Considerations on longitudinal dynamic effects of unbraked vehicle in passenger train composition – parametric study

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Abstract. The study investigates the trains’ longitudinal dynamic evolutions in certain unusual situations that may be encountered, even rarely, in railway operation. It is about the case of operating passenger trains having in composition a vehicle with isolated braking system. This is a state that, according to regulations, is generally not acceptable, but there are circumstances that can conduct to exceptions. Our purpose is to find out by numerical simulations the influence that certain parameters, such as the number of vehicles of the train, the weight of locomotive and the position of the unbraked vehicle, have on the longitudinal dynamics of passenger trains during braking actions. The numerical simulations were performed for trains in classical composition, meaning a locomotive hauling 3 up to 19 passenger vehicles, thus covering virtually all the current situations encountered in operation. In simulations there were considered all the possible placements of the unbraked vehicle within the train body. The main outcomes, submitted to a comprehensive analyse, are the maximum in-train forces and the position in long of the train of the most affected couplers by longitudinal dynamic compression (buff) and tensile (draft) forces. The time dependency of in-train forces is also discussed.

1. Introduction
Traffic safety is of paramount concern in railway operation and efficient braking systems are required to cope with the trends of increasing velocities and tonnages. The braking systems performance are expressed by braked weight or by decelerations, clearly stated by international regulations. Rules and limits are established, usually related to stopping distances that have to be respected in operation.

Even if the fact that train braking is a complex process became practically a truism, we want to remind some aspects. The main braking system still in large use on railway vehicles is the UIC pneumatic system. The commands are initiated by means of a brake controller by varying the air pressure in the brake pipe of the train, which actuate on each vehicle the specific pressure sensitive equipment that consequently establishes the necessary local pneumatic connections. In particular, braking commands are given by air pressure decrease in the brake pipe and each air distributor determines correspondent increase of pressure in the brake cylinders of the respective vehicle. The release action is commanded by increasing the pressure in the brake pipe, up to the nominal pressure, usual 5 bar, when brake cylinders are fully vented.

Given the air compressibility and the length of the braking pipe, it is a limited speed of pressure variation propagation, so the air distributors are successively actuated in long of the train. In the initial phases of the braking process, this generates differences in braking forces between the vehicles in the head and those of the tail of the train, until the desired air pressure level is attained in all cylinders. This particular process evolution determines oscillatory movements in the train body and longitudinal...
forces in couplers, forces that in specific conditions may become very high, affecting the traffic safety. This is one of the main reasons for studying the longitudinal dynamics of trains during braking actions, interest primarily manifested on freight trains, given the length and the great number of heavy and generally different types of vehicles in componece [1-7].

Passenger trains, even shorter and composed in generally of similar coaches as construction and operational characteristics, with relatively small differences between tare and maximum weight, are running with higher velocities. Consequently, higher retardation forces are required and braking systems are designed to operate to wheel/rail adhesion limits. While wheel slide protection devices are therefore specific and mandatory features for passenger vehicles. Besides their positive roles in case of impaired adhesion, by the operating mode can conduct to important differences in braking forces between the vehicles of the train and so the forces acting in couplers increase. More than that, the passenger trains are in majority hauled by locomotives with significant higher mass compared to each other vehicle of the train, meaning in fact a large inertial mass in the front of the train. Also, one must consider the passengers’ comfort, which can be affected. Such aspects generate specific behaviour on the longitudinal dynamics of the train and targeted researches are ongoing [8-12].

The existent general frame established for railway operational procedures do not exclude the occurrence, even rarely, of certain unusual situations. One of these constitute the basis of the present study, considering that besides the practical interest in evaluation the possible effects, can enhances scientific understanding of various factors that influence the braking process of passenger trains.

The actual study aims to unveil the trains’ longitudinal dynamics generated by the existence in the body of passenger trains of a vehicle having disabled its braking system. This is a state that, according to regulations, is generally not acceptable, but there are circumstances that can conduct to exceptions. Unexpected failure of a vehicle’s brake system in operation is an example. More than that, in our country at least, it was an old habit of trains conductors to avoid using the main braking system of the locomotive while the traffic safety seemed to be not jeopardised. Unfortunately, we are not very sure that this custom has definitely disappeared.

Despite the fact that, on our knowledge, without referring in any way on how the braking capacity of the trains is affected, there were not reported other undesirable effects, we consider at least interesting if not also useful to have a projection of longitudinal train dynamics in such conjuncture.

Our purpose is to investigate the influence of certain parameters on the longitudinal dynamics of passenger trains during braking actions in case that one of the vehicles cannot provide any braking force, regardless of the reason of this malfunction. Namely, in this study we focused on the number of vehicles of the train and the weight of locomotive, knowing that it represents an important concentrated mass placed in the head of the train, compared to each passenger vehicle. The main outcomes, submitted to a comprehensive analyse, are the maximum in-train forces with the correspondent arrangement of the couplers most affected by the longitudinal dynamic compression (buff) and tensile (draft) forces. The time dependency of in-train forces is also on interest.

The study is based on numerical simulations, performed for trains in classical composition, respectively a locomotive hauling 3 up to 19 passenger vehicles, thus covering virtually all the current situations encountered in operation. In simulations there were considered all the possible arrangements of the unbraked vehicle within the train body.

Because during the process the braking forces are most influential on the longitudinal dynamics of the train [3-4, 13-16], the first stage of our research was targeted on the evaluation of their effects regardless any other factors. So, train sets in uniform composition were initially considered: vehicles with identical constructive, technical and operational characteristics, also in terms of braking systems and having the same weight. In this stage, the resistances were also neglected.

Taking the results as a baseline, the next stage of our research consisted in simulations considering the trains hauled by a locomotive and, for the passenger vehicles, the same data used in the previous step of the study were maintained. In this stage, targeted on obtaining results in a larger similarity with reality, propulsion resistances were also taken into account. According to the objectives pursued, the
sets of simulations have been performed considering the usual weight of locomotives on six or four axles, currently in use for hauling passenger trains.

2. Theoretical aspects and model

Given the complexity of the braking process, it is agreed that basically, mechanical effects and the consequent response of the train are to a large extent dependent and influenced by the pneumatic features of the braking systems involved. Accordingly, theoretical approaches to longitudinal dynamics of trains during braking actions are conditioned by a suitable joint of mechanical and pneumatic models [3, 13-16, 17-20].

As mechanical perception, the train is usually considered as an elastic-damped system which consists of rigid masses – the vehicles, connected by elements that restrict their relative motion and operate specifically – the coupler assemblies composed of shock and traction devices having adequate elastic and damping characteristics, generally dependent on the relative displacement and speed between adjoining vehicles. In a multibody formalism, for a generic “i” vehicle (as part of the train), defined by the mass \( m_i \) and running with the speed \( \dot{x}_i \), the longitudinal displacement \( x_i \) is the cumulated effect of:

- braking forces \( F_{b,i} \),
- resistances \( W_i \),
- forces acting in couplers \( P_{i,i} \) and \( P_{i} \),
- and inertial force \( I_i \) (see figure 1).

The differential equation (1) describing the longitudinal movement of the vehicle is [4, 13-14, 20]:

\[
 m_i \ddot{x}_i + P_{i,i+1} - F_{b,i} - W_i - P_{i-1,i} = 0
\]

**Figure 1. Mechanical model of the train.**

Applying equation (1) to all \( n \) vehicles and considering the boundary conditions \( P_0=P_n=0 \), it results the nonlinear differential equation system of second order describing the longitudinal dynamic evolution of the mechanical model associated to the considered train in braking process. The key problem in applications consists in adequate modelling the couplers and the retardation forces, the braking and resistance respectively.

As regard the couplers, it is well known that these have very important influences on the longitudinal dynamics of the train, with running stability implications, the specific operational behaviour is very complex due to the variable stiffness-damping characteristics, hysteretic properties, preloads of elastic elements etc. The assembly has a key role in longitudinal dynamics of trains and has been approached in several ways, more or less sophisticated, targeting a viable simulation model, appropriate in such studies [7, 10, 13, 20-25].

A comprehensive review of current techniques in dynamics modelling of friction draft gears is presented in [26].

In our studies, we considered the most frequently in use system in Europe, composed of a pair of side buffers, a draft gear and a screw coupling at each front end of the vehicle. More specific, we took into consideration the typical constructive solutions of buffers and draft gears based on metallic elastic rings (RINGFEDER type), because most of the Romanian railway vehicles fleet is featured with such equipment. These are acknowledged by having particular operational force \((P_i - \text{stroke} (\Delta x_i x_{i+1} - x_i))\)
characteristics, given the presence of dry friction which determines significant differences between compressive and tensile behaviour [10-11, 24-25].

This aspect was addressed by means of relative velocity \( \Delta x_i \) between adjoined vehicles, associated to its sign. It was assumed smoothening approach of the specific discontinuities of friction forces in the elastic rings of RINGFEDER elements and the forces \( P_i \) in couplers were determined as algebraic sum of elastic and friction forces [10-12, 24]:

\[
P_i(\Delta x_i, \Delta \dot{x}_i) = \begin{cases} 
  k_s \Delta x_i + c_s |\Delta x_i| \tanh(u \Delta \dot{x}_i), & f o r \Delta x_i < 0 \\
  0, & f o r \Delta x_i = 0 \\
  k_t \Delta x_i + c_t |\Delta x_i| \tanh(u \Delta \dot{x}_i), & f o r \Delta x_i > 0 
\end{cases}
\]  

In equation (2), \( k \) and \( c \) are equivalent constants depending on the elastic and friction characteristics of metallic rings featuring the devices and \( u >> 1 \) is a scaling factor addressing the rate of \( \tanh \) function variation from near -1 to near +1, while indexes \( s \) and \( t \) make the difference between respectively the shock (buffers) and traction apparatuses of the coupling.

The retardation forces generated by the main braking system, i.e. disc brakes in the present study, have two main specificities: the maximum braking force \( F_{b,\text{max}} \) is limited by the wheel/rail adhesion force \( F_a \) and, as friction-dependent in operation, the braking force is the direct effect of the actual air pressure \( p_{BC} \) in brake cylinders of the vehicle. For a given vehicle having the mass \( m \), considering \( \mu_g = 0.33(1 + 0.011V_{\text{max}})^{-1} \) the usual wheel-rail adhesion coefficient dependency on the maximum constructive running speed \( V_{\text{max}} \) [km/h] and defining by \( \xi \) a constant term cumulating the constructive characteristics of the braking system, e.g. number and dimensions of brake cylinders, type and amplification ratio of brake riggings, resistance forces due to both the brake cylinders back spring and automatic slack adjuster devices, in mathematical expression one can define the above mentioned particularities as follow [10-12, 16]:

\[
F_{b,\text{max}} = F_a = m \mu_g 
\]  

\[
F_b = \xi \mu_D p_{BC}(p_{BC,\text{max}})^{-1} 
\]

In equation (3), \( g = 9.81 \text{ m/s}^2 \) stands for the gravitational acceleration and in (4), \( \mu_D \) is the friction coefficient between discs and pads, while \( p_{BC,\text{max}} = 3.8 \pm 0.1 \text{ bar} \) is the maximum air pressure achievable in brake cylinders according to the regulations in force.

Given the mechanics of generating and transmitting forces from the brake cylinder piston rod to brake pads [11, 16] and taking into account equations (3) and (4), the braking force is:

\[
F_b(t) = \begin{cases} 
  0 & \text{if } p_{BC}(t) < 0.4 \text{ bar, else} \\
  0.33 m g p_{BC}(t)[(1 + 0.011V_{\text{max}}) p_{BC,\text{max}}]^{-1} 
\end{cases}
\]

As regard the resistances, in theoretical approaches there are considered distinctively the propulsion resistances (permanently present while a train/vehicle is moving on a straight and horizontal), usually described on the basis of Davis’ equation, respectively the supplementary resistances (intermittent opposing forces, acting only in certain conditions, e.g. grades, curves, wind etc.) which are added algebraically when appropriate [13, 20, 27]. According to the aims of the present study, there were considered only the propulsion resistances, by means of the empirical formulations considered appropriate for the majority of Romanian rolling stock in operation [27].

Referring to the pneumatic processes effects involved by the braking process and having crucial impact on longitudinal dynamics, two essential aspects were addressed [3-4, 10, 13, 16, 19-20]: establishing the moments when air distributors successively actuate the braking system of each vehicle in long of the train and the subsequent time dependency of the air pressure evolution in the brake cylinders of each vehicle.

In particular, it was considered a constant average speed \( w_b \) for the propagation of the braking actuation air pressure wave. Assuming that the actuation of the braking system for the first vehicle in
train coincides with the braking command initiation \( t_i = 0 \), the next following moments of actuations were defined according to the length \( l_i \) and position of each of the \( n \) vehicles in train:

\[
t_{i+1} = \frac{1}{w_b} \sum_{i=1}^{n-1} l_i
\]  

(6)

As regard the time dependency of pressure in brake cylinders following the actuation moments established in equation (6), it was based on experimental data acquisition on the computerized brake system static rigs in the Laboratories of Faculty of Transport in Politehnica University of Bucharest. There were determined the filling characteristics for emergency braking actions on KE 1b air distributor, currently featuring Romanian rail vehicles. The pressure transducers have a sample rate of 0.02 s and recorded information was adequately implemented into the simulation program [10-12].

3. Numerical simulations

3.1. Assumptions and main input data

The whole frame designed for the numerical simulations was conceived to allow obtaining results as useful and relevant, consistent to the stated purpose of the study. In this respect, a small number of variable parameters considered as most influential was selected, while the effect of others was largely cancelled or at least substantially diminished by means of appropriate simplifying assumptions.

Some of the most important are listed below:
- the vehicles of the trains are identical in terms of design, dimensions, operational characteristics and weight, except the locomotives, which are consistently heavier than a passenger coach;
- the vehicles are equipped with UIC pneumatic fast acting braking system and are designed for maximum constructive velocity of 160 km/h, so they are consequently featured with disc brakes;
- the maximum braking force of each vehicle depends only on mass and constructive velocity, corresponding to the limits allowed by wheel/rail adhesion in normal conditions;
- the air distributors perform identical filling time and filling characteristic of the braking cylinders on all vehicles of the trains;
- the trains are running on a straight and horizontal track, which basically allows for the assumption that no supplementary resistances are involved, except the propulsion resistances;
- the trains are submitted to emergency braking performed at a speed equal to the maximum constructive velocity of the component vehicles;
- during the braking action, no sliding or wheelsets blocking are considered.

Aiming to cover the usual range of passenger train lengths, in our present study we performed numerical simulations for trains composed of 4 up to 20 vehicles. More than that, complying with the assumed target, the single unbraked vehicle was considered to be placed successively in all the possible positions in the train body. That means that for each train having \( n \) vehicles in composition, there were carried out \( n+1 \) simulations, including the normal operating situation, respectively of all the vehicles develop braking force. The latter case was considered in order to constitute a referential to which the other situations to be compared.

Our study is presenting three complete sets of simulations. In order to highlight primarily the direct influence of braking forces, the first set were performed for train sets in uniform composition (of identical vehicles), neglecting the resistances. The other two are focused on “classical” trains, hauled by a locomotive, as usually encountered on large scale in operation. In these cases, targeting for implementing a much closer to reality mechanical model of the train in the simulation program, the forward resistances were also considered.

Given the specific of passenger trains, respectively to be pulled by locomotives constituting important concentrated mass, on longitudinal dynamics prospective, the study is extended also on the differences induced by different weights of the traction vehicle. Simulations were performed for the case of four axles locomotives (usual), but also considering six axles locomotives, as mostly in operation on Romanian railways. As additional assumption stands in these stages identical forward resistance of the locomotives.
The most significant input data for the numerical simulations are listed below:
- the length of each vehicle \( l = 25 \text{ m} \);
- mass of passenger vehicle 50 t, mass of locomotives 80, respectively 120 t;
- filling time of brake cylinders 3 s and maximum air pressure within \( p_{\text{BC, max}} = 3.83 \text{ bar} \);
- train velocity at emergency braking command 160 km/h;
- average propagation speed of braking actuation in long of the train’s brake pipe \( v_{\text{BC}} = 250 \text{ m/s} \).

The coefficients applied in equation (2) for buffers and traction gears, determined on the basis of the characteristic diagrams of RINGFEDER-type buffers built in Romania by ICPVSA for trailed passenger vehicles [28] and compliant to international prescriptions are presented in table 1.

| Buffer       | Traction gear | Scaling factor |
|--------------|---------------|----------------|
| \( k_s \) [N/m] | \( c_s \) [N/m] | \( k_t \) [N/m] | \( c_t \) [N/m] | \( u \) |
| \( 2.8 \cdot 10^6 \) | \( 2.8 \cdot 10^6 \) | \( 5.46 \cdot 10^6 \) | \( 2.43 \cdot 10^6 \) | \( 10^4 \) |

It is to mention that in this research, the duration of the simulated processes was set to the first 10 s following the emergency braking command. All simulations carried out in preparing this study indicated that the most important effects occur during this time slot, after which there is a continuous and almost constant decrease of the forces and until the complete stop of the train, meanwhile the oscillations in train body are rapidly vanished.

3.2. Results

According to the aims of the study, the interest was focused mainly on the peak in-train forces in couplers and on the diagrams describing the time-dependency evolution of the longitudinal forces in the train body during the braking actions.

It is to mention that buff forces are considered positives, while the draft ones are negatives, as usual in such simulations.

By following the scheduled frame for the numerical simulations, it was obtained a very large volume of results.

As regard the level of highest buff and draft forces in couplers, the results are presented in summarized manner, distinctly for each of the three complete sets of simulations.

For the case of train sets, the maximum in-train forces in couplers for emergency braking in normal operational conditions, respectively for the situation of the existence of one vehicle with inactive braking system, are presented in table 2.

| Number of vehicles in train set | All vehicles braked | 1 vehicle unbraked |
|-------------------------------|---------------------|-------------------|
|                               | Buff [kN] | Draft [kN] | Buff [kN] | Position of unbraked veh.\(^a\) | Draft [kN] | Position of unbraked veh.\(^a\) |
| 1                             | 16.0     | -4.7      | 44.1      | 3-\( \square \) | -73.5     | \( \square \)-3 |
| 6                             | 28.7     | -13.6     | 49.4      | 5-\( \square \) | -89.7     | \( \square \)-5 |
| 8                             | 44.3     | -25.1     | 55.0      | 4-\( \square \)-3 | -100.1    | \( \square \)-7 |
| 10                            | 66.2     | -39.9     | 77.8      | 6-\( \square \)-3 | -106.9    | \( \square \)-9 |
| 12                            | 88.1     | -59.9     | 100.1     | 8-\( \square \)-3 | -121.1    | 2-\( \square \)-9 |
| 14                            | 114.3    | -80.0     | 126.9     | 8-\( \square \)-5 | -132.2    | 3-\( \square \)-10 |
| 16                            | 141.3    | -102.4    | 160.2     | 11-\( \square \)-4 | -159.4    | 3-\( \square \)-12 |
| 18                            | 173.3    | -128.5    | 189.1     | 11-\( \square \)-6 | -204.1    | 1-\( \square \)-16 |
| 20                            | 207.0    | -157.3    | 225.1     | 13-\( \square \)-6 | -259.5    | 2-\( \square \)-17 |

\(^a\)figures represent the number of vehicles with active brake system placed in front, respectively after the unbraked (\( \square \)) vehicle in the train body.
The position of the unbraked vehicle (symbolized by the sign ■) in the train body conducting to the respectively resulted highest levels of buff, respectively draft forces, are also determined and presented in table 2, in columns 5 and 7.

For the case of trains hauled by 80 t locomotive (L), the results defining the maximum in-train forces in couplers during emergency braking are presented in table 3 in a particular manner.

There were distinctly highlighted: normal operational conditions (all the vehicles having active braking systems), the situation of one vehicle running unbraked in the train body and, given the 60% higher mass of the locomotive compared to each passenger coach and placed in the head of the train, the correspondent maximum buff and draft forces resulting if the braking system of the traction vehicle is out of action.

### Table 3. Peak in-train forces for trains hauled by 80 t locomotive.

| Train composition | Maximum in-train forces [kN] | 1 veh. unbraked<sup>a</sup> | Loc. unbraked |
|-------------------|------------------------------|-----------------------------|---------------|
|                   | All veh. braked | Buff | Draft | Buff | Draft | Buff | Draft |
| L + 3v            | 19.1          | 0.0  | 48.8  | (3-■) | -54.4 | (■-3) | 13.9  | -54.4 |
| L + 5v            | 31.9          | 0.0  | 51.9  | (5-■) | -63.9 | (■-5) | 38.2  | -63.9 |
| L + 7v            | 51.8          | -10.9| 62.4  | (4-■-3)| -68.8 | (4-■-3)| 29.0  | -68.8 |
| L + 9v            | 73.2          | -28.4| 84.6  | (6-■-3)| -71.3 | (■-9) | 43.7  | -71.3 |
| L + 11v           | 98.1          | -46.1| 110.3 | (6-■-5)| -84.2 | (2-■-9)| 64.8  | -77.6 |
| L + 13v           | 125.2         | -66.9| 139.4 | (8-■-5)| -123.1| (2-■-11)| 87.3  | -98.4 |
| L + 15v           | 156.2         | -92.4| 171.1 | (9-■-6)| -150.3| (1-■-14)| 113.0 | -145.3|
| L + 17v           | 188.5         | -116.8| 205.6 | (10-■-7)| -189.7| (■-17) | 138.8 | -189.7|
| L + 19v           | 223.9         | -144.9| 241.5 | (12-■-7)| -216.9| (■-19) | 168.8 | -216.9|

<sup>a</sup> in brackets, the position of unbraked vehicle in the train body conducting to maximum level of forces

For the case of passenger trains hauled by 120 t locomotive (L), the main results are summarised in the same manner in table 4.

### Table 4. Peak in-train forces for trains hauled by 120 t locomotive.

| Train composition | Maximum in-train forces [kN] | 1 veh. unbraked<sup>a</sup> | Loc. unbraked |
|-------------------|------------------------------|-----------------------------|---------------|
|                   | All veh. braked | Buff | Draft | Buff | Draft | Buff | Draft |
| L + 3v            | 20.1          | 0.0  | 50.2  | (3-■) | -73.5 | (■-3) | 10.0  | -73.5 |
| L + 5v            | 37.2          | -7.9 | 52.4  | (5-■) | -89.7 | (■-5) | 15.2  | -89.7 |
| L + 7v            | 58.1          | -27.5| 69.5  | (4-■-3)| -100.1| (■-7) | 27.9  | -100.1|
| L + 9v            | 80.6          | -49.2| 92.7  | (4-■-5)| -106.9| (■-9) | 43.4  | -106.9|
| L + 11v           | 106.3         | -59.5| 120.6 | (6-■-5)| -121.1| (■-11)| 60.1  | -121.1|
| L + 13v           | 134.6         | -86.5| 149.5 | (7-■-6)| -132.2| (■-13)| 80.3  | -132.2|
| L + 15v           | 166.9         | -115.7| 182.2 | (9-■-6)| -159.4| (1-■-14)| 104.8 | -154.4|
| L + 17v           | 199.5         | -141.8| 217.1 | (10-■-7)| -204.1| (7-■-10)| 130.1 | -201.5|
| L + 19v           | 236.0         | -170.1| 254.4 | (10-■-9)| -259.5| (8-■-11)| 157.9 | -245.4|

<sup>a</sup> in brackets, the position of unbraked vehicle in the train body conducting to maximum level of forces

At this point, some more clarification is necessary to produce a meaningful understanding of the data presented in tables 2-4.

As previously declared, for each train length, simulations were performed taking into account all possible arrangements in the train composition for the vehicle considered to have the brake system isolated. For illustration, in table 5 are presented the results obtained for the complete set of nine simulations performed in the case of the train composed of seven passenger vehicles hauled by a four axle locomotive having a mass of 80 t.
In table 5 one can observe that if a single vehicle of the train in the presented composition does not develop braking forces, its position in train is actually determinant for the level of in-train forces. The highest level of draft forces is reached (bold, italic) if the first vehicle (the locomotive) is the one in this case. As regard the buff forces, operating with the 5th vehicle of the train unbraked, results in maximum compression force in train (bold).

Table 5. Peak buff and draft forces in couplers depending on the position of the unbraked vehicle in train body (passenger train of 7 coaches hauled by 80 t locomotive).

| coupler | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 8       | 33.2| 42.2| 48.5| 51.8| 48.9| 45.8| 33.1| 0   | -10.1| -10.9| -9.0| -7.2| -5.5| -3.4|
| 1       | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 2       | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 3       | 37.8| 50.7| 35.4| 39.9| 40.0| 38.0| 26.9| 0   | -30.5| -29.4| -21.9| -19.9| -21.6| -25.8|
| 4       | 40.9| 51.0| 60.1| 40.1| 39.7| 38.2| 26.7| 0   | 0     | 0     | 0     | 0     | 0     | 0     |
| 5       | 35.7| 47.9| 56.0| 59.6| 57.6| 39.1| 26.8| 0   | 0     | 0     | 0     | 0     | 0     | 0     |
| 6       | 33.2| 43.1| 51.2| 57.1| 57.1| 53.3| 28.2| 0   | 0     | 0     | 0     | 0     | 0     | 0     |
| 7       | 33.2| 42.3| 48.6| 52.6| 53.2| 51.4| 53.3| 0   | 0     | 0     | 0     | 0     | 0     | 0     |

*a the numbering of the couplers is in ascending order starting with 1, between first and second vehicle in train composition

As results, along with the highest level of buff and draft forces and particular conditions leading to, which represent important information for operational decisions having impact on the safety of traffic, knowing the time-dependency evolution of longitudinal forces in couplers during the braking actions has crucial role in better understanding how the trains’ braking process unfolds.

In this regard, due to the high number of simulation performed, we presenting figures 2-7, just for exemplification, the evolution of in-train forces during the first 10 s of the braking action for certain representative situations.

There were selected diagrams considered illustrative for the present research, in respect to each of the three stages of numerical simulations previously enounced.

![Figure 2. Maximum buff forces in emergency braking from 160 km/h, all vehicles braking, for 8 vehicles train set.](image1)

![Figure 3. Maximum draft forces in emergency braking from 160 km/h for 8 vehicles train set (the 5th vehicle unbraked).](image2)
conditions specified in the figures. To cope with a decent resolution in text, there are presented the results for trains composed of eight vehicles. Although it is a relatively small number of couplings, the forces evolutions are similar to longer trains, up to the maximum of 20 vehicles, as limits were stated in this work.

4. Analyse, discussion and comments
The results of the simulations were used with the aim of getting a comprehensive projection of the effects induced on the longitudinal dynamics of passenger trains submitted to braking actions, if operated with one unbraked vehicle in components.

Referring primarily to the highest levels of in-train forces, the results can be compared in several ways. Without taking into account any other disturbing factors, including resistances, the “pure” effect of braking forces on buff and draft peak forces in couplers is highlighted in figure 8. The diagrams are based on the values presented in table 2 and indicate an increase of the in-train forces if a single vehicle of the train provides no braking force. An interesting observation regarding the evolution of the process, referring to this trend, it proves to be more accentuated as regard the draft forces.

A closer examination of the diagram indicates that the overall effect of increasing forces in couplers is more intense the shorter the train set is and decreases for train composed of more than 8...10 identical vehicles. The increase rates of in-train forces relative to the normal operational
situation, with each vehicle of the train effectively braking, expressed as percentages and presented in figure 9, stand as argument for this affirmation.

![Figure 8](image1.png) ![Figure 9](image2.png)

**Figure 8.** Maximum in-train forces in uniform composition trains for emergency braking started at 160 km/h (effects due to braking system only).

**Figure 9.** Increase rate of in-train forces in train sets for emergency braking in case of one vehicle unbraked (effects due to braking system only).

Figures 10-13, depicting in original manner the numerical results summarised in tables 3 and 4, present the result of joined effects of propulsion resistances and of a large mass in the head of the train (the locomotive), cumulated with the influence of braking system previously presented, considering 3 up to 19 passenger coaches in classic train composition.

It worth noticing that, compared to the weight of the passenger vehicles (in the current study considered 50 t), the locomotives are with 60%, respectively 140% heavier. In particular, their influence on the longitudinal dynamics is expected to be noticeable especially if not participating to the braking process along with the other vehicles in train. Given that aspect, there were treated distinctly the possible operational situations of inactive braking system either for the traction vehicle, or for one of the passenger coaches.

For comparison, the maximum levels of in-train forces in the normal process of braking, with all the vehicles of the train, are also inscribed.

![Figure 10](image3.png) ![Figure 11](image4.png)

**Figure 10.** Maximum buff forces for emergency braking started at 160 km/h in passenger trains hauled by 80 t locomotive.

**Figure 11.** Maximum draft forces for emergency braking started at 160 km/h in passenger trains hauled by 80 t locomotive.

Examining figures 10 and 12, it is to observe that in the presence of the unbraked locomotive in the head of the train, the level of maximum buff forces is the lower the train has more passenger wagons in composition. One may notice that the effect is reversed if a coach is unbraked in the train body.

A little more spectacular are the drawbacks on buff forces (see figures 11 and 13). The existence in
the composition of the train of a vehicle having the braking system isolated, whichever would be that, causes an important increase in the level of draft forces. Moreover, the locomotive weight has an interesting influence on the longitudinal dynamic forces on the maximum level of draft forces in the case of a vehicle that is not braking in the train body.

![Figure 12](image1.png)  
**Figure 12.** Maximum buff forces for emergency braking started at 160 km/h in passenger trains hauled by 120 t locomotive.

![Figure 13](image2.png)  
**Figure 13.** Maximum draft forces for emergency braking started at 160 km/h in passenger trains hauled by 120 t locomotive.

It can be seen from figures 11 and 13 that, for trains in identical composition, with the same number of trailed passenger vehicles, in studied cases the locomotive weight makes the difference. In the case of trains operated with 80 t locomotive, the highest values of draft forces are depending both on the length of the train and of the mass and position of the vehicle with disabled braking system. Not using the braking system of the locomotive results in higher tensile forces in couplers for trains of less than 12 or more than 16 vehicles (see figure 11). The influence of unbraked heavier locomotive (120 t) on draft forces is exceeded by the effects of a passenger vehicle providing no braking force in trains having more than 14 vehicles (see figure 13).

Of more practical interest might be a projection of the perceptual increase rate of maximum in-train forces relative to the case of braking actions performed in normal conditions (all vehicles have active braking system). Figure 14 show that the maximum buff forces level in a train having in component an unbraked vehicle, compared to the forces developed in normal braking process is almost the same and decreases the longer the train is. The traction vehicle’s weight placed in the head of the train has practically no influence. The peak level of draft forces (see figure 15) is much more affected by the existence of an unbraked vehicle in train (about three times higher compared to correspondent buff forces). Also, the locomotive’s weight becomes important.

![Figure 14](image3.png)  
**Figure 14.** Rate of buff forces level with one vehicle unbraked in train, relative to trains having all vehicles with operational braking systems.

![Figure 15](image4.png)  
**Figure 15.** Rate of draft forces level with one vehicle unbraked in train, relative to trains having all vehicles with operational braking systems.
The large volume of the simulations results permit approaches addressing another level of the problem that might be of interest, at least for the theoretically interested, but with potential practical implications as well. It is about the distribution of most affected couplers in train, resulted under the previous defined conditions and assumptions.

Tables 6 and 7 highlight the position of the couplers submitted to the highest in-train forces for identic trains hauled by locomotives having different weights.

**Table 6. Distribution of most affected couplers in trains hauled by 80 t locomotive**

| Train structure | Couplers |
|-----------------|----------|
| 1 veh. unb.     |          |
| L + 3v          | ▲         |
| L + 5v          | ▲         |
| L + 7v          | ▲         |
| L + 9v          | ▲         |
| L + 11v         | ▲         |
| L + 13v         | ▲         |
| L + 15v         | ▲         |
| L + 17v         | ▲         |
| L + 19v         | ▲         |

| Allveh. br.     |          |
| L + 3v          | ▲         |
| L + 5v          | ▲         |
| L + 7v          | ▲         |
| L + 9v          | ▲         |
| L + 11v         | ▲         |
| L + 13v         | ▲         |
| L + 15v         | ▲         |
| L + 17v         | ▲         |
| L + 19v         | ▲         |

*a symbols in table: ▲ is assigned to maximum draft force and ◄ is assigned to maximum buff force

Both tables are structured to allow a simple and direct comparison between the two defined cases for evaluation: having a vehicle in the train composition that operates without active braking system and the normal situation in operation, respectively all the vehicles of the train are braking at full capacity, as expected in emergency braking.

**Table 7. Distribution of most affected couplers in trains hauled by 120 t locomotive**

| Train structure | Couplers |
|-----------------|----------|
| 1 veh. unb.     |          |
| L + 3v          | ▲         |
| L + 5v          | ▲         |
| L + 7v          | ▲         |
| L + 9v          | ▲         |
| L + 11v         | ▲         |
| L + 13v         | ▲         |
| L + 15v         | ▲         |
| L + 17v         | ▲         |
| L + 19v         | ▲         |

| Allveh. br.     |          |
| L + 3v          | ▲         |
| L + 5v          | ▲         |
| L + 7v          | ▲         |
| L + 9v          | ▲         |
| L + 11v         | ▲         |
| L + 13v         | ▲         |
| L + 15v         | ▲         |
| L + 17v         | ▲         |
| L + 19v         | ▲         |

*a symbols in table: ▲ is assigned to maximum draft force and ◄ is assigned to maximum buff force
As observed in connection to diagrams in tables 6 and 7, one can affirm that, by and large, the braking process of the trains having in component one of the vehicles with inactive braking system has a poor influence on the position of the couplers most affected by buff forces. These continue to be situated in the central part of train. On the other hand, the position of the couplers submitted to the highest draft forces is much more influenced, both by the lack of braking force at a vehicle and by the weight of the locomotive. Nevertheless, the length of the train is also an important parameter.

When the braking systems of all vehicles are active, the peak draft forces generally affect the couplers between the vehicles in first third/quarter part of the train.

In case of operating with an unbraked vehicle, in trains hauled by an 80 t locomotive, the results indicate a clear distinction for the most affected coupler. In trains composed of up to 10 vehicles, the connection between the locomotive and the first coach is most solicited, while for longer trains the highest draft forces act at the tail of the train.

If the same trains, in similar conditions, are hauled by a 120 t locomotive, the maximum draft forces affect mostly the connection between the locomotive and the first passenger vehicle.

However, for a more complete picture of the dynamics of the braking processes involved, analysing the evolution in time of the in-train forces is a source of interesting information. In this section, figures 2-7, considered as illustrative in context, will be referred.

When considering that all vehicles develop braking forces, which practically represents the usual operational procedure, analysing the diagrams presented in figures 2, 4 and 6 one can note obvious similarities as regard the development and evolution of in-train forces during the braking action.

In fact, an already expected pattern is displayed in these cases. The graphs show a fast and steadily climbing of buff forces up to maximum values attained in about 1.5 s following the braking command, the process continuing by their decrease till vanishing when air pressure in brake cylinders, respectively the braking forces of each vehicle reach the commanded level. Given the elastic characteristics of couplers, the potential energy accumulated in buffers determine a recoil movement and tensile forces begin to act, generating oscillations in the train body.

The amplitude of in-train forces diminishes rather fast due to the damping characteristics of shock and traction devices of the couplers.

Turning to the differences between the evolutions presented in figures 2, 4 and 6, a series of remarks are required.

In the case of uniform train composition and neglecting any other influences except braking forces, effective in-train forces begin to develop only after the threshold of minimum 0.4 bar pressure is attained in brake cylinders of the first vehicle, as obvious in figure 2. When considering the presence of propulsion resistances that keep a certain compression in train, buff forces start to evolve from the very beginning of the braking process (see figures 4 and 6).

The same compression, associated to the higher weight of considered locomotives, slightly modifies the evolution of in-train forces, but still inscribing into the same pattern.

Referring to the values of maximum in-train forces, (see also tables 2-4), resistances and higher mass of locomotive tend to increase the buff forces while the influence on draft forces depend on the first vehicle’s weight. It is also to mention that our results indicate that short trains are submitted only to compressions during the braking actions.

For the case of passenger trains operating with a vehicle having isolated braking system, our comments refer to figures 3, 5 and 7 and follow the same procedure. Analysing the diagrams, it appears clearly a high difference in the evolution of in-train forces if compared to figures 2, 4 and 6. This observation is in fact consistent with what was expected, if keeping in mind that the main cause of the longitudinal dynamic reactions in the train body submitted to braking actions resides in the difference in braking forces between vehicles. In our case, the 5th vehicle of the train, unlike all others, is considered unable to develop any braking force. For theoretical reasons, the first consequence is that vehicles that precede it will undergo supplementary compressions, while the following vehicles will be subject to an additional stretch.
Exactly such an evolution of in-train forces can be seen in figure 3. After reaching of maximum air pressure in brake cylinders of the vehicles (ca 4 s) and, consequently, the maximum braking forces act steady on each vehicle (except the 5th one, operating with disabled braking system), constant buff forces are exerted on first four couplers, while in the last three couplers of the train act draft forces.

Further on, these forces remain constant up to standstill, because simulation is performed taking into account only the braking force. In such a situation, the differences on longitudinal forces between the vehicles of the train keep accordingly constant and the same for the relative displacements. Consequently, the forces in couplers do not continue to evolve in any way.

A closer examination of the diagrams presented in figures 2 and 3 conducts to an interesting observation: basically, the evolution of in-train forces in the presence of vehicle with disabled braking system is in respect of the same pattern, meaning a damped oscillatory development of forces, but spread almost uniformly against the 0 line of forces.

In absolute values, the stabilized buff and draft forces become inversely proportional to the couplers distance relative to the unbraked vehicle. It is an important difference between extreme stabilised in-train forces, exceeding 50 kN in the presented case, but one must remember that on the 5th vehicle is missing a 58.6 kN brake force.

When taking into account the propulsion resistances and higher weights of considered locomotives, the in-train forces follow the same pattern (see figures 5 and 7). As values level, the longitudinal dynamic forces in couplers are slightly affected by the locomotive’s weight: peak buff forces increase with about 12% and maximum draft forces decrease with about 6% for the train hauled by the heavier locomotive.

5. Conclusions
The investigation of longitudinal dynamics of passenger trains during braking actions if operating with one of the component vehicles having the braking system isolated was approached by numerical simulation. The main variable parameters considered were the number and type (locomotive or trailed) of the vehicles in the component of the trains and the type and position in the train body of the vehicle operating with isolated braking system. The main outcomes that have been analysed in this framework are the magnitude of the in-train forces, the position of most solicited couplers and the time-dependency evolution of the longitudinal dynamic forces during the braking process.

The conclusions of the actual study are grounded on a large volume of data resulted by performing several hundreds of numerical simulations, consistent to a scheduled dedicated frame.

All the outcomes, values and time dependent diagrams, were submitted to a comprehensive analysis, extended mainly on the targeted aspects considered to clarify the subject.

Keeping in mind the input data and the assumptions presented in section 3.1, the main conclusion of the study can be summarised as follows:
- as expected, operating with an unbraked vehicle in the train body results in altering the whole longitudinal dynamics of the train during the braking action process;
- there are certain positions of the unbraked vehicle in train enhancing the highest effects, distinctly for buff and draft forces;
- for such arrangements, the magnitude of in-train forces increases, but draft forces are more substantially affected;
- the response in shorter trains is generally higher, especially if compared to the correspondent effects in case of the normal operational situations, of having braking forces developed by each vehicle of the train’s component;
- if the locomotive, as head of the train, has the braking system inactive, the buff forces magnitude is lower and the draft forces are higher, for both as reported to the normal operational situations (all vehicles braked);
- regarding the maximum longitudinal forces in couplers, for similar trains operated with an unbraked vehicle in component, the influence of the locomotive’s weight is negligible, unlike the effect on draft forces;
- a heavier locomotive is less influential on the position of most solicited couplers of the train;
- in the case of operating a train having in component a vehicle with the braking system disabled, the pattern of longitudinal in-train forces evolution during braking, except their magnitude, differs essentially after the initial oscillatory episode by presenting a clear distinction between the “pressed” and the “flattened” part of the train. The front part of the train up to the unbraked vehicle remains compressed, while the rest of the train remain stretched until stopping or brake release.

Even this research explores a particular and relative rarely encountered situation in passenger trains braking, we consider that the results can be of interest in operation and certainly contributes to create a more complete picture of the longitudinal dynamics of trains submitted to braking actions.

We are continuing to work on this subject and to extend it also for freight trains, where such issues are more frequent.

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