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PRESSURE MEASUREMENTS ON REAL HIGH-SPEED TRAINS TRAVELLING THROUGH TUNNELS

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Abstract. *From November, 2006 to March, 2008 a series of tests were performed onboard a wide variety of trains in order to check their response to pressure waves generated while passing through tunnels. In this communication part of the experimental results are presented, showing the pressure waves generated and focusing on the differences caused by some parameters involved such as train length and shape or tunnel lengths. The results are in accordance with the train wave signature method and the one-dimensional pressure wave theory.*

1 INTRODUCTION

In the last years a deep transformation of the Spanish railway transportation system is being produced due to the large increase of high-speed railway lines. This has given rise to a flourishing period of innovation in both high-speed infrastructure and vehicle technology. In this frame of vehicles travelling at speeds as high as 300 km/h, or even larger, aerodynamic effects play a role in the vehicle operation, and so aerodynamic problems have focused the attention of many scientists.

Research efforts have been significantly directed to the design of high-speed trains running through tunnels because of the need to travel at high velocity notwithstanding the presence of geographical obstacles, such as mountains or rivers. Issues related to the aerodynamics in open spaces become even more involved when the vehicle runs through a gallery, since compression and expansion waves are generated when the train passes an opening or encounters a change in the tunnel cross-section. These waves produce discomfort for the passengers and give rise to further complications such as the possible damage of the vehicle and the release of spherical micro-pressure waves from the tunnel apertures, which causes environmental disturbance.

The aerodynamic problems occurring when a train travels at high speed in a tunnel are more complicated than the ones arising in open air travel. The aerodynamic drag and pressure loads on the train are strongly dependent on the pressure waves in the tunnel. Aerodynamic drag travelling in a tunnel can significantly increase, compared with that in open air. When a high-speed train enters a tunnel, a compression wave is formed ahead of the train which propagates along the tunnel at nearly sonic speed (in the same way, an expansion wave is formed at the train end). When these finite amplitude pressure waves reach the tunnel exit, the compression wave is partly reflected back into the tunnel, forming an expansion wave, and is partly emitted outside as a micro-wave. A complex wave interaction occurs inside the tunnel due to successive reflections of the pressure waves at the exit from and the entry to the tunnel. So the train meets the waves several times during its passage in the tunnel. When combined, the waves can cause relevant aerodynamic loads on the vehicle and tunnel structure, and can also affect the passenger’s comfort, when the train air tightness is not enough to attenuate the transmission of the pressure waves into the vehicles.

A number of papers dealing with such phenomena can be found in the literature, the problem being extensively studied both theoretically and experimentally. From the theoretical point of view the aerodynamics of a train travelling inside a tunnel (the aerodynamics of train/tunnel systems) is governed by a three-dimensional, unsteady, turbulent, compressible flow. However some attempts have been made to develop simple one-dimensional models which in many cases provide sufficiently accurate explanations of experimental data. On the experimental side, many laboratory tests have been performed to analyse the influence of a wide range of parameters on the waves appearing inside the tunnel (most of these parameters being concerned with the tunnel entrance geometry). Measurements in real trains, although they have been done, are scarce, probably because of the economic cost associated with experimentation with real train vehicles.

2 THE TESTS

From November, 2006 to March, 2008 series of tests were conducted onboard a wide range of trains. The main goal of these tests was to validate the capability of the air conditioning systems and the air tightness of the trains to cope with the variations of pressure generated when the trains entered into and travelled through a tunnel. The measures presented in this paper were taken with the aim of understanding the internal variations of pressure and not as the primary result of the tests.

The tunnels that were most interesting and posed most problems were located between the towns of Sagides (159 km away from Madrid) and Ricla (250 km away from Madrid) in the railway to Zaragoza.

In order to achieve the speed needed and to be free to pass as many times as possible through the same tunnels, tests were performed during the weekend nights, starting at 23.00 and concluding at 06.00. In these conditions the railway was assigned to the train, so the tests could be conducted with almost no interference from the traffic control. As a result, a minimum of two passes were performed through each of the sixteen tunnels, providing a large amount of data.Table (1) shows the tunnels in which these tests were performed.

Tunnel	Length (m)	Area (m^2)
Sagides	1786	100
Alhama	630	110
Bubierca	2433	80
Las Dehesillas	861	115
Castejón	392	100
Ateca	464	100
La Almunia	1014	100
Marivella	620	110
Paracuellos	4784	75
Sabiñan	554	110
Purroy	847	110
Las Minas	302	95
Villanueva de Jalón	1009	100
Torrecilla	888	110
Los Cortados	325	95
Las Calesas	120	95

Table 1: Tunnels in which tests were performed.

Being the goal to check the comfort of the passengers, it was a requisite of the train line operator RENFE to test all the trains that were suitable for the line, and at a later stage the “Séneca” laboratory train was added. This is a very special train, since it is commonly used for studying the line and it is a very short train but with high speed capability. Furthermore, the train’s motor coach geometry is almost identical to that of other trains in service at the moment. In Table (2) a list of characteristics of the trains that were studied is presented.

Train	Length (m)	Top speed (km/h)
Train A	201	350
Train B	200	350
Train C	107	250
Train D	250	230
Train E	107	250
Train F	48	160
Train G	180	250
Train H	85	350

Table 2: Characteristics of trains involved in the tests.

3 INSTRUMENTATION USED AND DATA CONDITIONING

The instrumentation consisted mainly on several pressure sensors. Some of them were installed to measure the internal pressure and are not of this paper's interest. The rest were installed to sense the static pressure in the outside of several parts of the train, and its measures are discussed in this communication.

The equipments used during the test were conditioned by the fact that the train availability was very short, since all the instrumentation had to be mounted, used and dismantled during one night.

Being the results of the tests depending on the air tightness, sealing had to be kept, and so the instrumentation was designed accordingly. In order to get the pressure signals from the outside, false button plates were installed at the doors with 8 mm pressure taps. In some cases the static pressure port of the train was used, placing the sensors in parallel to those belonging to the train.

The instrumentation used for each train was slightly different, due to the requisites of each train manufacturer, but the backbone of the equipment was almost the same.

The sensors were installed in pairs in three sections of the train, namely the head, a point near the centre and the tail. Each pair consisted on a internal pressure sensor and an external pressure sensor. Measurements were made during passes in both directions, so the instrumentation placed at the motor coaches behaved sometimes as "head" and sometimes as "tail". Sensors in both motor coaches of the train were placed at a distance of nearly 10 metres away from the train ends.

Electric noise was one of the first concerns, due to the fact that signal wires would have to go across the electric equipment rooms of the trains and extend for as long as 100 metres. Pressure sensors with a standard 4-20 milliamp current output were selected to reduce the noise and also high-quality shielded cable was used.

The foreseen high speed of the studied phenomena imposed the need for piezo-electric transmitters with one millisecond response time.

Altitude change effects were of the same order as the expected pressure variations. To prevent the saturation of the sensors, electrically operated valves were installed, so the pressure was equalized on both sides of the sensors prior to the entry into the tunnel. A few seconds before the entry, the reference port was closed, and the pressure measured was almost zero at the entrance of the tunnel. This allowed the use of differential pressure sensors with a range of only ±7000 Pa in most cases.

Even with the valves installed, in several cases the variations caused by the altitude change are of the same order as the variations caused by the interaction between train and tunnel. This can be seen in Fig. (1).

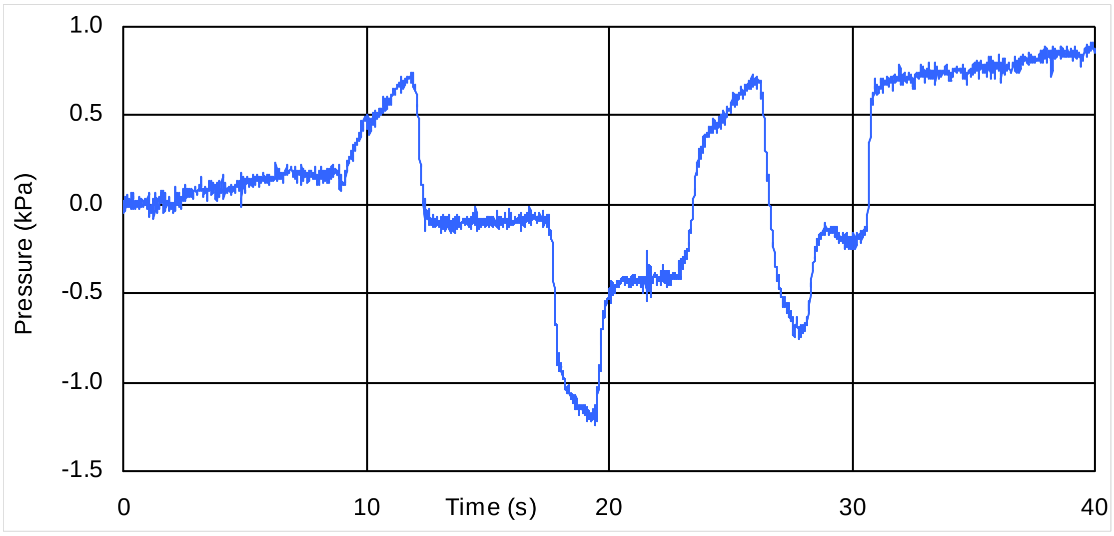

Figure 1: Pressure variations at Sagides tunnel. Train speed 245 km/h. Measurements from the head of the train during the whole pass through the tunnel

In order to get a good synchronization of the samples all the signals were collected by a single central acquiring device, a National Instruments CompactDaq chassis with two analog to digital modules, each one capable of acquiring four channels. A sampling frequency of 100 Hz proved to be appropriate, showing the effects with sufficient detail while keeping a contained size of the data file.

The acquisition modules used were two National Instruments 9215 with 16 bit resolution and the capability of measuring four channels simultaneously. Precision resistors were installed to convert the milliamp signal to a voltage signal.

Data was collected without any filtering and Butterworth low-pass filters were applied later to the acquired signals.

Additionally to the pressure signals, the temperature was monitored and in several cases the command signals to the air conditioning system were also acquired.

To protect the equipment from the low quality of the electric power available in the trains and to cover the neutral zones, a UPS was installed.

4 ANALYSIS OF THE RESULTS.

4.1 Different tunnel Lengths.

When a train enters a tunnel, it generates a set of pressure waves that are reflected at the end of the tunnel in the form of expansion and compression waves. This process is repeated several times and so the train encounters the reflection of the waves that the train itself has generated. The length of the tunnel is the main factor that determines the time elapsed between the entry of the train and the moment of the first and successive reflected wave encounters. The shape of the pressure variations is, then, almost the same while the time elapsed between those variations depends on the tunnel length.

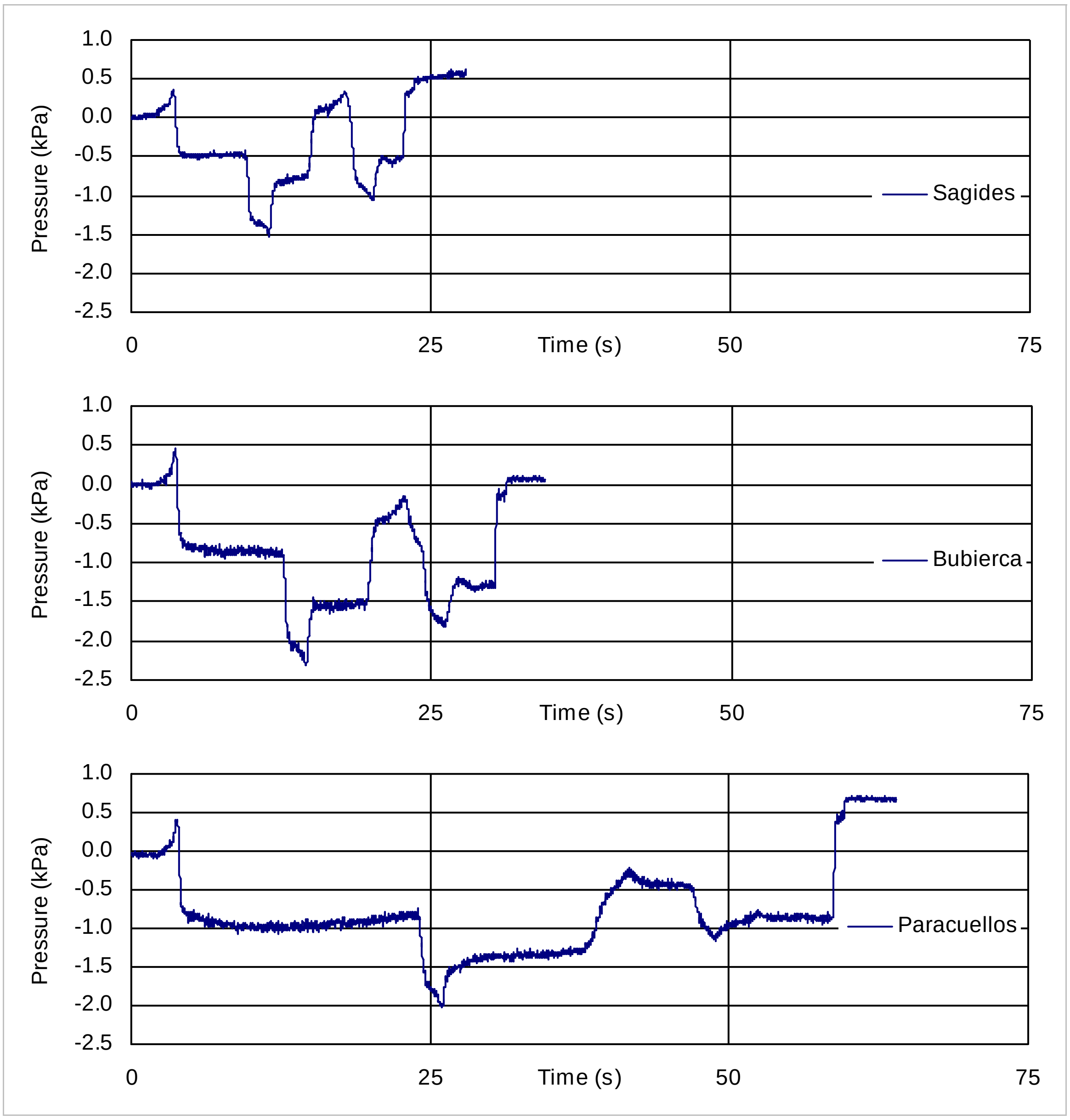

Figure 2: Pressure variations at the tunnels of Sagides (1786 m), Bubierca (2433 m) and Paracuellos (4784 m). Train speed from 285 km/h (Sagides) to 300 km/h. (Bubierca and Paracuellos). Measurements from the head of the train B during the whole pass through the tunnel.

4.2 Different trains passing through the same tunnel.

The train speed is the key factor for the wave intensity. In Fig. (3) we can see the effects on several trains with different speeds. Also, as the train stays longer in the tunnel, more reflected waves have time enough to reach the train. To see this increase in the number of waves, the train has to stay into the tunnel more than a certain critical time.

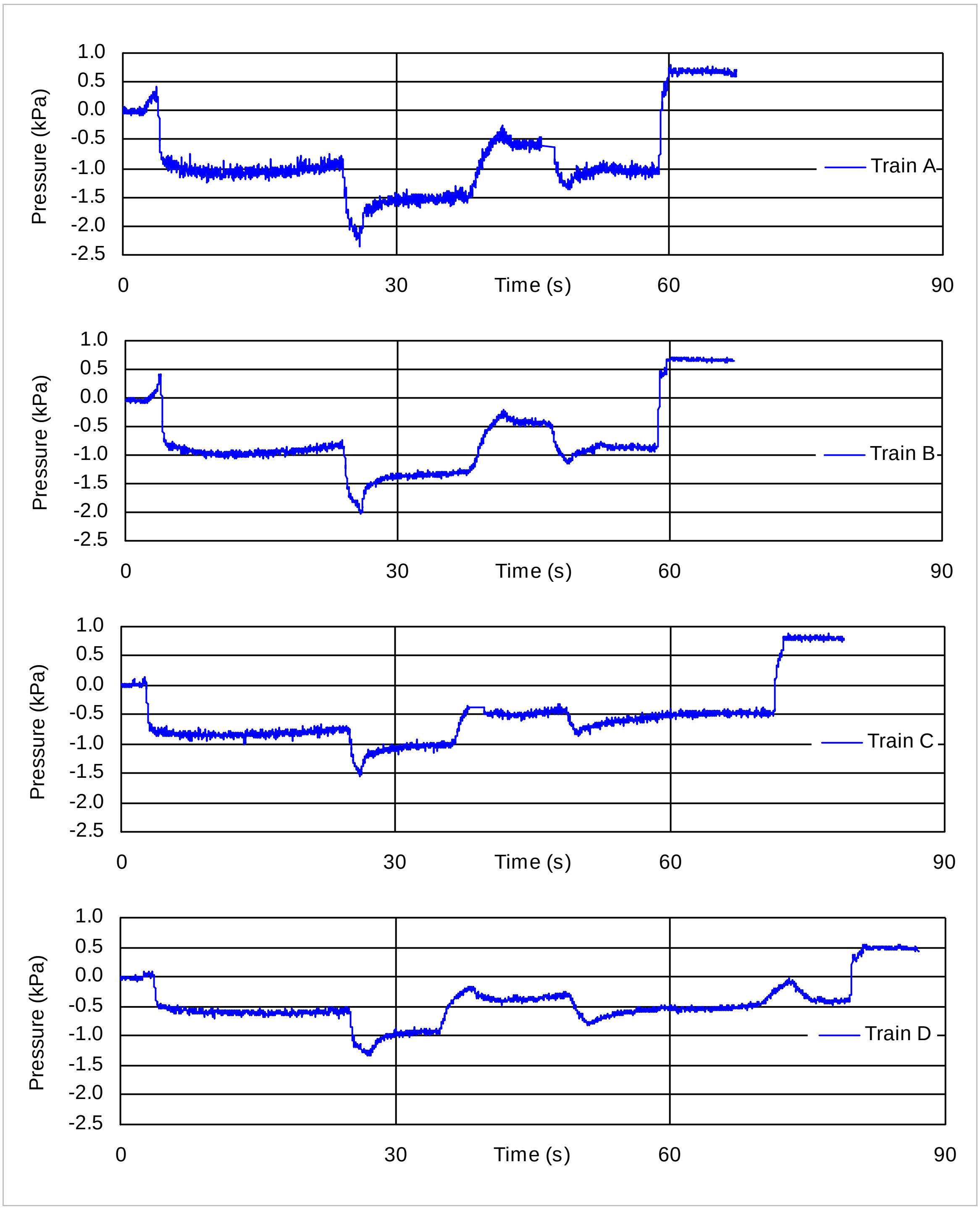

Figure 3: Pressure variations at Paracuellos tunnel generated by several trains. Train speed varying between 220 and 300 km/h. Data from the center sensor.

4.3 Different train lengths.

During the tests we had the opportunity to compare two different trains with the same shape but very different lengths. The main differences were found in the pressure variations in the head at the entry into the tunnel. As we can see, the overpressure builds up in a very similar way, but the expansion wave generated by the tail reaches the head of the shorter train earlier than the longer one's.

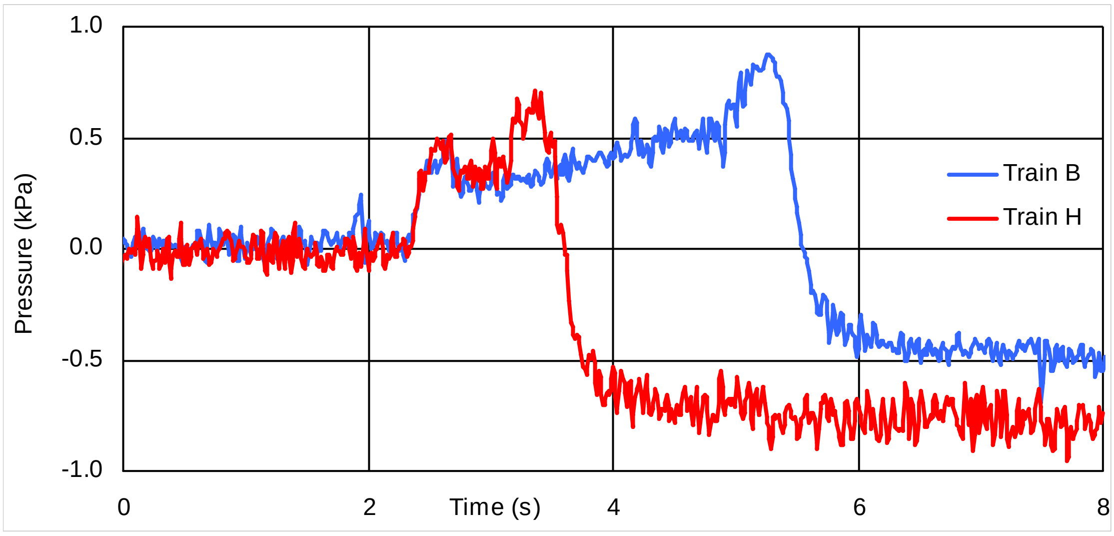

Figure 4: Pressure variations at the entry of Paracuellos tunnel generated by two trains with similar shape and different length. Train B is 200 m long, train H is 85 m long. Speed 300 km/h. Data from the head sensor.

4.4 Different train shape.

While the shape of the train head does not seem to determine the values of the pressure variations for a given speed, it seems to determine the way in which the overpressure builds. In the case shown in Fig. (5) both trains were travelling at 300 km/h. Both trains have similar length and cross-section. The larger amount of noise seen in the graph for the train marked in red can be of either aerodynamic or electrical origin.

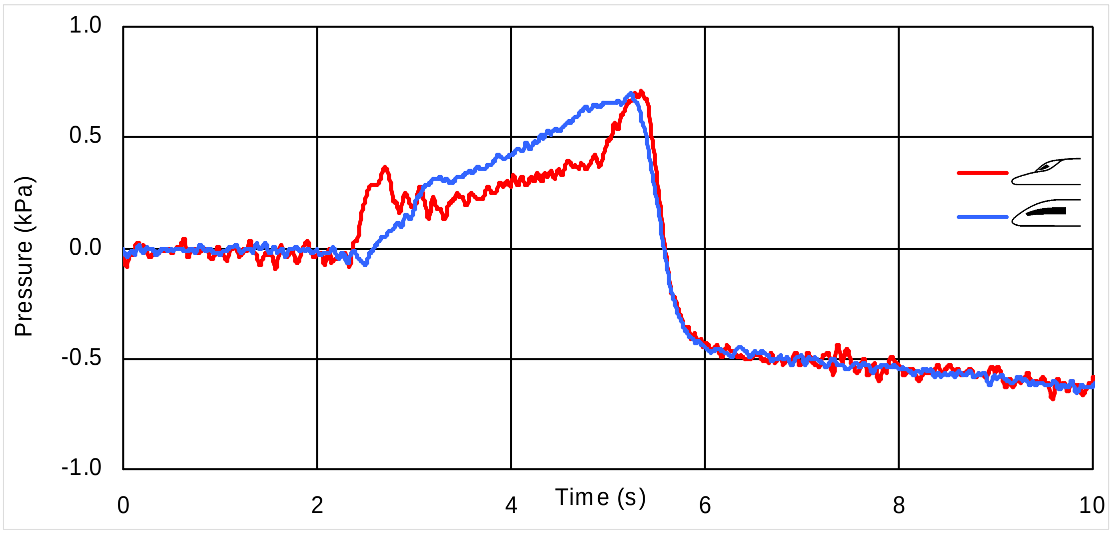

Figure 5: Pressure variations at the entry of Paracuellos tunnel generated by two trains. Data from the head sensor. Train speed 300 km/h

4.5 Pressure variations at different sections of the train

As can be seen in Fig. (6) different sections of the same train undergo different variations of pressure. While the head causes a compression wave and receives an overpressure as high as 800 Pa, in the rear section there is no overpressure, and an expansion wave is created. Similar results are obtained in all the trains under study, being the explanation quite simple: While the head of the train encounters still air, the tail encounters air in motion accelerated by the viscous forces established between the train and the tunnel. The deeper under pressure is explained by the higher velocity of the air in the tail of the train.

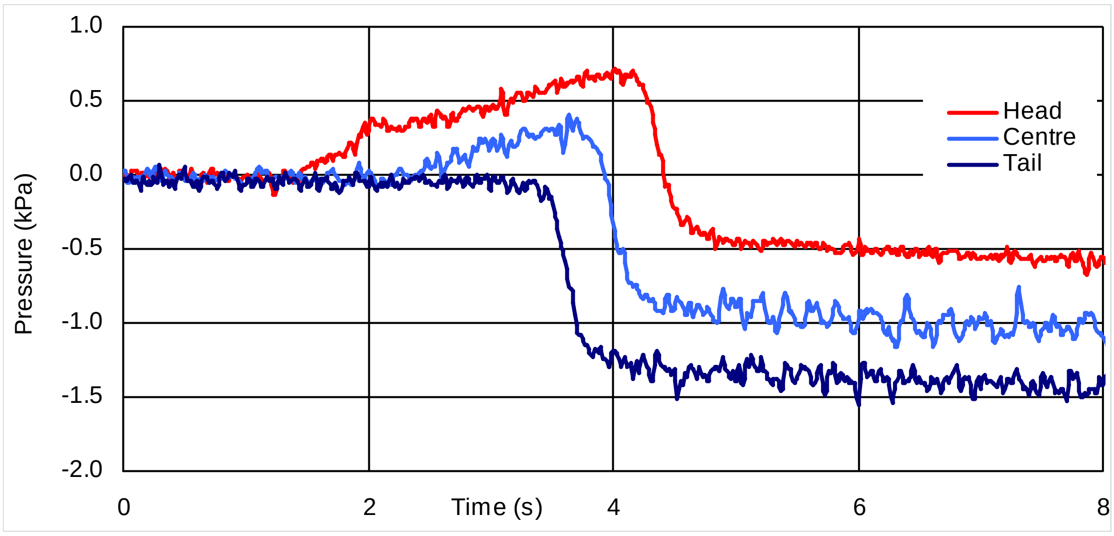

Figure 6: Pressure variations at several sections of the train. Entry of the Paracuellos tunnel onboard train A at an approximated speed of 300 km/h

5 COMPARISON WITH PREVIOUS THEORIES

When a train enters a tunnel, its head generates a compression wave. This wave propagates along the tunnel at nearly sonic speed. In the same way, an expansion wave is formed at the train end and propagates at the same speed. These waves are depicted in Fig. (7) as CW (compression wave, in green) and EW (expansion wave, in blue).

The finite amplitude pressure waves reach the tunnel exit, and then the compression wave is partly reflected back into the tunnel, forming an expansion wave, and is partly emitted outside as a micro-wave. Correspondingly, the expansion wave is reflected as a compression wave.

In the upper part of Fig. (7) the pressure variation for train B while crossing Paracuellos tunnel is shown. In the lower part a scheme shows the pressure waves generated, being the vertical axis the distance traced adimensionalised with the total length of the tunnel.

The pressure changes that the train undergoes are generated by the encounter with the pressure waves that the train itself has generated. Then, in the figure, the pressure changes correspond to the crossing of the lines representing the waves and the position of the train.

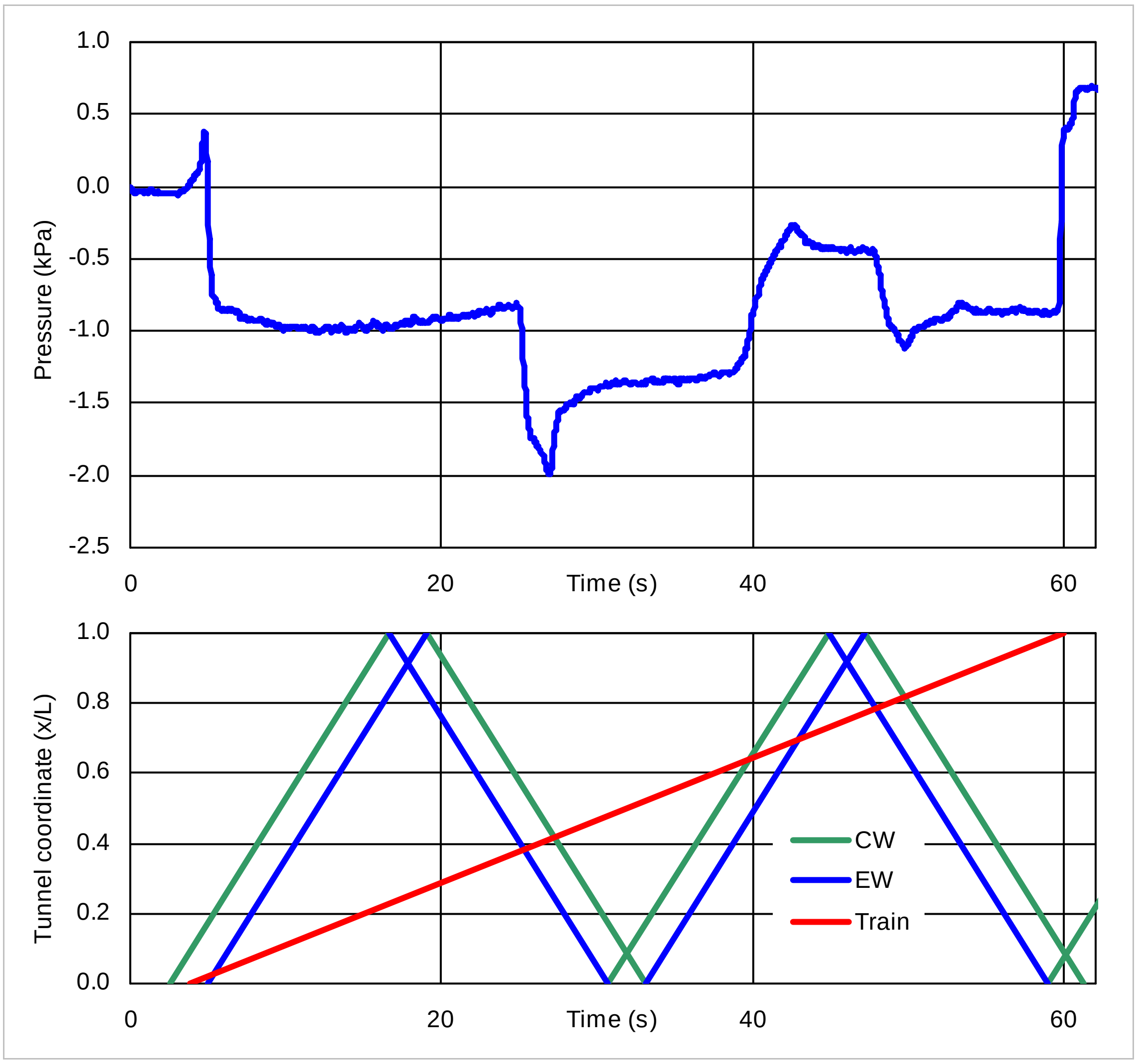

Figure 7: Comparison between pressure wave theory and experimental data from Paracuellos tunnel onboard train B at an approximated speed of 300 km/h

The measurements presented in this communication are in accordance with the train wave signature and the pressure wave theories, summarized in Fig. (7) but also show a greater detail in certain aspects. For example, the shape of the first compression wave is clearly different between the trains under study, a detail that cannot be deduced from any of the theories mentioned. These details, and also the influence of the tunnel geometry or section and many other parameters involved are to be studied deeper in the future. The processing and understanding of large amounts of data such as the ones briefly presented in this paper is a long term and time-consuming task that has to be taken with care and patience in order to extract the high quantity of information contained inside.

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