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# Numerical and Experimental Analysis of the Pressure Signature for different High-Speed Trains

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## Abstract

This paper describes a procedure for the validation of numerical codes able to reproduce the pressures in tunnel due to the passage of trains. In the first step, the parameters of the numerical code are set by matching the train-tunnel pressure signature measured during a single-passage of different types of train within the tunnel and in the second step, without changing the parameters, the crossing of two trains is simulated.

Within the paper, the methodology is applied to the numerical mono-dimensional code DB-Tunnel while the experimental data are those collected during an experimental research programme carried out in the tunnel La Fornace, on the Italian high-speed railway from Roma to Firenze. The accuracy of the numerical code estimation is evaluated in terms of the maximum pressure generated in the tunnel by the train passing/crossing because this is the key parameter, according to the TSI standard for railway infrastructures.

**Keywords:** train-tunnel pressure signature, train crossing, numerical mono-dimensional code, experimental field tests.

# 1 Introduction

*"The relevant pressure changes caused by trains running in a tunnel may be measured at full-scale, estimated from approximating equations, predicted using validated numerical methods or measured using moving model tests. ... Full-scale test data may be the basis for train and tunnel acceptance and homologation."*

This is the introduction of the European Standard EN 14067-5 "Requirements and test procedures for aerodynamics in tunnels" and the work presented in this paper exactly deals with this subject.

As described in the standard [1,2], a railway vehicle running in a tunnel generates pressure waves, that propagate along the tunnel at sonic speed and then reflected by the tunnel end, and a pressure field, that surrounds the train and moves together with it. The main issue in this phenomenon is that a train meets the pressure waves self-generated several time during its passage in the tunnel and, furthermore, it may intersect the pressure waves or the pressure field produced by another train crossing the same tunnel. This means that, in case of two trains, the maxima pressure variations acting on tunnel, on the trains and, consequently, on their passengers (which has to be lower than 10 kPa), not only depend on the tunnel, on the trains and on their speeds but also depend on the relative time delay between the entrance of the first train and the entrance of the second one.

Practically, it is impossible to carry out an experimental campaign with two trains crossing in a tunnel, testing all the possible delays and measuring the pressure along the entire tunnel length and on the two trains; this means that it is necessary to use a validated numerical model to assess the performances of high-speed trains in tunnels. Many are the numerical investigations mentioned in literature [3-8] but, on the other hand, there are no example of solid validations of these numerical models with experimental data, especially regarding to the crossing of two trains [9-14].

The goal of this paper is to propose a procedure for the validation of numerical codes able to reproduce the pressures in tunnel due to train passage. To collect a wide database for validation, an experimental campaign has been carried out on the Italian high-speed railways Roma-Firenze. The selected tunnel allows to observe the train pressure signature for many types of trains in order to analyse the differences between the different trains.

The validation procedure is composed by two step; in the first one the numerical software DB-Tunnel [15] was used to reproduce, by best-fitting, the experimental data of the single passages of different trains at different speeds. Once this target is reached, in the second step, the crossings of two trains measured during the experimental campaign are simulated without changing the train and tunnel parameters set in the first step.

The results obtained are promising and a future possible development is to measure the same phenomenon with pressure sensors placed on-board a test train. In this way it will be possible to identify the characteristics of many different tunnels and, finally, to simulate all the possible train crossing intervals looking for the maximum pressure variation that may occur.

# 2 Description of the phenomenon

The effect of the interaction between the pressure field that surrounds a running train and a tunnel is the generation of pressure waves that propagate along the tunnel at sonic speed. In particular, the entry and the exit of train nose and tail in the tunnel generate four pressure waves that move along the tunnel at sonic speed and are partially reflected in correspondence of discontinuities (i.e. the entrance and the exit of the tunnel, the train itself, another train in the tunnel, vent-hole, caves, …). Furthermore, also the pressure field that surrounding the train perturbs the pressure in the tunnel.

The pressure variations generated by the interaction between train and tunnel have a particular time history, named train-tunnel pressure signature (TWS in Figure 1) and the parameters that are analysed in order to verify the train homologation are related to this trend. This particular evolution of the pressure is a feature of the train and of the tunnel and it is a function of different parameters such as the train speed, the geometry of the train and of the tunnel (area, perimeter, length and superficial roughness) and the environmental conditions (ambient temperature and pressure).

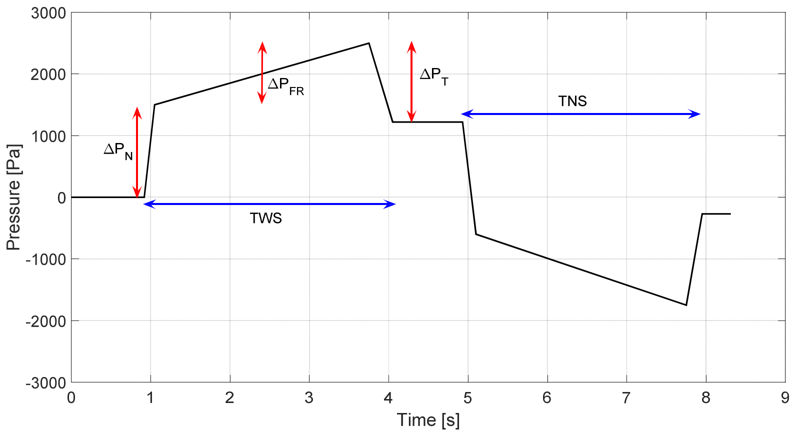

Figure 1: Example of the first part of the pressure signature.

Nevertheless, the whole phenomenon lasts for a longer time than the train passage in the tunnel and is more complex than the assumption that are beneath to the one-dimensional models used for the numerical reproduction of the pressure variations.

In order to simplify the problem all the pressure waves generated can be separated in three different components.

1. Entry
   The train wave signature (TWS as called in [8]) is generated by the interaction between the train and the tunnel portal, propagates along the tunnel at sonic speed and is partially reflected (with opposite sign) and partially refracted in correspondence of each discontinuity until it is completely damped by the friction.

   As it is shown in Figure 1, three pressure jumps characterize this first part:
   - $\Delta P_N$, the sudden and positive leap due to by the entry of the train nose in the tunnel;
   - $\Delta P_{FR}$, another increase in pressure but with a lower slope due to the friction effects caused by the entry of the train body into the tunnel;
   - $\Delta P_T$, the sudden and negative drop generated by the entry of the train tail in the tunnel.

2. Crossing
   Once the train entered the tunnel, the pressure field around it generates another type of pressure wave that moves in the tunnel with the train (train near-field signature, TNS). As shown in Figure 1, the shape of these pressure waves is

similar to the TWS although it has the opposite sign and the values of the ΔP are a bit higher due to the blockage effect of the train.

3. Exit
   When the train leaves the tunnel a second TWS, similar to the first one, is generated and starts to move at sonic speed into the tunnel.

# 3 Experimental tests

In order to characterize the pressure signatures of different trains the tunnel *La Fornace* on the Roma to Firenze high-speed line was chosen (whose main characteristics are summarized in Table 1).

| **LENGTH [m]** | **SECTION [$m^2$]** | **TRACK** | **INFRASTUCTURE SCENARIO** | **MAXIMUM SPEED [km/h]** |
|---|---|---|---|---|
| 1611 | 60 | DOUBLE | BALLAST | 250 |

Table 1: Main characteristics of the La Fornace tunnel.

In particular, this tunnel is free from obstacles for the pressure waves such as vent-hole and caves so that the pressure signature measured could be as clean as possible from disturbances.

## 3.1 Setup

All the sensors used in the experimental campaign were installed inside the tunnel and were acquired synchronously. The speed of the trains was measured by two couples of photocells so that is also possible to recognize the length of the train and, consequently, the typology. The pressure evolution in the tunnel during the passages of the trains was measured using three absolute pressure transducers placed at different position with respect to the entrance of the tunnel as shown in Figure 2.

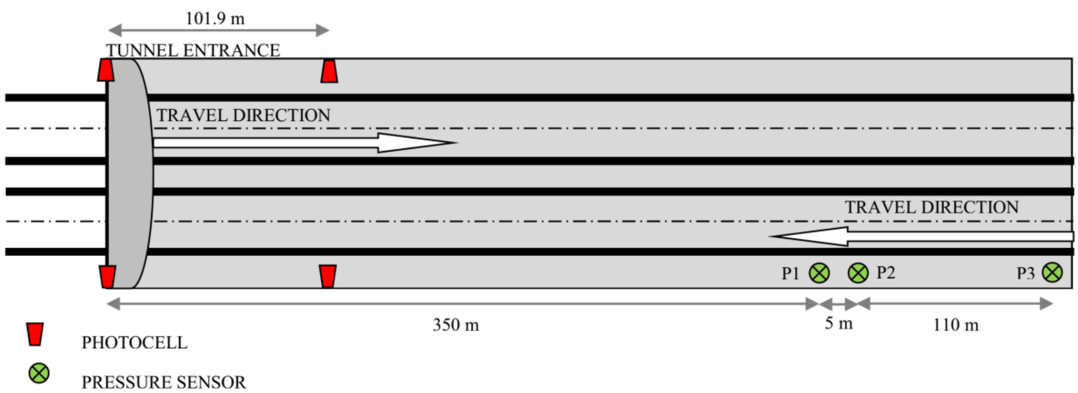


Figure 2: Experimental setup of the instrumentation installed in the tunnel La Fornace.

Finally, also the environmental conditions (pressure and temperature) were measured during the experimental campaign using a weather station.

In order to measure the passages of different trains during three entire days of normal commercial service, the acquisition system used was stand-alone and triggered with the couples of photocells. In this way it was possible to record more than 100 passages of single trains and, especially, also 11 train crossings inside the tunnel.

## 3.2 Experimental results

### 3.2.1 Time-histories

As already mentioned, the validation procedure is based on two steps and, as a consequence, the targets of the experimental campaign were especially two: the identification of the train-tunnel pressure signatures for different high-speed trains (in the single passage case) and the measurements of the pressure variations generated by two trains crossing inside the tunnel.

With regard to the first objective, several passages of four different types of trains were recorded. The main characteristics of these high-speed trains are summarized in Table 2.

| **TRAIN** | **TRACTION** | **NUMBER OF CARS** | **NUMBERS OF BOGIES** | **TRAIN LENGTH [m]** | **NOSE LENGTH [m]** | **CROSS SECTION [$m^2$]** | **NUMBER OF PASSAGES** |
|---|---|---|---|---|---|---|---|
| TRAIN a | concentrated | 13 | 26 | 330 | 4 | 11.2 | 23 |
| TRAIN b | distributed | 7 | 14 | 190 | 6 | 9.8 | 68 |
| TRAIN c | distributed | 8 | 16 | 200 | 6 | 11 | 10 |
| TRAIN d | distributed | 11 | 12 | 200 | 5.5 | 11 | 34 |

Table 2: Main characteristics of the different types of train.

Some examples of the first part of the measured pressure time-histories (train-tunnel pressure signature or TWS [8]) are shown in Figure 3 and in Figure 4. In order to be able to compare the measurements, the speed of these trains is as close as possible to the reference one of 250 km/h (maximum variation < 0.5 %).

From the comparison between the measurements of the sensor 1 and sensor 3, it is clearly visible that in case of train *a* the position 1 is too close to the entrance of the tunnel since the train head reaches the pressure sensor before the pressure wave due to the tail entry. On the other hand, from the sensor in position 3, it is possible to evaluate also the $\Delta P_{FR}$ of train *a,* but not the whole $\Delta P_T$. Another experimental evidence is that pressure drops are not affected by the position of the two sensor probably because they are quite close ($\Delta x$ = 100 m) and the loss due to friction is negligible.

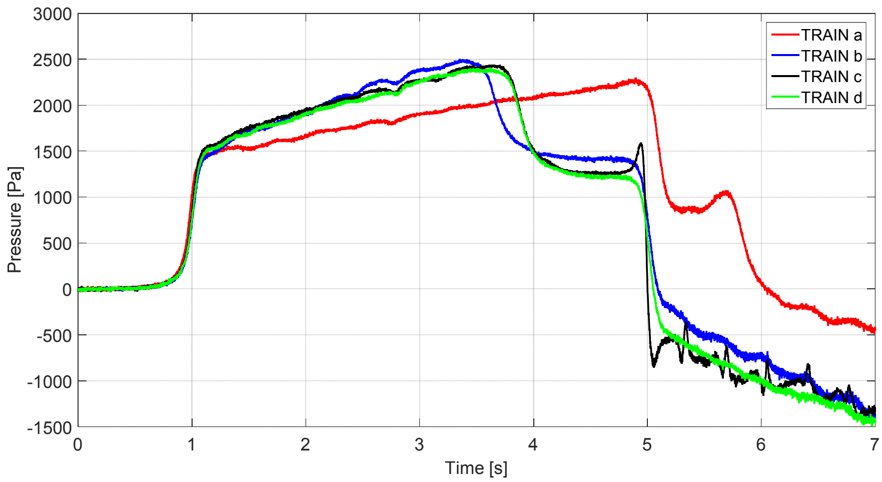


Figure 3: Examples of the pressure signatures measured by P1.

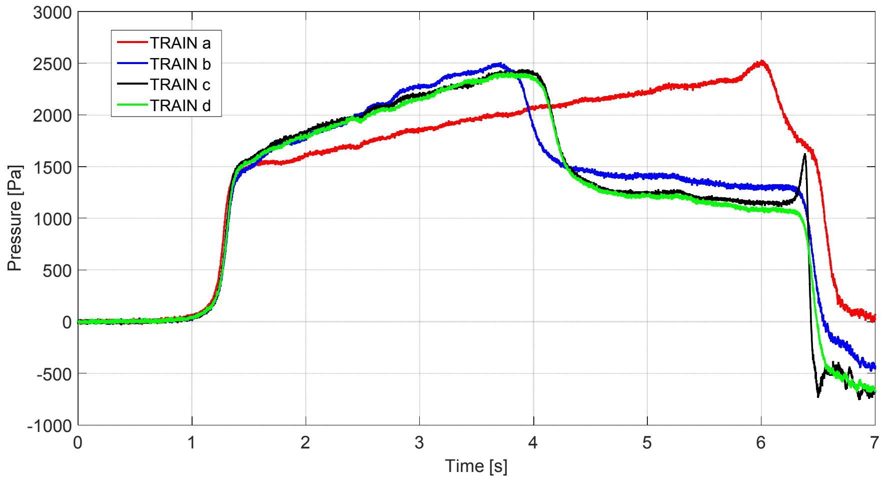


Figure 4: Examples of the pressure signatures measured by P3.

Comparing the different trains, it can be said that $\Delta P_N$ and $\Delta P_{FR}$ are almost equal for the four trains while $\Delta P_T$ shows the largest variations. In particular, with regard to the $\Delta P_{FR}$, although the total difference is almost the same in the four cases, the slopes, intended as the $dP/dt$ ratio, are very different, in particular for the train *a*. This behaviour is probably due to the different shape of the central part of this type of train: being a train with concentrated traction, its central section is characterized by an imperial smooth and continuous since it is free from pantographs.

To be thorough, it has to be underlined that the pressure evolution of train *c* has a different behaviour when the train passes in front of the sensor (≈ 5s in Figure 3 and ≈ 6.4s in Figure 4). This dissimilarity is due to the fact that this type of train crossed the tunnel on the opposite track; that means that these trains transit closer to the sensor and the visible fluctuations are due to the pressure pulses of the slip stream.

### 3.2.2 Statistical analysis

During three days of recording, several passages of each type of train were measured so that it was possible to carry out a statistical analysis [16]. In the following, for all the recorded train passages, the mean value and the standard deviation of the three characteristic parameters of the signature ($\Delta P_N$, $\Delta P_{FR}$, $\Delta P_T$) are presented.

The first issue in the evaluation of the three ΔP from the experimental data is that the pressure changes gradually: for this reason, the parameters have been evaluated considering the intersection of the tangent lines to each sections as shown in Figure 5.

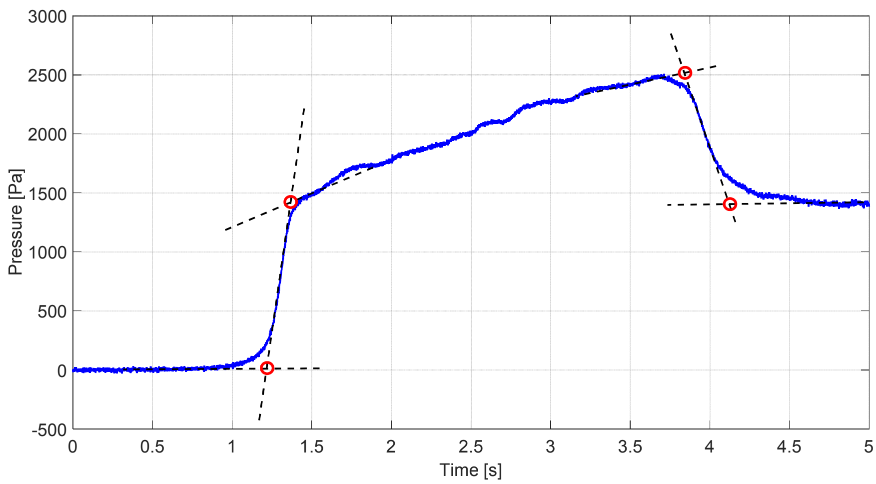


Figure 5: Representation of the method used to evaluate the ΔP.

The second problem is the variability of the train speed of each transit. Although the speeds of the selected data are very close to the reference one (250 ± 1%), in order to be able to compare all the train passages these parameters are normalised to the reference speed using the following relation:

$$\Delta P_{i\_n} = \Delta P_i \frac{v_{ref}^2}{v^2}$$

where $v$ is the speed of the train measured during each test. The results are reported in Figure 6 in terms of mean values and corresponding error bar (mean values ± two times the standard deviation).

These results can provide important information about the influence of geometrical characteristics of the train on the pressure variation during the running of the train in tunnels. For example, $\Delta P_N$ is a function of the cross section of the train, or, in general, function of the blockage ratio defined as the ratio between the section of the train and the section of the tunnel. On the other hand, the length of the nose seems to affect only the slope of the pressure drop but not the value of $\Delta P_N$.

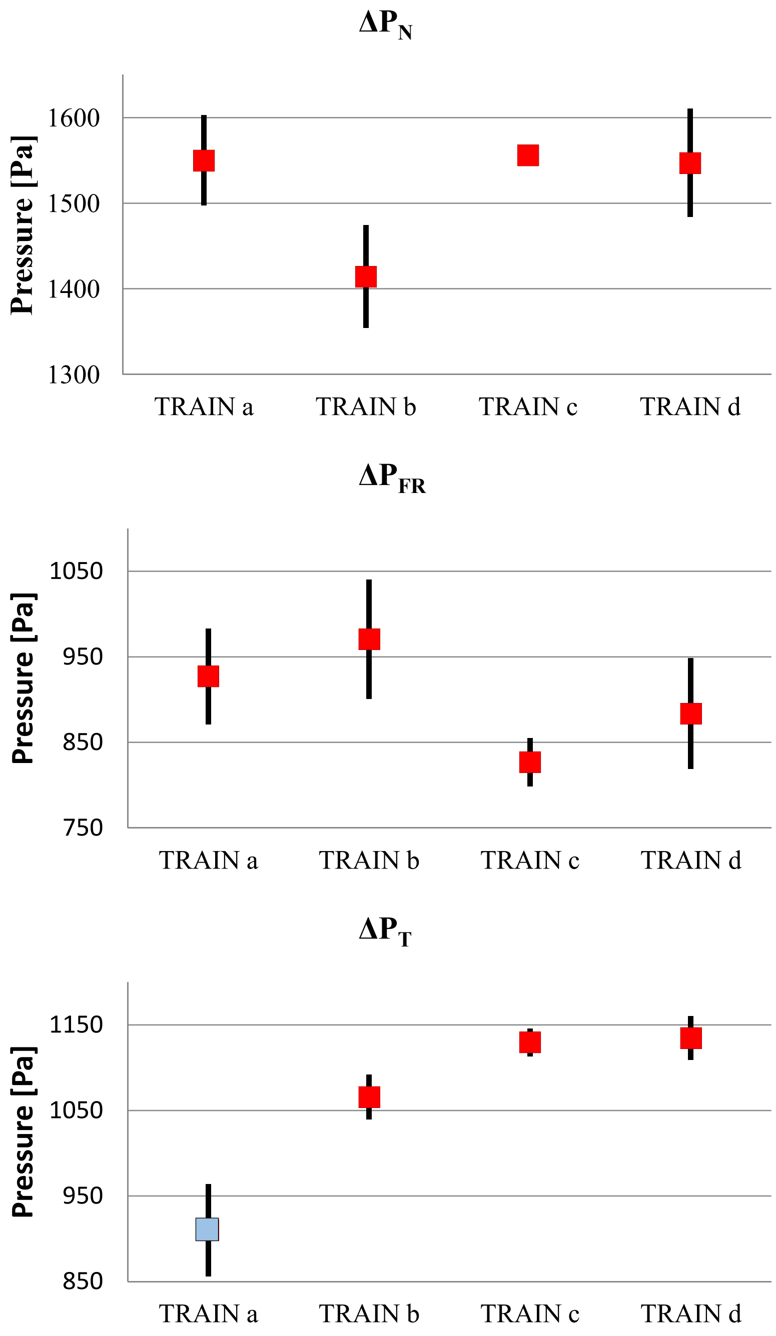


Figure 6: Pressure variations of the four high-speed trains considered. (The mean value of the $\Delta P_T$ of train a is only a part of the whole value)

### 3.2.3 Crossings of two trains

As mentioned above, during the experimental campaign 11 crossings of two trains inside the tunnel were measured. Using the two couples of photocells it is possible to identify the type, the speed and the entry instant of each of the two trains as reported in Table 3 (*Δt* is the time delay of train 2 with respect to train 1).

| # | TRAIN 1 | SPEED 1 [km/h] | TRAIN 2 | SPEED 2 [km/h] | Δt [s] |
|---|---|---|---|---|---|
| 1 | TRAIN a | 246,2 | TRAIN a | 249,9 | -2,5 |
| 2 | TRAIN a | 250,1 | TRAIN a | 232,4 | -5,0 |
| 3 | TRAIN a | 248,0 | TRAIN a | 246,0 | -4,5 |
| 4 | TRAIN a | 247,4 | TRAIN a | 238,4 | -3,2 |
| 5 | TRAIN a | 244,8 | TRAIN a | 222,0 | -13,5 |
| 6 | TRAIN b | 252,8 | TRAIN a | 245,7 | -7,4 |
| 7 | TRAIN b | 238,3 | TRAIN b | 251,8 | -8,1 |
| 8 | TRAIN b | 252,6 | TRAIN d | 251,9 | -2,6 |
| 9 | TRAIN d | 251,8 | TRAIN a | 252,8 | -5,8 |
| 10 | TRAIN d | 245,3 | TRAIN d | 252,7 | -8,6 |
| 11 | TRAIN a | 230,2 | TRAIN b | 236,9 | -9,2 |

Table 3: Type, speed and time delay of the trains involved in the crossings.

By way of example, in Figure 7 the pressures measured in the fourth crossing are reported. In these cases, the pressure waves generated by the two trains are superposed and, furthermore, they interact with one another. As a consequence the resulting ΔP is higher with respect to the single train passage.

For this reason, it is clear that it is necessary to have a numerical model able to reproduce this phenomenon, in any possible condition, able to predict the maximum pressure variation.

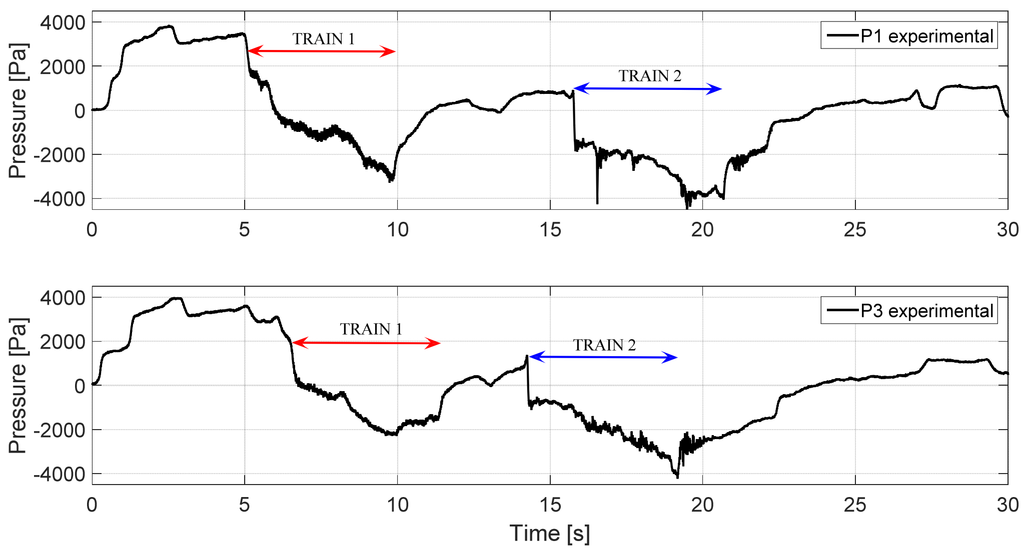


Figure 7: Pressures measured in position 1 and 3 in the crossing number 4.

# 4 Numerical simulation

As previously said, the main purpose of the numerical simulations is the estimate of the worst case of two trains crossing simultaneously in the same tunnel, intended as the critical time delay between the entries of the two trains that leads to the highest pressure variation.

The first step, however, is to estimate the parameters of the numerical models (train friction, tunnel friction, portal losses, damping, etc.) by a best-fitting technique using the data of the single passages of each type of train.

The software used for the numerical simulation is ZugDB02 of the program package DB-Tunnel. In this software, the parameters which have to be identified are:

- the friction of the train;
- the friction of the tunnel;
- a generalized damping;
- the loss coefficients of the train heads.

Furthermore, in order to have a better fitting between experimental data and numerical results it is necessary to make small adjustments also to the geometrical characteristics (section, perimeter and length of the train, length of the tunnel) and to the environmental conditions. In the author's opinion, these corrections are necessary because the aerodynamic interaction between train and tunnel is complex and the "aerodynamic shapes" of the train and of the tunnel seem to be slightly different from the "geometrical shapes".

## 4.1 Single train

The results of the optimized simulations of the single train cases are shown from Figure 8 to Figure 11. The total reported time allows to reproduce the entire phenomenon and some pressure waves reflections between the tunnel portals.

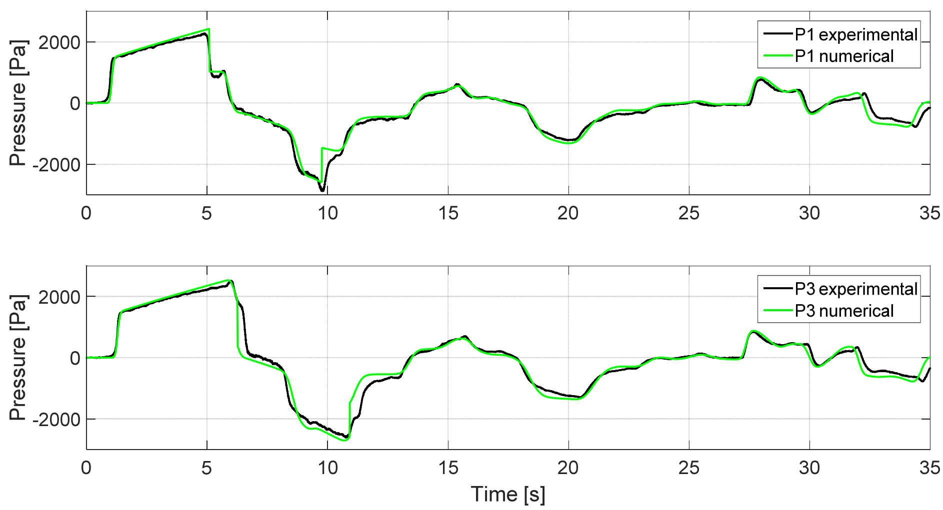


Figure 8: Time histories of the pressure measured and simulated; train a.

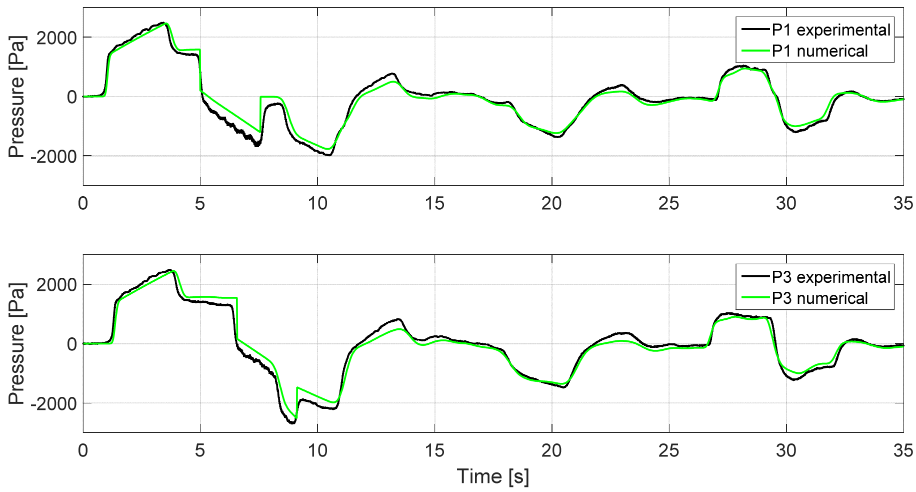

Figure 9: Time histories of the pressure measured and simulated; train b.

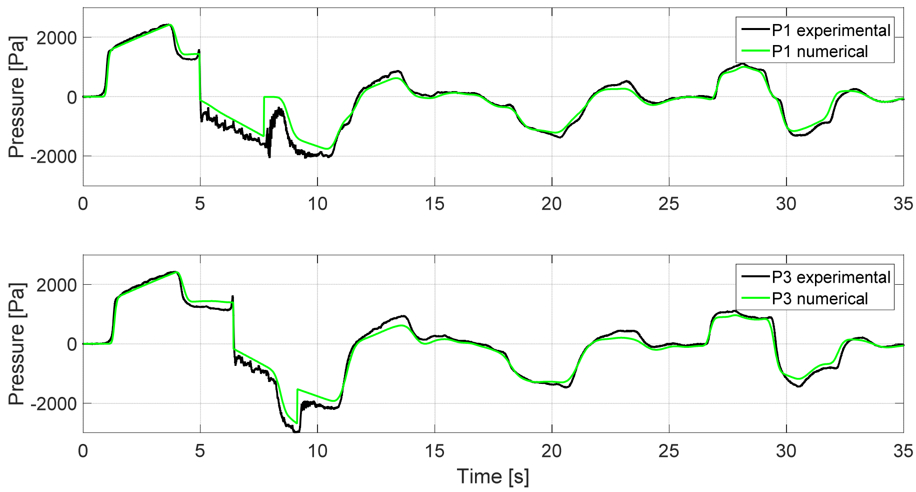

Figure 10: Time histories of the pressure measured and simulated; train c.

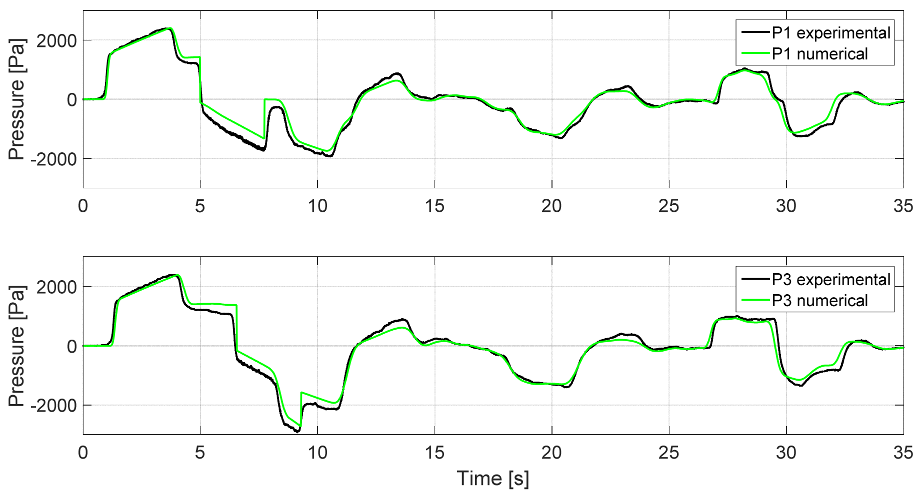

Figure 11: Time histories of the pressure measured and simulated; train d.

The comparison between the experimental data and the simulations prove the performance of the numerical model once that all the parameters have been optimized (see Table 4). The main error committed by the simulations is the underestimation of the pressure drop of the TWS that leads to an underestimation of the total ΔP as visible in Table 4.

| TRAIN | TRAIN LENGTH [m] | NOSE LENGTH [m] | CROSS SECTION [m$^2$] | PERIMETER [m] | $\lambda_{TR}$ [-] | $\xi_{TR}$ [-] | $\lambda_{TU}$ [-] | $h_{TU}$ [-] | ΔP P1 [-] | ΔP P3 [-] |
|---|---|---|---|---|---|---|---|---|---|---|
| TRAIN a | 320 | 4 | 11.2 | 11.8 | 0.014 | 0.6 | 0.0547 | 0.17 | -4% | 1% |
| TRAIN b | 180 | 6 | 9.8 | 11.3 | 0.029 | 0.8 | 0.0547 | 0.17 | -6% | -5% |
| TRAIN c | 190 | 6 | 11 | 11.6 | 0.020 | 0.7 | 0.0547 | 0.17 | -6% | -4% |
| TRAIN d | 190 | 5.5 | 11 | 11.6 | 0.020 | 0.8 | 0.0547 | 0.17 | -5% | -4% |

Table 4: Optimized parameters used in the simulations and errors.

## 4.2 Crossing of two trains

Once this numerical model has been validated for the single train passage, also the recorded situations with two trains crossing together have been simulated using the same parameters of the single passages. An example of the achieved outcomes is visible in Figure 12. The simulation accurately reproduces the experimental data, except the pressure fluctuations due to the slipstream of the trains that is not implemented by the numerical model. In general, this error leads to an underestimation of the maximum pressure variations evaluated by the simulations with respect to the ones measured in the tunnel, as summarised in Table 5.

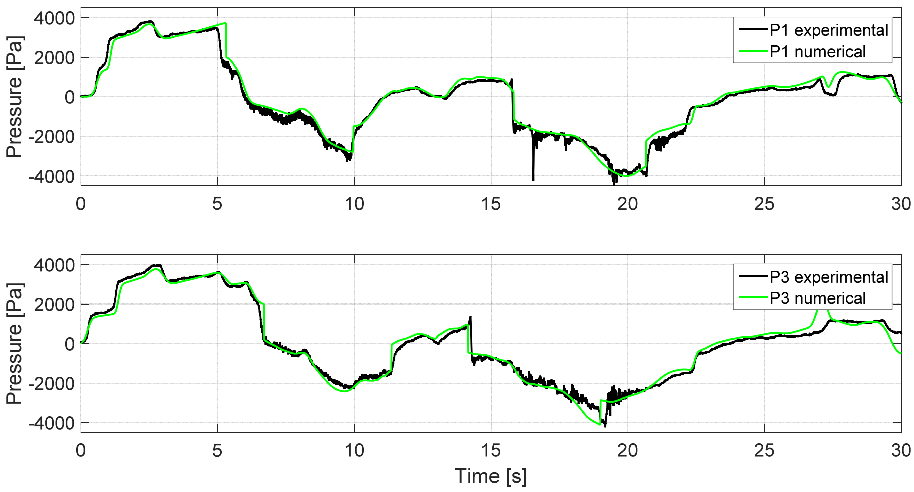


Figure 12: Time histories of the pressure measured and simulated in the crossing number 4.

| | TRAIN 1 | SPEED 1 [km/h] | TRAIN 2 | SPEED 2 [km/h] | Δt [s] | Δp P1 [-] | Δp P3 [-] |
|---|---|---|---|---|---|---|---|
| 1 | TRAIN a | 246,2 | TRAIN a | 249,9 | -2,5 | -9% | -3% |
| 2 | TRAIN a | 250,1 | TRAIN a | 232,4 | -5,0 | -13% | -24% |
| 3 | TRAIN a | 248,0 | TRAIN a | 246,0 | -4,5 | -13% | -9% |
| 4 | TRAIN a | 247,4 | TRAIN a | 238,4 | -3,2 | -8% | -4% |
| 5 | TRAIN a | 244,8 | TRAIN a | 222,0 | -13,5 | -15% | -20% |
| 6 | TRAIN b | 252,8 | TRAIN a | 245,7 | -7,4 | -12% | -1% |
| 7 | TRAIN b | 238,3 | TRAIN b | 251,8 | -8,1 | -1% | 5% |
| 8 | TRAIN b | 252,6 | TRAIN d | 251,9 | -2,6 | -11% | -7% |
| 9 | TRAIN d | 251,8 | TRAIN a | 252,8 | -5,8 | -25% | -7% |
| 10 | TRAIN d | 245,3 | TRAIN d | 252,7 | -8,6 | -13% | -6% |
| 11 | TRAIN a | 230,2 | TRAIN b | 236,9 | -9,2 | -9% | -6% |

Table 5: Summary of the errors between the maximum pressure variations evaluated in the simulations and the ones measured in the tunnel.

# 5 Conclusions

In this paper a procedure for the validation of numerical codes able to reproduce the pressures in tunnel due to train passage is proposed.

The parameters of the numerical code are set by matching the train-tunnel pressure signature measured during a single-passage of the train within the tunnel and then, without changing the parameters, the crossing of two trains is simulated.

Within the present paper, the proposed methodology has been applied to the numerical mono-dimensional code DB-Tunnel. A wide database was collected thanks to an experimental campaign carried out in the tunnel La Fornace, on the Italian railways Roma-Firenze. Several passages of four different types of trains as well as a dozen of train crossings were registered during three days.

The comparison between numerical and experimental signature (single passage) in terms of time-history is very good for all the four considered trains. The error in the evaluation of the maximum variation of pressure with the single passage is around -5%, due to an underestimation of the pressure drop, due to the entrance in the tunnel of the train tail.

The simulations of train crossings show higher errors in terms of evaluation of the maximum variation of pressure, but generally lower than -15% (except some cases where the error reached -25%). In any case, the numerical estimation is always lower than the experimental values because the pressure pulses due to the slipstream of the two crossing trains is not modeled in the numerical code.

In conclusion, the results obtained are promising. A future possible development is to measure the same phenomenon with pressure sensors placed on a test train. In this way, it will be possible to identify the characteristics of many different tunnels and, finally, to simulate all the possible situations looking for the maximum pressure variation that may occur.

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