Influence of Application Time Regulated Limits on Longitudinal Dynamic Forces in Passenger Short Trains during Braking Process

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Abstract: - This paper investigates an original aspect in the study of longitudinal dynamics of trains submitted to braking actions: the influence of application time admitted ranges on in-train forces. Basic theoretical aspects are outlined and experiments were carried out in order to accurately determine the filling characteristics of brake cylinders. These were implemented in an original simulation program used for the study of three vehicles train. Results, discussions and conclusions reflect significant increases in the level of both compression and tensile in-train forces. The evolution and the disposition of these forces in the long of the train are also affected.

Key-Words: railway vehicles, longitudinal dynamic forces, air brake distributor, application time, filling characteristics, air pressure increase rate

1 Introduction

In railway transportation, the main issue dominating all other aspects is the traffic safety and, in this respect, it is obvious that train braking is a critical and very complex problem, given numerous and large interconnected masses running assembled at increasingly higher speeds.

According to the specific character, train braking generally involves chaining and overlaps of numerous phenomena of different kinds - mechanical, thermal, pneumatic, electrical etc. The actions of these processes take place in various points of the vehicles and act on different parts of the train, with varying intensities and particular evolutions. The major problem is that all must favorably interact for the intended scope, to provide efficient, correct and safe braking actions.

In this regard, as essential safety feature, the main braking system has to provide consistent controllable braking forces on the entire destined traffic speed domain, permitting controlled speed reductions, stop at fixed point and to maintain stationing at a standstill on slopes. Currently, railway vehicles must necessarily be equipped with indirect compressed air brake (UIC-type). The main operational particularity is that brakes are released as long as in the train’s brake pipe the pressure is maintained at the “regime level”, generally 5 bar (relative pressure). Braking commands are set by its decrease [1].

The system is recognized as very reliable and simple both in construction and in operation, but due the air compressibility and the length of the train, it is always a time lapse between the reaction of the leading vehicle and the response of the rear ones.

Corresponding to the propagation rate of air pressure signal, the braking effects come into action successively in the long of the train so that, while some cars are slowing down, others are trying to push, still not braked, from the rear. This creates conditions during transitional braking stages, immediately following the command of pressure variation in the brake pipe, to develop important longitudinal in-train reactions causing stress to the couplers and affecting passengers’ comfort, even the traffic safety [2].

To mitigate such phenomena, a specific delay in filling duration of the brake cylinders until reaching the commanded pressure level have to be functionally provided by the air distributors on each vehicle. In operational use, there are common the fast-acting (3...5 s application time) and slow-acting (18...30 s application time) brakes [1].

Given the important effects of longitudinal dynamics of trains during braking process, railway scientists have developed theoretical and experimental studies complemented with computer applications for the analysis of specific phenomena, see for instance [3-21]. Most of these studies are mainly focused on long, heavy freight trains, due to the more obvious effects determined by the length of the brake pipe and numerous big masses interconnected.
However, serious arguments indicate that in passenger trains, although the in-train forces level might be lower, the travelers’ comfort can be affected [8, 9, 15-17].

An interesting aspect related to longitudinal dynamics of passenger trains, enunciated in [8], is the effect of regulated limits between 3 and 5 s accepted for application times in the case of fast-acting brake systems [1].

The main target of the research is to investigate comprehensively this problem for the case of short passenger trains. Basic theoretical aspects are outlined and experiments were carried out in order to accurately determine the filling characteristics of brake cylinders that were implemented in an original simulation program used for the study of three vehicles train. Results, discussions and main conclusions are presented in the last part of the paper.

2 Theoretical aspects

2.1 Mechanical model of the train

The classical approach for theoretical studies on in-train longitudinal forces is a mechanical cascade-mass-point model in which vertical and lateral dynamics are usually neglected [13, 21, 22 etc.].

Known that train vehicles are linked to each other by couplers, traditionally based on combined use of draw-gears and buffers, the model is an elastic-damped lumped system consisting in 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).

While running, the train vehicles are mainly submitted to the following longitudinal forces: $Rm_i$, the vehicle’s main resistances, $Rs_i$ the supplementary resistances mainly caused by tracking slope and curvature and $P_{i-1}, P_i$ the in-train forces between adjacent vehicles, cumulating elastic and damping forces acting on the shock and traction apparatus between $i-1$ and $i$, $i$ and $i+1$ respectively vehicles. During braking actions, the braking forces $F_{br}$ act in an opposite sense of motion and, in such studies, is obvious that are most important and their time history in the first stages following the braking command is crucial.

Considering $x_i$ and $\dot{x}_i$ the position and the instantaneous acceleration of a certain $i$ vehicle of the train submitted to the influence of the exterior forces, the equation of motion is:

$$m_i \ddot{x}_i = -F_{br,i} - R_i - P_{i-1} + P_i \quad (1)$$

for $i = 1, 2, \ldots, n$ and $P_n = P_{n-1} = 0$.

Applied to all component vehicles of the train, eq. (1) constitutes a differential nonlinear equation system of second degree.

2.2 Pneumatic aspects

In the case of UIC braking system, commands are transmitted along the train as pressure reference and the braking system of every vehicle specifically interacts with the complete pneumatic plant of the train.

There are two important aspects influencing the longitudinal behavior: the moments when each air distributor begins to command the filling of the brake cylinders and the subsequent evolution of the air pressure in the brake cylinders. Accordingly, there are two different aspects that are usually emphasized: the propagation of braking signal along the brake pipe and the response of the distributor [7, 13, 14, 18].

In this respect, the evolution of complex processes consequently to a braking command (performed by establishing the pneumatic connection between the brake pipe and atmosphere through the driver’s brake valve) is very intuitive presented by Karvatski [23]. He identified the following stages: the propagation of an air wave along the brake pipe, followed by a pressure drop determining the successive actuating of each air brake distributor according to its sensitivity and the subsequent pressure increase in the brake cylinders in compliance with the filling characteristics.

![Fig. 1. Mechanical model of the train](image-url)
For the present study, consistent to the main target, the brake actuating moments were determined according to the length of the vehicles, considering a constant braking propagation rate in long of the train.

As regard the filling characteristics of air brake distributors, problems are in detail presented in § 3.

2.3 Braking forces
For the case of disc brake equipped vehicle having individual self-adjusting brake rigging, the braking force can be determined:

\[ F_{b,i} = F_p \cdot i_i \cdot n_{bc} \cdot \frac{2 \cdot r_m}{D_o} \cdot \mu_d \cdot \eta_{br} \]  
(2)

where: \( F_p \) is the force exerted on the brake cylinder piston rod \([N]\), \( D_o \) [m] the wheel diameter and \( r_m \) [m] the medium friction radius.

The dimensionless terms are: \( i_i \), the brake rigging amplification ratio, \( n_{bc} \) the number of brake cylinders of the vehicle, \( \mu_d \) the friction coefficient between brake pads and disc and \( \eta_{br} \) the mechanical efficiency of the brake rigging.

The force transmitted by the piston rod depends on the brake cylinder diameter \( d_{bc} \) [m], the instantaneous relative air pressure in the brake cylinder \( p_{bc,i} \) [N/m²], and is influenced by the resistance forces due to the brake cylinders back spring \( F_R \) [N] and by the self-adjusting mechanism incorporated in the piston rod and \( R_{ia} \) [N]:

\[ F_p = \frac{\pi \cdot d_{bc}^2}{4} \cdot p_{bc,i} - (F_R + R_{ia}) \]  
(3)

Assuming that certain terms and factors representing constructive and functional characteristics are constant for the same vehicle during braking actions, as long as the value of the friction coefficient between brake pads and disc \( \mu_d \) can be considered almost invariant [24], during the application time the brake force may be regarded as directly depending on the instantaneous relative air pressure in the brake cylinder:

\[ F_b = f(p_{bc}) \]  
(4)

As known, the disc brake is wheel-rail adhesion dependent. A fundamental requirement in designing is avoiding, in normal conditions, the axles blocking during the braking actions. Mathematically, this means that at wheel-rail contact level, the braking forces \( F_b \) must not exceed the wheel-rail adhesion forces \( F_a \):  

\[ F_b \leq F_a = \mu_a \cdot m \cdot g \]  
(5)

\( \mu_a \) denoting the wheel-rail adhesion coefficient, \( m \) the mass of the vehicle and \( g \) the gravitational acceleration.

Wheel-rail adhesion is a random natural phenomenon influenced by a large number of parameters, some of which are difficult if not impossible to master. For adhesion estimation, certain empirical relations were formulated. In the present study, considering the case of clean and dry rails:

\[ \mu_a = \frac{0.33}{1 + 0.011 \cdot V_{max}} \]  
(6)

\( V_{max} \) [km/h] denoting the maximum constructive running speed of the considered vehicle.

It is important to notice that an exploitable braking force develops only after reaching an approx. 0.4 bar pressure within the brake cylinder. This occurs because before applying the pads on discs, the force exerted by the developing air pressure on the brake cylinder piston has to overcome the friction forces between the piston seal and cylinder and to perform all displacements determined by released positions of brake riggings, wear, elasticity etc. Once the pressure gets its maximum, it remains constant during the process and, consequently, the same is for the braking forces of the considered vehicle.

Consequently, the braking forces can be evaluated as follows:

\[ F_b = \begin{cases} 0 & \text{if } p_{bc} < 0.4 \text{bar} \\ \frac{p_{bc}}{p_{bc,max}} \cdot \mu_a \cdot m \cdot g & \text{if } 0.4 \leq p_{bc} < p_{bc,max} \\ \mu_a \cdot m \cdot g & \text{if } p_{bc} = p_{bc,max} \end{cases} \]  
(7)

2.4 Mathematical model of couplers
Generally, the traditional couplers wide used in Europe are composed of a pair of lateral buffers, a traction gear and a coupling apparatus at each extremity of the vehicle. Their characteristics have significant influences for the longitudinal dynamics of the train, with running stability implications. According to the particular constructive and operational characteristics, the behavior of buffer and draw-gear devices is quite complex due to several nonlinear phenomena like variable stiffness-damping, hysteretic properties, preloads of elastic elements, draw-gear compliance, clearance between the buffers discs etc.

In the context of in-train forces, the characteristics of couplers elements have major influence (see fig. 1), hence the necessity to establish appropriate relations permitting to
compute the forces and strokes in shock, traction and coupling devices.

Buffers and draw-gears widely equipping railway vehicles are based on metallic elastic rings (RINGFEDER type), using friction elements to fulfil the required damping effects.

The general characteristics of these devices mainly depend on the stroke \( \Delta x \) representing in fact the relative displacement between neighbor vehicles and on the relative velocity \( \dot{\Delta x} \) associated to its sign (see fig. 2).

In Eq. (8) there were considered \( k_c \) and \( k_f \) constants depending on the elasticity of the elements and on the friction between the metallic rings inside, the supplementary indexes “\( b \)” and “\( f \)” referring to buffer and traction device respectively. In addition, \( x \) represents the stroke and \( \dot{x} \) the relative speed for the considered element of the couplers.

In order to determine the constants \( k_c \) and \( k_f \), the present model was based on the characteristic diagrams of RINGFEDER-type buffers built in Romania by ICPVA-SA that equip trailed passenger vehicles [25, 26]. Keeping the international prescriptions [27, 28] and according to [29], the values established values are presented in § 4.

The actual model is in detail explained, preliminary work and tests to achieve and define this solution can be found in [17].

### 3 Experiments and analysis of filling characteristics

Railway passenger vehicles have to be equipped with fast-action UIC brake system and, as previously presented, the air pressure increase rate in brake cylinders is fundamental for the longitudinal in-train forces evolution.

Consequently, brake cylinder pressure increase vs. time is an important characteristic and the main parameter associated is the application time, measured between the moment when the air begins to enter the cylinder and that when the pressure in the cylinder reaches 95% of its maximum; for fast-action brakes must be between 3 and 5 seconds [1].

In order to increase the precision of the simulations results by using real pressure evolutions in the brake cylinders, accurate measurements were performed.

A KE-1c type air distributor taken from a railway vehicle in service was tested on the computerized system in the Braking Laboratory of the Transports Faculty in University POLITEHNICA of Bucharest, in order to establish the braking characteristics.

Data acquisition was performed using pressure transducers for the interest pneumatic chambers, the brake pipe and the brake cylinder, monitoring also parameters in other functional-related subassemblies, e.g. command chamber of air brake distributor and auxiliary reservoir. Details about the system are presented in [8].

Main results are described in fig. 3. According to the maximum pressure 3.881 bar, the application time was computed in respect to

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![Diagram](image-url)
procedures, resulting 3.88 s, almost in the middle of 3 … 5 s admitted by [1].

Consistent with the main target of the present study, using the experimental data, filling characteristics were determined for the extreme permitted limits. The comparative evolution is presented in fig. 5.

As long as the leading cause of dynamic longitudinal forces in the studied case is the instantaneous difference of braking forces among the vehicles of the train, the filling characteristic rigidity has major influences along with the braking wave rate in the braking pipe.

Studying the air instantaneous pressure increase rate in the brake cylinder (see fig. 6), results indicated, as expected in fact, that first derivative of pressure evolution is higher for shorter application times. Still, there were to be noticed not only the high level that values attended, but also the important differences between the extreme characteristics, even compared to the experimental one, situated, as mentioned, almost in the middle of the admitted limits.

4 Simulation assumptions and data
Consistent to the main target of the study and given the multiple factors influencing the development of in-train forces during braking regime, a major preoccupation was to identify and eliminate, as much as possible, any aspect potentially disturbing the direct influence of filling characteristics.

Hence, certain constraints and simplifying hypotheses were assumed. Most relevant were:
- train in a very simple composition, consisting of identical vehicles in terms of technical, constructive and loading characteristics. Consequently, main resistances could be neglected:
- a minimum number of vehicles, to minimize the influence of train’s length;
- classical couplers consisting of Ringfeder type buffers and traction devices;
- screw couplings tightened up, with no clearance between the buffer discs;
- vehicles equipped with disc brakes, to keep the independency of braking forces regarding instantaneous running speed and clamping forces acting on pads;
- dry and clean track, with no curves or slopes;
- an emergency braking is performed from the considered running speed;
- average transmission speed of brake action of 250 m/s in long of the train.

In this respect, the main initial data for simulations were:
- three identical 50 t mass vehicles train;
- length of a vehicle: 25 m;
- initial running speed: 160 km/h;
- maximum braking force of each vehicle: 58.6 kN, according to eq. (5, 6);
- buffers characteristics (see eq. 8):
  \[ k_{e,b} = 2800 \text{ kN/m}, \]
  \[ k_{f,b} = 1400 \text{ kN/m}; \]
- traction devices characteristics (see eq. 8):
  \[ k_{e,t} = 5460 \text{ kN/m}, \]
  \[ k_{f,t} = 2430 \text{ kN/m}; \]
- time difference between the moments of successive actuation of individual vehicles braking system in long of the train is considered 0.1 s.

The simulations duration was set to 6 s because while braking forces tend to stabilize to the maximum value along the train, a rapid amortization of the studied phenomena occurs.

It is to mention that in the simulation resulting diagrams, compression forces between neighbored vehicles are presented as “positive”, while the tensile ones as “negative”.

Two preliminary simulations were performed, considering the brake forces evolution from the very moment of the commanded action, respectively after attempting the minimum level of 0.4 bar in the cylinders (see § 2.3).

Experimental braking characteristic defined by the application time of 3.88 s was implemented for all the three vehicles in the train composition. Time histories of longitudinal dynamic forces evolution are presented in fig. 7 and 8. Important differences are evident in both evolution and maximum levels of in-train forces.

If in the first case, quite smooth and concordant development of dynamic longitudinal forces is consistent to the experimentally determined air pressure evolution in brake cylinders (see fig. 3).

![Fig. 7. Time history of in-train forces considering the whole filling characteristic](image1)

![Fig. 8. Time history of in-train forces considering brakes actuation at 0.4 bar pressure in brake cylinder](image2)

The second case proves that the successive already established pressure (approx. 0.4 bar) in the brake cylinders determines substantial braking forces differences between vehicles. The simulations results indicate not only faster and higher increase of compression forces in train, but also supplementary and rapid variations of the compression forces (see first 0.3 s, veh 1-2, in fig.8).

The evolution of in-train forces is completely changed in the first second of the process, indicating also important instantaneous differences in the long of the train. Moreover, compared to the first case, the maximum compression forces become almost twice bigger between the last vehicles, while between the first ones keep a comparable level. In fact, during the first second after the brake action command, in operation almost no braking force is exerted (see § 2.3 and fig. 3).

The main conclusion of the preliminary simulation is the necessity of using in the
mathematical model only the above 0.4 bar brake cylinder pressure domain of the filling characteristics. Otherwise, incorrect results and substantially lower maximal values would seriously affect any analysis concerning the influence on traffic safety.

Consistent with all relevant information above presented, fig. 9 schematically presents the simulated cases performed in the present study.

![Fig. 9. Schedule of simulations](image)

The first simulation cases group (1a–1c) were intended to highlight the influence of the accepted filling time levels considering an uniform composition of the train from this point of view.

The other cases groups were set to determine the influence of combined extreme admitted filling time levels on the longitudinal dynamic forces exerted between the train vehicles during braking actions.

5 Results and discussions

For the first group of simulations, the time histories of longitudinal dynamic forces evolution are presented respectively in fig. 10, 8 and 11.

The evolution of in-train forces in 1a-1c cases is quite resembling and concordant to the classic pattern: rapid compression of the train in first braking stages, followed by a more lasting decompression, depending almost directly on the application time. The tensile longitudinal forces are in these cases quite insignificant, both as values and evolution.

![Fig. 10. Time history of in-train forces, case 1 a](image)

![Fig. 11. Time history of in-train forces, case 1 c](image)

The amplitude of in-train forces oscillations decrease appreciable and simultaneous in each case after a period concordant to the filling time.

Maximum in-train forces are mostly those that can lead to serious problems for traffic safety, requiring a more comprehensive approach.

Analyzing the results presented in fig. 12, in the studied cases, the highest values are far from raising concerns.

Still, for uniform train composition, it is to notice that most unfavorable situation is connected to the shortest filling time, but not notable in these cases. Practically, the increase of application time from 3 to 5 s leads to a decrease of approximately 10% regarding the highest in-train forces. Nevertheless, these results represent actually a confirmation of the considerations presented in § 3 in connection to the brake cylinder pressure increase rate.

However, it is necessary to point out that in operation there is a low probability to have uniform
train composition as regards the application time of brakes. It is a natural tendency of the nozzles provided in the assembly of air brake distributors for ensuring the filling time to accumulate, over time, dust or other particles that diminish their inner diameter.

Fig. 12. Maximum compression longitudinal forces in uniform train composition (case study 1a, b, c)

That was a determinant argument to investigate the other proposed group of simulation (see fig. 9).

According to previous presented results, the second group of case studies (2a-2c) combines the shortest filling times, supposing highest reactions, with a vehicle equipped with an air brake distributor ensuring the longest admitted application time.

The results of the simulations are presented in fig. 13, 14, 16. Such combinations determine spectacular modification in evolution, layout and level of in-train forces.

Fig. 13. Time history of in-train forces, case 2 a

Higher differences in instantaneous braking forces between neighboring vehicles conduct to significant differences not only in evolutions and in values, but also as force types (compression – tensile) acting in the couplers in long of the train.

Very significant and representative is case 2b.

If fig. 14 and 15 are simultaneously analyzed, the evolution of braking forces in the long of the train perfectly explains the high compression between first and second vehicle, given the increasing difference in braking forces (for about 1.5 - 2 s). As regards the last two vehicles, after the first 0.3 s while the braking force of the second vehicle is higher, increasing differences begin to make the difference. Consequently, after a rapid compression between the second and the third vehicle, a decompression followed by an increasing tensile force development.

Fig. 14. Time history of in-train forces, case 2 b

In all these situations (see fig. 13, 14, 16), as opposed to previous cases 1a-1c, important tensile in-train forces occur, causing supplementary stress on the screwed coupling.

Maximum in-train forces for the 2a-2c group of case studies are presented in fig. 17, keeping the same sign convention (compression forces – positives, tensile ones – negatives). For reference, there are inserted values corresponding to case 1a (uniform composition of the train, 3 s filling time).

Such brake characteristics combinations in the train composition conduct to much higher levels of dynamic longitudinal forces. Case 2c determines a maximum compression force of 16.5 kN, acting
between last two vehicles, 130% greater than in reference case (1 a). Case 2a conducts to the highest tensile force 12.65 kN between first two vehicles, almost 16 times bigger than in reference case.

Case 3a determines a maximum compression force of 16.43 kN, acting between first two vehicles, more than three times greater than in reference case (1 a), still almost equal as value to case 2c. Case 3c conducts to the highest tensile force 12.7 kN between last two vehicles, about 16 times bigger than in reference case, still almost equal as value to case 2a.

6 Conclusion

The main conclusions regarding the influence of the application time regulated limits on longitudinal dynamic forces in passenger short trains during braking process can be summarized as follows:

- in homogenous disposition in train, different filling times have no major influences on maximum longitudinal reactions, predominantly being an effect of compression evident in the first stages of braking. The level of these forces is quite low, far of affecting the traffic safety;
- in the case of different application times on vehicles of the train, important differences of in-train forces evolution occur, the highest values increasing spectacular. The maximum effect is focused on tensile forces transmitted between neighbored vehicles through the screwed couplings.

The results indicate clear that the influence of filling times cannot be neglected in longitudinal train dynamics studies referring to braking regime.

Given that in operation the application times provided by the air brake distributors are randomly situated in the range of 3 up to 5 s, a recommendable manner to take into account the corresponding effects on in-train forces is by means of certain multiplying coefficients according to the most unfavorable possible situations.

References:


