About the Influence of Mass Distribution on the Dynamic Longitudinal Reactions along a Short Passenger Train during Braking Actions

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Abstract: - In the case of short classical passenger trains, due to the fact that the locomotive may represent about 15 – 35% from the total mass of the train, placed in one extremity of the system, it is to expect specific distributions and evolutions of longitudinal dynamic compression and traction forces between the vehicles during braking actions. These aspects are theoretically determined and analyzed, considering set trains and classical ones, both in pull and push operations, for usual masses of the locomotives and passenger cars.

Key-Words: - train braking actions, braking forces, longitudinal dynamic in-forces, railway vehicles mass, train set, push-pull train

1 Introduction
One of the most usual and frequent actions in railway operation, of great importance in a safety sense, the trains’ braking, is in fact an extremely complex and specific process.
The basic braking system for railway vehicles is an indirect compressed air one. For safety reasons, the brakes are released while in the general brake pipe of the train is maintained an air pressure of about 5 bar and the braking command is given through a depression generated by the driver using a mechanic’s tap. Each vehicle is equipped with an air brake distributor which modulates the air pressure in the brake cylinders according to the difference between the reference 5 bar pressure and the depression determined in the main brake pipe. Since the air depression has a finite speed of propagation, it is obvious that the air brake distributors will get the command successively along the train, depending on the constructive, functional and operating characteristics of each braking system, but being also strongly influenced by the length and composition of the train.
Consequently, at the beginning of the braking action, different braking forces are developed to the vehicles, determining dynamic longitudinal forces in the body of the train which, under various specific conditions, may reach high values and affect even the ride safety.
During the braking actions, various processes and phenomena develop. These are acting in various places of each vehicle and in the assembly of the train, with different intensities. Essential is that the effects of all these actions favorably interact in order to ensure an efficient, correct and safe braking.
Studies regarding the longitudinal dynamics of trains during braking actions are mainly focused on long, heavy freight trains, due to the more obvious effects determined by the length of the general brake pipe and the numerous big masses interconnected.
In the case of short trains, it is to notice that vehicles are equipped with rapid action air brake distributors. These determine an increasing pressure gradient in the brake cylinders of 0.7 - 1.2 bar/s, relative to 0.1 - 0.2 bar/s in the case of slow action ones used in case of long trains. During the filling time, until the commanded pressure is attained in all brake cylinders along the train, the instantaneous differences of braking forces between the vehicles of short trains are consequently bigger.
More than that, in case of classical passenger trains, the locomotive has usually at least a two times larger mass than the cars, that specific mass distribution along the short trains is expected to influence supplementary the in-forces.
That is why we consider important to evaluate theoretically and to analyze the distribution and the evolution of longitudinal dynamic compression and traction forces between the vehicles of short trains submitted to braking actions, taking into account some usual vehicles masses, connected in structures for passenger trains.
**Theoretical bases**

A classical approach for theoretical studies of the dynamic longitudinal forces developed during the braking actions along trains equipped with automated compressed-air brakes is a mechanical cascade-mass-point model in which vertical and lateral dynamics are neglected [1,2,3 etc]. Assuming that the train is composed of \( n \) vehicles, these are linked to each other by couplers, traditionally based on combined use of a draw-gear and buffers. Consequently, the model is an elastic-damped lumped system consisting in \( n \) individual rigid masses \( m_i \), representing each vehicle connected through elements having well defined elastic \( c_i \) and damping \( \rho_i \) characteristics (see fig. 1).

Generally, a certain \( i \) vehicle of the train is mainly submitted to the following exterior forces: \( F_{fi} \), the instantaneous braking force of the vehicle, \( Rn_i \), the vehicle’s normal resistance, \( Rs_i \), the supplementary resistance due mainly to the tracking slope and curvature and \( P_{c,i}, P_i \) are the in-train forces between the adjacent vehicles representing cumulated elastic and damping forces acting on the shock and traction apparatus between \( i-1 \) and \( i \), \( i \) and \( i+1 \) respectively vehicles. Considering \( x_i \) and \( x_i^\prime \) the positions and the instantaneous accelerations of the \( i \) vehicle, the motion equation is [2]:

\[
m_i \cdot x_i = - F_{fi,i} - Rn_i - Rs_i - P_{c,i+1} + P_i .
\] (1)

In the present study, we neglected the \( Rn_i \) forces considering that the relative instantaneous velocity differences between the vehicles of the train determine insignificant differences of normal resistances between the cars, especially if the vehicles are similar. We also considered that during the braking action the train is running on a straight and no curved track.

Under these conditions, the motion equations are:

\[
M \cdot \ddot{X} = - F - P_{c,i} + P_r ,
\] (2)

where \( M \) is the mass matrix, \( X \) is the state vector, \( F \) is the vector of the braking forces, \( P_{c,i} \) is the vector of the front shock and traction apparatus forces and \( P_r \) is the vector of the rear forces.

For establishing the \( P \) forces, one must consider the behavior of the coupling system which is quite complex due to the presence of many non linear phenomena like variable stiffness and damping characteristics, preload of buffers and clearance, etc. In the case of passenger trains, the vehicles are coupled to each other with no clearance between successive buffers, which are preloaded. In our study, we considered non-linear characteristics of the shock and traction apparatus and the commonly used Coulomb friction model [4]. The specific friction forces in the shock and traction apparatus depends on the relative displacement \( x \) and velocity \( v = \dot{x} \):

\[
P = \frac{[c_{nc} - \Delta c \cdot \tanh(k_{anh} v)x](1 - \psi)}{2} - \frac{[c_{nf} + \Delta c \cdot \tanh(k_{anh} v)x](1 + \psi)}{2} .
\] (3)

The index \( c \) is for the buffers, while \( t \) is for the traction apparatus and \( \psi \) is a weight function. We assumed that a negative value for \( x \) means that the apparatus is compressed and a negative value of \( v \) means that the cars tend to come closer.

The numerical model of the train submitted to a braking action was previously developed and tested by the authors [4].

Regarding the modeling of the braking forces, it is known that for railway vehicles running over 160 km/h, the classical UIC pneumatic disc brake system is compulsory.

For such braking systems, the instantaneous braking force of a certain \( i \) vehicle depends on the instantaneous relative air pressure within the brake cylinders \( p_{cf,i}(t) \):

\[
F_{fi,i}(t) = K \cdot p_{cf,i}(t) .
\] (4)

In the previous relation \( K \) is a constant depending mainly on specific parameters such as the vehicle’s brake system constructive and functional characteristics. The maximum braking forces developed by each vehicle must be within the limits of the wheel-rail adhesion forces, in respect with:

\[
F_{f,i}(t) = \frac{\mu_a \cdot m_i \cdot g}{P_{cf,\text{max}}} \cdot p_{cf,i}(t) ,
\] (5)

![Fig. 1. Mechanical model of the train.](image-url)
\( \mu_a \) denoting the wheel-rail adhesion coefficient and \( p_{cf, \text{max}} \) the maximum possible air pressure that may establish within the brake cylinders.

In order to ensure a high accuracy related to the air pressure evolution in the brake cylinder, for the evolution of \( p_{cf}(t) \) we used information directly from a complex computerized system for testing the air brake valve distributors for railway vehicles. Measurements were performed in our Railway Braking Systems Laboratory of the Faculty of Transportation, University POLITEHNICA of Bucharest.

3 Case study

As an application, we present in this paper the cases of a six identical vehicles short trains submitted to an emergency braking action started at a running speed of 180 km/h.

We considered different passenger trains’ composition, taking into account the usual possibilities, as follows:

a.) train sets consisting of 6 identical vehicles of 40…70 t;

b.) classical trains composed of an 80 or 120 t locomotive in pull operation of 5 identical passenger vehicles of 40…70 t;

c.) push-pull trains for the case of an 80 or 120 t locomotive in push operation of 5 identical passenger vehicles of 40…70 t.

It is to denote that, even if passenger trains are generally being used in pull operations, it is an obvious tendency for train combinations in pull as well as in push operations [5].

From our point of view, this is an important modification, because the locomotive used in push operations, situated at the end of the train, has a 2…3 times larger mass than the passenger cars, modifying consistently the mass distribution.

We considered that each vehicle is equipped with rapid indirect compressed air brake system with brake discs. The air brake valve distributors have the functional characteristics corresponding to 3.16 s filling times, as experimentally determined. We decided to use such a filling time, almost equal to the minimum imposed values, because our previous studies enhanced the fact that usually, longer filling times conduct to certain decreasing of the longitudinal dynamic reactions in the train body [6].

Moreover, we also took into consideration the following simplifying hypothesis:

- the initial compressions of the elastic elements of the shock and traction apparatus were neglected;
- a tight coupling within the component vehicles, as regulated for passenger trains;
- an average steady braking wave propagation speed along the train of 250 m/s, the minimum imposed regulated value.

Numerical simulations of the system with the different forces models were carried out in Matlab with the solver ode45, until numerical stability and reasonable results were reached. The relative tolerance of the solver proved to be the most important parameter for the numerical model involved and it was finally set to \( 10^{-9} \).

4 Analyze of the results

For the case of the 6 vehicles train sets, the main results regarding the evolutions of the studied dynamic longitudinal reactions developed due to an emergency braking action from 180 km/h are presented in fig. 2.

It is to notice that the evolution and distribution of in-forces along the train are similar, indifferent the masses of the identical vehicles are.

In order to appreciate the effects of different trains compositions, we referred mainly to the maximum compression, respectively traction in-forces, which have practical importance in offering an image of the maximum efforts the couplings are submitted. As pointed out in the diagrams presented in fig. 3, during the braking action, the maximum compression forces, as well as the traction ones, develop mainly in the middle of the train, between the third and the fourth vehicles of the train.

The in-forces (see fig. 4, a) have an almost linear dependence on the mass of the component vehicles of the considered train set. The maximum traction forces are always lower than the correspondent compression forces, in similar conditions. Still, they have a more considerable relative increase in respect to the relative growth of the vehicles mass (see fig. 4, b). In that latter diagram, the relative forces and masses values are related to the case of 40 t vehicles.

For the case of 6 vehicles in classical and push-pull trains, relevant results regarding the evolution of the dynamic longitudinal reactions developed between vehicles during an emergency braking action from 180 km/h are presented in fig. 5. The presented diagrams were obtained considering that the 5 passenger coaches component of the trains have a mass of 50 t each. Even a visual analyse of the diagrams may emphasize that in the case of classical trains (see fig. 5, a and b), the evolution and the distribution of the in-forces along the train are almost similar for the middle part of the train. Still, in the extremities, a heavier locomotive (120 t) determines higher values between the first two vehicles, while a lighter one (80 t) conducts to an
Increase of these reactions between the last two vehicles of the train. In the case of push-operated trains, the maximum longitudinal forces are generally higher and their distribution between the vehicles is modified (see fig. 5, c and d). The forces become more important in the second part of the train.

A better image of the comparative values and distribution of maximum forces between the component vehicles of the trains for the above presented situations is pointed out in the diagrams in fig. 6, a (maximum compression forces) and b (maximum traction forces). As a referential, each diagram contains the distribution of maximum forces for the case of a train set composed of six vehicles, 50 t each. It is to notice that the relative increase of maximum in-forces is higher in case of classical trains than in case of push-pull trains, as

**Fig. 2.** Evolution of the dynamic longitudinal reactions along a six identical vehicles train set, submitted to an emergency braking action from 180 km/h: 1 – between veh. 1 and 2; 2 – between veh. 2 and 3; 3 – between veh. 3 and 4; 4 – between veh. 5 and 5; 5 – between veh. 5 and 6.

**Fig. 3.** Distribution of maximum longitudinal reactions between the six identical vehicles trains in case of emergency braking action from 180 km/h.
shown in diagrams presented in fig. 7. For the cases presented in these diagrams, the same referential was adopted. This relative approach indicates more clearly the important increase of in-forces in the vicinity of the locomotive, having larger mass than the rest of the train’s vehicles. Also, even if in absolute values, the maximum traction forces are lower than the compression one, their relative increase in the case of classical trains is much higher in case of heavier locomotive in pull operation.

5 Conclusion
The results of our study show that the composition and mass distribution are very important for the evolution and the distribution of dynamic
Compression and traction forces acting between the vehicles of short passenger trains during braking actions. An approximate proportional relation was determined between masses and maximum in- forces, but the increase of traction forces is higher than of the compression ones. The position of the locomotive, in front or on the back of the train, determines an enhancement of dynamic longitudinal forces in the first or second half of the train.

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