Considerations on longitudinal dynamics of passenger trains with blocked wheelsets during braking

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Abstract. The aim of the study is to highlight the fact that, besides the other well-known aspects, wheelsets blocking during braking actions performed in poor wheel/rail adhesion conditions has important influence on the longitudinal dynamics of the train. The study is based on MATLAB numerical simulations, performed for passenger trains consisting of four vehicles. There were considered the possible operational situations specific in low adhesion condition braking, determined by the pitch effect, i.e. the possible blocking of one up to all wheelsets of the vehicle. The results presented in the paper cover two situations: train set composed of identical vehicles, considering only the braking forces and, respective, classical configuration train hauled by a locomotive with a larger weight compared to each coach, resistances being also taken into account in simulations in that case. The outcomes indicate important dynamic effects in the train body, highlighting the importance of using performant wheel slide protection devices, essential not only for traffic safety reasons, but also useful in terms of in-train level of forces. It is to mention that these results represent the initial step of a more comprehensive ongoing study.

1. Introduction
Train braking is a complex process closely related to the safety of operation and, therefore, subject to continuous theoretical and experimental research aiming to find optimized solutions in development and improvements, according to the actual trends of increased tonnages and higher velocities. The direct requirements regarding the traffic safety are evaluated mainly through the braking power, which is clearly stated by regulations and usually related to the stopping distances.

Specific functional and operational particularities generate in-train forces that, in certain situations, may affect the train integrity and the passengers’ comfort. Hence, there is a growing interest as regard the longitudinal dynamics of trains.

It is stated that instantaneous differences between braking forces developed by each vehicle of the train generates relative motions between adjacent vehicles, causing significant solicitations on couplers. By its operational mode, the classical UIC pneumatic system, which is widely in use, results in a successive actuation of the vehicles’ braking systems in long of the train, which, in that case, is considered the fundamental and most important source of longitudinal dynamic reactions [1-4].

It should be noted that the usual brake blocks or disc brake systems are wheel/rail adhesion dependent. In low adhesion conditions, important sliding occurs and, in absence of corrections, leads to the blocking of affected wheelsets, which cease to rotate and are dragged along the rail. The main adverse effects are longer stopping distances and wheel flats, both affecting the safety of traffic [5].
Even if passenger vehicle are featured with wheel slide protection devices, operations may be affected by failures. In such cases, the braking force exerted by the wheelset drops rapidly and stabilizes to the level of the friction force given by the actual wheel/rail friction coefficient. At the end of the impaired adhesion section, the wheelsets regain the necessary adhesion and the braking force returns to its initial value. Even ignoring other aspects, the mere fact that vehicles enter and leave the low-adhesion section successively causes significant differences in braking force. Accordingly, higher in-train forces are expected in couplers.

The aim of the study is to evaluate, by means of numerical simulations, the effect on longitudinal dynamics of short passenger trains in braking process when a low adhesion section is encountered and certain axles of the vehicles are blocked while travelling on that sector.

2. Theoretical aspects and model

Longitudinal dynamics simulation modelling is based on the classic train mechanical perception as elastic-damped lumped system consisting in individual rigid masses representing each vehicle, connected through elements having well defined elastic and damping equivalent characteristics, in respect to the individual couplers’ devices particularities [1-4]. Neglecting the vertical and horizontal displacements and considering the multibody formulation, for a generalized “i” vehicle of the train having a \( m_i \) mass and running on a straight and horizontal track, the forces governing the displacement \( x_i \) are: the braking forces \( F_{b,i} \) and the resistances \( W_i \) as retardation forces, the forces \( P_{n,i} \) and \( P_{s,i} \) acting in couplers and the inertial forces \( I_i \).

The differential equation describing the longitudinal movement of the vehicle is [6, 7]:

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

For a train consisting of \( n \) vehicles, by attaching the boundary conditions \( P_{0,1} = P_{n,n+1} = 0 \), one obtain the differential nonlinear equations system describing the movements of the mechanical system.

Basically, the models and the correspondent simulation program applied in this study are a version of those developed by our team and related details are presented in a series of papers, e.g. [6, 7]. The same constructive solutions of lateral buffers and traction devices with metallic elastic rings (RINGFEDER type) were considered, as well as the specific propulsion resistances appropriate for the majority of Romanian passenger vehicles in operation. As regard the pneumatic aspects, the same procedure of considering a constant average transmission rate of braking signal within the train main pipe was applied and experimental data achieved on the computerized brake systems in the Laboratories of Faculty of Transport in University POLITEHNICA of Bucharest were implemented in the simulation program [6, 7].

According to the target and aims of the present study, an original approach on braking forces was developed. Fundamentally, the highest affordable braking force \( F_{b,\text{max}} \) at wheel/rail contact for railway vehicles featured with shoes or discs is limited by the adhesion force \( F_a \), depending on the vehicle’s mass \( m \), and on the wheel/rail adhesion coefficient \( \mu_a \), usually considered in the design calculations by values according to “normal conditions” (\( g = 9.81 \text{ m/s}^2 \) is the gravitational acceleration):

\[
F_{b,\text{max}} \leq F_a = m g \mu_a
\]  

In particular, for vehicles destined to maximum velocities \( V_{\text{max}} \geq 160 \text{ km/h} \), compulsory featured with disc brake system, the designed braking force can be established, according to equation (2) [6]:

\[
F_{b,\text{max}} = 0.33 m g (1 + 0.011 V_{\text{max}})^{-1}
\]  

It is known that wheel/rail adhesion depends on numerous parameters, some of these randomly affected by local weather conditions, cleanliness of contact treads and other parameters [5]. In poor adhesion, if equation (2) is no longer met, wheelset blocking occurs. The blocking of each axle of the vehicle is also influenced by the pitch motion, which results in specific transfers of vertical loads between bogies and axles. Submitted to decelerations, in the case of four axles vehicles, the correspondent differences in vertical forces on each axle determine a specific order of wheelsets
tendency in blocking, relative to the direction of movement. The most sensitive is the last wheelset and then are following, in order, the second, the third and, finally, the first one [8].

During braking actions on sections comprising a low adhesion sector, the following time sequence is relevant: \( t_0 = 0 \) corresponding to the air brake distributor actuation; \( t_{0.4} \) (achieving 0.4 bars in brake cylinders); \( t_i \) (initiation of important sliding while entering the low adhesion sector); \( t_k \) (blocking of wheelset); \( t_r \) (beginning of adhesion regain); \( t_e \) (total regain of adhesion); \( t_b \) (end of braking action).

Noting \( p_{rel}(t) = \frac{p_{BC}(t)}{p_{BC,max}} \) as ratio between the instantaneous air pressure \( p_{BC} \) and maximum level \( p_{BC,max} \) in brake cylinders and considering the usual equations defined for normal adhesion conditions (see, for instance, [6]), the vehicle’s braking force in cases involving axles blockings can be described in the following manner:

\[
F_{h,max}(t) = \begin{cases} 
0, & \text{if } 0 \leq t < t_{0.4} \\
\frac{p_{rel}(t) \cdot F_{h,max}}{n_v}, & \text{if } t_{0.4} \leq t < t_i \\
\left[ \frac{n_v - n_k}{n_v} p_{rel}(t) \cdot F_{h,max} + n_k \vartheta_i \right] / F_{h,max}, & \text{if } t_i \leq t < t_k \\
\left[ \frac{n_v - n_k}{n_v} p_{rel}(t) \cdot F_{h,max} + n_k \vartheta_i \cdot \vartheta_r \right] / F_{h,max}, & \text{if } t_k \leq t < t_r \\
\left[ \frac{n_v - n_k}{n_v} p_{rel}(t) \cdot F_{h,max} \right] / F_{h,max}, & \text{if } t_r \leq t < t_e \\
\left[ \frac{n_v - n_k}{n_v} p_{rel}(t) \cdot F_{h,max} \right] / F_{h,max}, & \text{if } t_e \leq t \leq t_b 
\end{cases}
\]

In equation (4), for the case of a vehicle on \( n_v \) axles, \( n_k \) represents the number of vehicle’s wheelsets blocked during braking process and \( \vartheta_i, \vartheta_r \) the mean variation ratio of braking force during the process of losing/regaining the adhesion.

3. Numerical simulations

3.1. Main input data and assumptions

The simulations were performed for short, four vehicles composed passenger trains submitted to emergency braking action from 160 km/h. All vehicles are considered of 25 m length, equipped with UIC pneumatic braking system acting on two disc brakes per wheelset. A constant friction coefficient between discs and pads is assumed.

Two complete set of simulations constituted the framework to cover two distinct situations: \( A \) – trainset of identical vehicles and \( B \) – train in classical composition consisting of a locomotive hauling three coaches. In the situation of the uniform composition train \( A \), the propulsion resistances were neglected, permitting to get a hypothetical image of the effects due exclusively to the effective braking forces variations generated by running on a track containing a low adhesion sector.

The sequence of each vehicle’s entering on the adhesion affected sector corresponds to the computed time for successively travelling the 25 m length with the effective train velocity. A complete set of simulations comprises the possible situations that may be encountered in operation specific to low adhesion condition braking determined by the pitch effect, i.e. the possible blocking of one up to all wheelsets of a vehicle (cases 1 to 4). Simulations are performed in each case for all the 15 possible combinations corresponding to the four vehicles of the train. For comparison, the braking process in normal adhesion conditions (case 0) is also considered. The main input data are summarized in table 1.

| mass [t] | braking characteristics data | blocking process | \( \vartheta_i \) | \( \vartheta_r \) |
|----------|-------------------------------|------------------|----------------|----------------|
| passenger vehicle | loc. | maximum. pressure in brake cylinders [bar] | filling time [s] | duration [s] | wheel/rail friction coefficient |        |
| 120      | 50   | 3.803 | 3.36 | 13 | 0.025 | 7 | 4.5 |
The mean propagation rate of the brake signal in the long of the main pipe of the train in emergency braking was considered 250 m/s, as minimum admitted by regulations.

3.2. Results and comments

The targeted results of the whole set of more than 120 simulations are, according to the aims of the present research, the highest levels of buff and draft forces in couplers. These are summarised, for each case, in table 2, where there are also indicated the correspondent combinations.

As expected, the maximum in-train forces increase almost linear with the number of blocked wheels (see figure 1) and draft forces are more affected. Concerning the effect of braking forces only (train set), in all studied situations draft forces are lower than the compression one. As expected, the maximum in-train forces increase almost linear with the number of blocked wheels (see figure 1).

### Table 2. Maximum in-train forces in couplers

| Train type | Case | Combination | Max. buff forces\(^c\) [kN] | Max. draft forces\(^c\) [kN] |
|------------|------|-------------|-----------------------------|-----------------------------|
| train set  | 0    | 0000        | 8.137 13.137 15.594         | -1.981 -3.567 -4.122        |
|            | 1    | 1xxx        | 9.711 15.977 15.594         |                             |
|            | 2    | 0011        | 18.694 31.724 18.254        | -8.096 -13.985 -18.148      |
|            | 3    | 1100        | 14.385 13.137 15.594        | -35.406 -37.731 -19.778     |
|            | 4    | 0011        | 36.635 63.248 36.868        | -16.170 -28.417 -36.246     |
|            | 1100 |             | 19.160 13.137 15.594        | -47.158 -50.575 -26.231     |
| classic    | 0    | 0000        | 19.135 19.066 15.197        | 0.000 0.000 0.000           |
| train hauled by locomotive | 1    | 0111        | 23.700 19.066 15.197        | -7.959 -5.055 -5.816        |
|            | 2    | 1xxx        | 19.135 19.066 15.197        | -20.749 -22.757 -21.946     |
|            | 3    | 0111        | 44.567 34.683 21.165        | -19.357 -12.227 -13.926     |
|            | 4    | 1111        | 64.247 56.186 29.659        | -72.375 -60.133 -50.575     |
|            | 1xxx |             | 85.160 74.386 39.161        | -96.769 -80.778 -61.578     |

\(^a\) Designated by the number of wheelsets blocked during braking/vehicle  
\(^b\) Significance is: 0 – vehicle braking in wheel/rail adhesion limits; 1 – vehicle with wheelsets blocked during braking  
\(^c\) In italics, the maximum in-train forces/train for each case

As expected, the maximum in-train forces increase almost linear with the number of blocked wheels (see figure 1) and draft forces are more affected. Concerning the effect of braking forces only (train set), in all studied situations draft forces are lower than the compression one. As expected, the maximum in-train forces increase almost linear with the number of blocked wheels (see figure 1).
It is to notice that draft forces are more affected and, concerning the hypothetic effect of braking forces only (train set – $A$), in all studied situations draft forces are lower than the compression one.

Considering in simulations a higher mass of the locomotive as first vehicle in classic train and the resistances, if axles blocking occur during braking, draft forces become higher than the compression ones (red lines in figure 1).

The results also indicate that the highest in-train forces act in the middle of the train if only the braking forces are considered (train set), while in the classic composition train, the larger mass of the locomotive and the resistances determine higher effects in the first coupler (see figure 2).

Two more observations resulting from data presented in table 2 are important to highlight: the maximum in-train forces keep the almost same limits if only one wheelset of a single vehicle of the train blocks during the braking action; in the case of classic train composition ($B$), it results that it is sufficient for a single axle to block on the first vehicle and, regardless of the situation of the other vehicles, the largest draft forces are developed.

A brief analysis of the in-train forces evolution in normal adhesion conditions show that resistances keep the train compressed during the whole braking action and, associated to 140% mass increase of the first vehicle, conducts to 22% higher buff forces (see figure 3), compared to the effects in longitudinal dynamics generated by braking forces only, in uniform composition train (see figure 5).

![Figure 3](image3.png)  
**Figure 3.** In-train forces (locomotive and three coaches train) in emergency braking performed at 160 km/h, in normal adhesion conditions.

![Figure 4](image4.png)  
**Figure 4.** In-train forces (locomotive and three coaches train) in emergency braking with blocked wheelsets in case 4, combination 1111 (table 2).

![Figure 5](image5.png)  
**Figure 5.** In-train forces (four vehicles train set) in emergency braking performed at 160 km/h, in normal adhesion conditions.

![Figure 6](image6.png)  
**Figure 6.** Braking forces (locomotive and three coaches train) in emergency braking with blocked wheelsets in case 4, combination 1111 (table 2).
Still, given the purely theoretical interest on the train set in this present study, higher attention has been paid regarding the classical train, while more practical information are expected. Figures 3 and 4 show that successive entry and exit of vehicles in the low adhesion zone significantly alter the evolution of in-train forces. At the ends of the low adhesion track section important peaks of draft and buff forces occur, which are quite rapidly dampened given the specific characteristics of couplers elements. It is noteworthy the consistency of the in-train forces evolution with the time evolution of the braking forces for each vehicle (see figures 4 and 6).

It is also interesting to find that rapid variations of maximum braking forces in the limits of 20% (corresponding to one wheelset/vehicle blocked) has insignificant effect on buff level forces, as compared to the same braking action performed in normal wheel/rail adhesion conditions (see table 2 and figure 1).

In terms of traffic safety, if all wheelsets of all the vehicles in train are affected, the stopping distance increase from 869 m to 944 m, resulting in a decrease by 16% of the braking performance expressed by braked weight percentage.

4. Conclusions
The main generic conclusion relying on the results in the assumed conditions and initial data is, in a summarized form, the following: wheelsets blockings during the braking process cause major changes to the entire longitudinal dynamics and lead to substantially higher in-train forces, the effect being particularly noticeable in the case of draft forces. Still, in the case of four vehicles passenger train, these outcomes, though somehow spectacular, are not likely to affect the train integrity.

In particular, the simulations results indicate that it is possible to establish certain limits of braking forces variations, so that the level of in-train forces corresponding to braking actions performed in normal conditions not to be exceeded.

Last but not least, the results reinforce the fact that passenger vehicles must be equipped with performant wheel slide protection devices that, it is of course the best, to operate independently on each wheelset. So, the braking force provided by the vehicle is more adaptable to the actual wheel-rail adhesion conditions. Consequently, minimum of retardation forces variations are expected in low adhesion braking, keeping an adequate in-train forces level and, on the other hand, less affecting the braking performance.

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