolators for electrical substations, etc. [8].

![Friction springs rings][1]

Figure 1. Friction springs rings [8].

In the railway field, these springs are used as elastic and damping elements for collision devices. Under high-speed and high transport (high tonnage) traffic conditions, the kinetic energy developed by the mass of the vehicles in motion is very high.

Thus, the forces developed between the components of a train will act on the buffer and draw-gear devices and will be transmitted through the chassis along it. These forces can reach, under certain conditions, important magnitudes, becoming dangerous from the point of view of traffic safety.
The deformation force of the buffer depends on the relative displacement between the two vehicles, the relative speed between them, the elasticity coefficient and the damping ratio.

The characteristic diagrams highlight this through the surface area between the loading and unloading curves of the Ringfeder® spring.

The determination of forces on draw-gear devices can be done, as we presented in the paper [4] using the formula:

$$ F_{dl,i}(x_i, \dot{x}_i) = \frac{1}{2} \left[ (1 - \text{sgn}(x_i) \cdot (k_e x_i + k_f \dot{x}_i) \cdot \tanh(u \cdot \dot{x}_i)) 
+ (1 + \text{sgn}(x_i) \cdot (k_{ec} x_i + k_{fc} \dot{x}_i) \cdot \tanh(u \cdot \dot{x}_i)) \right] $$

(1)

where $x$ is the stroke, $\dot{x}$ the speed of such devices, $k_e$ and $k_{ec}$ represent specific constants for elastic and friction forces that develop in the traction device, $k_f$ and $k_{fc}$ - specific constants for elastic and friction forces that develop in the collision device, and $u$ is a scaling factor.

2.2. The vehicle model

Since it is a train, as we have already presented in other occasions [4, 9-12] the model used in the calculation programme is formed of $n$ rigid bodies, representing the vehicles in the train composition, bound between them through elastic and damping elements that represents the draw-gear devices. These models are found in the majority of studies of this kind, worldwide [2, 5, 7].

![Figure 2. Forces acting on a vehicle.](image)

For any vehicle in train composition (except the first and the last vehicle) forces that act are: forces of inertia $I_i$ , braking forces $F_{bi}(t)$, resistances to motion $R_i(v(t))$ and forces from buffer and draw-gear devices (from the front vehicle $F_{i-1}(\Delta x_{i-1}, \Delta \dot{x}_{i-1})$, and from the rear vehicle $F_i(\Delta x_i, \Delta \dot{x}_i)$), for $i = 1, n$, where $\Delta x_i = x_i - x_{i+1}$ represents the relative motion from buffer and draw-gear devices (see figure 2).

For the first vehicle there are no forces on buffer and draw-gear devices found in front of the train, but only on those that enter in contact with the next vehicle in the train, and to the last vehicle there are no forces on buffer and draw-gear devices from the back of the train.

Thus, applying the laws of mechanics, $n-1$ nonlinear equations are obtained, each describing the motion between two consecutive vehicles.

For a vehicle $i$ it will be [4, 9, 10]:

$$ \ddot{y}_i = \frac{F_i(y_i, \dot{y}_i) - F_{i+1}(y_{i+1}, \dot{y}_{i+1}) + F_{f,i+1}(t) + R_{i+1}(v(t))}{m_{i+1}} + $$

$$ + \frac{F_i(y_i, \dot{y}_i) - F_{i-1}(y_{i-1}, \dot{y}_{i-1}) - F_{f,i}(t) - R_i(v(t))}{m_i} $$

(2)

It is specified that, in order to simplify the above equations, the notation $y_i = \Delta x_i$ was introduced.

2.3. Resistance to motion and braking force

Taking into consideration the vehicle $i$, the resistance to motion is determined by formula [11]:

...
where $r_{vi}$ represents the specific resistance to motion, and $g$ – the gravitational acceleration. It should be specified that the resistance to motion is a characteristic specific for each type of vehicle, which is calculated using empirical formulas, as follows [4, 11]:

- for freight wagons of the usual type: $r_v = 2 + \frac{V^2(t)}{1950}$ [N/kN];
- for electric locomotives: $r_v = \frac{1}{120} \left[ 296 \cdot 7,068 \left( \frac{V(t)}{10} \right)^2 \right]$ [N/kN]

where the vehicle speed is considered in km/h.

In order to calculate the maximum braking force developed by each vehicle, it must be ensured that the axles locked during the braking actions are not obstructed, so that the adhesion force between the wheel and the rail must not be exceeded during braking. Thus, in the program the calculated braking force will be [4, 9, 10, 11, 12]:

$$F_{fj}(t) = \mu_a \cdot m_i \cdot g \cdot \frac{p_{cfj}(t)}{p_{cfj max}}$$ [N]

where $\mu_a$ is the wheel-rail adhesion coefficient, $m_i$ represents the mass of each vehicle in the train body, $p_{cfj}(t)$ is the evolution in time of the pressure in the brake cylinder, determined experimentally on the bench of the Railway Vehicles Department, and $p_{cfj max}$ is the maximum set pressure.

3. Numerical application

For the simulations, a freight train consisting of 20 identical vehicles is initially adopted, then is considered a classical train - locomotive and identical wagons, the total number of vehicles remaining constant.

For the two cases of composition of the trains presented, the locomotive is considered to have a mass of 120 t and for the maximum weight of the wagons (including the load) it is considered the value of 65 t, representing a usual value in the freight transport.

The main parameters used are [11]:
- for buffers, the constant that depends on the elastic elements has the value $k_e = 4.1 \cdot 10^6$ N/m and the one depending on the friction force $k_f = 2.1 \cdot 10^6$ N/m;
- for the traction and coupling devices (mechanical coupling and traction hook), the constant that depends on the elastic elements is $k_{ec} = 5.46 \cdot 10^6$ N/m and for the friction force is $k_{fc} = 2.43 \cdot 10^7$ N/m;
- value of the scaling factor $u = 10^4$ [11].

For each train composition are carried out several scenarios regarding the positioning of non-braking vehicles in its body, a scenario that takes into account the national regulations in force, or which takes into account possible defects in service. A special case is represented by a possible failure of the locomotive braking system and the movement of the entire train to the point where the problem can be remedied. In the MATLAB built-in simulation program, the train is subjected to a rapid braking action from a maximum speed of 100 km/h, on a straight and horizontal track.

4. Results and discussion

The cases presented above have been based on national regulations which accept the following situations in the composition of a freight train: "between two vehicles with automatic brake systems, there shall be no groups of wagons with passage only, with a greater than:
- 12 axles (3 wagons) immediately after locomotives,
- 4 axles (1 wagon) ahead of the last three wagons in the train that must have the active automatic brake.

The malfunction of the locomotive braking system is also regulated, and if all the vehicles in the train have the active brake system it can run with the locomotive brake isolated to the first point where the problem is fixed, or the locomotive is replaced.

Running the simulation program in MATLAB were obtained the results presented for the two train compositions and the three cases considered for each in figures 3 ... 6.

![Figure 3](image1.png)  
**Figure 3.** Maximum forces distribution on buffers for the trainset – no locomotive.

![Figure 4](image2.png)  
**Figure 4.** Maximum forces distribution on the traction hooks for the trainset - no locomotive.

![Figure 5](image3.png)  
**Figure 5.** Maximum forces distribution on buffers for classical train – with locomotive.

![Figure 6](image4.png)  
**Figure 6.** Maximum forces distribution on the traction hooks for classical train -with locomotive.

Analysing the distribution of maximum forces demanding vehicle buffers, it is noticeable that the introduction of locomotives as additional mass (about 2 wagons) at the end of the train leads to a significant increase in maximum compression forces. This is illustrated in figures 3 and 4, the blue curves - all brakes, where the maximum compression force obtained at about half of the train increases by more than 10 kN.

Another important aspect highlighted is the significant decrease in compression forces when the body of the train is a vehicle that does not brake. When the first vehicle (which may be the locomotive) does not brake, it is noticeable that the buffers from the first vehicles are practically not subjected to compression, instead the traction couplings are strongly loaded. The most unfavourable case is obviously the lack of braking force on the group of three vehicles located in the train immediately after the locomotive.

The analysis of Figures 5 and 6 shows that stretching forces curves, although they keep the same aspect in both classical train and trainset situations, show great increases in the classic train case. Obviously, the worst case is when the first three vehicles after locomotives are running with the isolated brake.
However, in both situations, although there are regulations that allow train operation in these conditions, we recommend avoiding it as much as possible to protect the traction and coupling devices that are extremely loaded in the traction mode and should not be subjected to considerable force up to 140 kN in braking mode. The occurrence of cracks or even breakages of traction devices can be explained by the fact that, in addition to the traction mode, these devices are loaded during braking, the train stopping practically by stretching the traction hooks.

5. Conclusion
Analyzing the longitudinal dynamics of freight trains when the train is composed of vehicles that run on the isolated brake, the following conclusions can be drawn:
- if the locomotive or the first vehicle does not develop its own braking force, it is braked by the force developed by the rest of the vehicles in the train body, having the effect of loading the traction and coupling devices;
- in terms of stretching forces occurring at the level of the traction devices, two aspects are highlighted: the emergence of an instantaneous stretching force at the passage from the compression of the train to its stretch, and a stabilized stretching force that maintains the train stretched until it stops;
- the instantaneous stretching force is the one that along with the compressive force causes oscillatory phenomena in the train body;
- the most unfavorable case is obviously the lack of braking force on the group of three vehicles located in the train immediately after the locomotive.

As a result of the study, we can recommend avoiding as far as possible circulation situations with the isolated brake, which can be exempted only for the transport of dangerous products that require brake isolation.

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