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Influence of Aerodynamics in Tunnels Design

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Abstract

There are a significant number of factors to consider during tunnels design in order to increase effectivity in construction, reduce schedules, and provide more appropriate cross-sections for each tunnel depending on its location, conditions of exploitation and rolling stock among others.

When a high-speed train enters in a tunnel there is an overpressure and depression in head and tail that propagates along it at the speed of sound, reflecting each time they reach the portals of the tunnel. These variations of pressure, in addition to increasing the aerodynamic drag of the train, can affect the health and comfort of passengers.

Aerodynamically speaking, it is recommended meeting health and comfort criteria. The health criterion is mandatory in accordance with the Infrastructure Technical Specification of Interoperability (TSI). The comfort criteria are variable depending on the country and are usually more restrictive in terms of sizing the free cross-section of the tunnel.

During the last years, designers have developed methodologies and tools to use in calculations for achieving the best tunnel conditions for all the counterparts.

There are two consequences extracted as a result of the development of the methodologies. Firstly, the reduction of the free cross-section of the tunnel to the minimum values as required by the geometrical conditions. Secondly, being able to optimize train speed along the tunnel while complying with the aforementioned criteria, which leads to reductions in cost, improved conditions of exploitation and reduced travel times.

However, aerodynamics research cannot be limited to these studies. The future will require speed improvements and longer tunnels while keeping the same standards of safety and comfort. Currently new factors such as overpressures or depressions in tunnel installations or sonic boom effect are being investigated and included in project requirements.

In relation to this, INECO has developed a software capable of calculating the aerodynamic effects in every specific position within the tunnel, train or the installation. The software most interesting functionality is the capability of modelling and mitigate sonic boom effect.

Keywords: Aerodynamics, free cross-section, tunnels, speed, comfort criteria, health criterion.

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1. Introduction

When a high speed train enters in a tunnel there is an overpressure and depression in head and tail that propagates along it at the speed of sound, reflecting each time they reach the portals of tunnel. These variations, among other aspects like the increasing aerodynamic drag of train can affect the health and comfort of passengers.

To avoid the above effects designers, have to comply with several criteria. By one hand, the Health Criterion included in Infrastructure Technical Specification of Interoperability (TSI) that is mandatory. On the other hand, Comfort Criteria included in the different recommendations and national standards which at the end result more restrictive in terms of sizing of the final crosssection.

Throughout this paper, in a perspective vision about what these 25 years have been occurring will be transmitted in order to put in the reader's mind the fast evolution and improvements that the Aerodynamics Studies have introduced in the designing of high speed tunnels.

2. Current spanish regulation

In Spain two main standards are actually employed in relation to sizing the free cross-section due to aerodynamic constraints of high speed tunnels.

2.1 Health Criterion

Infrastructure Technical Specification of Interoperability (TSI), 2014, November 18th, regulates the health criteria. In the article 4.2.10.1 Maximum pressure variations in tunnels, states the following:

- Any tunnel or underground structure intended to be operated at speeds greater than or equal to 200 km/h has to provide that maximum pressure variation, caused by the passage of a train running at the maximum allowed speed in the tunnel, do not exceed 10 kPa during the time taken for the train to pass through the tunnel.
- Above requirement has to be fulfilled along the outside of any train complying with the Locomotives and Passenger TSI.

This is mandatory for all cases, and trains are considered non-sealed trains.

2.2 Comfort Criteria

For the regulation of comfort criteria, in Spain there are 2 main standards.

Draft of the IFI ("Instrucción Ferroviaria para el proyecto y construcción del subsistema de Infraestructura"), now in approval stage, states the following criteria:

TRAIN	TUNNEL	Pressure Difference (kPa)	t(s)
Non sealed trains	Single track	2	4
	Double track	4	4
Sealed trains (τ = 6s)	Single and Double tracks	1	1
		2	10

Table 1. Comfort criteria included in draft of IFI

However, ADIF (Spanish Railway Administrator) includes in the standard NAP 2-3-1.0 (2015), in section 3.2 “Comfort criteria” the following summarized in the next table:

TRAIN	TUNNEL	Pressure Difference (kPa)	t(s)
Non sealed trains	Single track	2	4
	Double track	4	4
Sealed trains (τ = 6s)	Single and Double tracks	1	1
		1.6	3
		2	10
		3kPa during all the time the train is in tunnel	

Table 2. Comfort criteria included in NAP 2-3-1.0 (ADIF)

NAP 2-3-1.0 (2015) also indicates that the UIC Leaflet 779-11 (2005) Code cannot be used for sizing, just for pre-sizing of the cross-section. However, during the first years of development of the high speed in Spain, the UIC Leaflet and the Recommendations from the Ministry of Works were also used.

3. First steps

25 years ago or maybe before, aerodynamic issue was a totally unknown phenomenon in Spain. The main reason was that this issue had never been considered because high speed lines were not a reality in Spain.

The way in which as designers considered this aspect was the following. First of all, the UIC Leaflet was considered for both constraints, health and comfort.

These first steps, which are described below, do not have to be the same as those in other countries, since the evolution in this area has been very fast. On the other hand, the dimensioning that is described is due to aerodynamic effects without taking into account the geometrical condition, always existing, and which was always taken into account as will be seen below.

During the firsts years of evolution in the design of tunnels of High Speed Lines, the tools that later would be available, have not been developed yet. This was the main reason why initially the calculations, or rather estimations, were made in Spain by means of the leaflets provided by UIC Code 779-11 (2005).

These leaflets were first developed in 1995, followed by the European Rail Research Institute (ERRI) Specialist Committee C218 that in 2005, through the use of the SEALTUN and AIRSHAFT programs, these international leaflets were created for users. The main idea of these leaflets was to facilitate the sizing of the high-speed tunnel cross-section. Note that all the recommendations, criteria and considerations that included these leaflets were the same ones that were included in the 2008 TSI’s.

The calculation factors that the leaflets from UIC Code considered for sizing cross-sections are the following:

- For single track tunnels it is assumed that only one train is in the tunnel at any given time. Although it is true, the current single track tunnels are much longer than then and could allow several trains in a tunnel at the same time.
- For double track tunnels, it is considered that crossing trains can enter at the same time or at different times in the tunnel.

The type of rolling stock that is contemplated is the following:

Type of train	Rate of speed considered (km/h)
Standard Modern train	180 – 220
Streamlined high-speed train	200 - 350

Table 3 Types of trains considered in UIC Code

However, it is also included the following footnote:

> *"For trains and speeds which are outside the scope of this leaflet, it is recommended that specific calculations be undertaken to determine the design area, using a one-dimensional computer simulation method of the type used in this leaflet for instance"*

- Interpolation is allowed when necessary, but extrapolation is not allowed. Furthermore, in this sense it is indicated that if extrapolation is necessary, specific calculations should be performed using a one-dimensional program.
- The passage of freight trains it is not contemplated, therefore if these are necessary the verification must be done by means of specific calculations.

In short, there were a number of constraints that were gradually limiting the use of the leaflets and directing the aerodynamic calculation towards the use of specific uni-dimensional calculation programs that allowed individual modelling for each case. The most important limitation was the length of the tunnels, which were increasingly longer so in some cases extrapolation was necessary and was not allowed.

It was therefore necessary to start using one-dimensional programs.

4. Thermotun

Throughout 2007, at INECO, an innovation project was developed, which consisted of validating the results obtained through the use of THERMOTUN software were the same as the full scale measurements performed in tunnels. While this software was recognized worldwide, as one of the best aerodynamic calculation software, in Spain was unknown, therefore INECO carried out the verification with the collaboration of ADIF.

During the development of the project, measurements were made in the tunnels of the Madrid - Zaragoza LAV, in particular in Dehesillas, Castejón and Bubierca double track tunnels.

Measurements were also made in the single track Guadarrama tunnel of LAV Madrid - Valladolid.

In addition, to assess the passengers exposure to pressures while crossing a tunnel, measurements were made with the inspection train. Pressure gauges were installed within the train for that purpose.

The characteristics of the instrumented tunnels are the following:

Tunnel	Length (m)	Free Crosssection (m²)	Average speed (km/h)*	Type of train
Dehesillas	861	81	275	S-102, S-103, S-104 y S-120
Castejón	392	115	278	
Bubierca	2,434	76	278	
Guadarrama	28,400	51.025	300	

Table 4 Characteristic of tunnels analysed by Innovative Project

The instrumentation was set as follow:

- Sensors in the tunnel: Three control sections were installed in each tunnel, one in the centre of the tunnel and the other two near the two portals. If the tunnel contained emergency stop areas or interconnection galleries, the control sections were intended to be located close to these zones.
- Air velocity, atmospheric pressure and temperature were measured. Anemometers were placed on the sidewalks and windlasses were installed at the top of the vault. To measure the piezoelectric pressure, sensors of pressure were used in the sidewalks at a height of a meter and a half. The sections in which the measurements were made were 120m from the inlet and outlet portals as well as the middle on the tunnel. In each section a speed and pressure meters were set up.

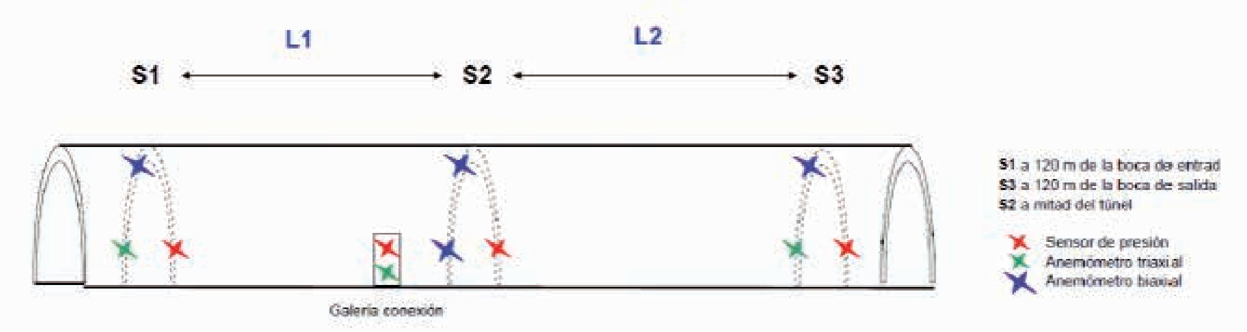


Figure 1 Control sections included in tunnels

- Sensors in the inspection train. The piezoelectric pressure sensors were placed on the roof of the train or installed on a metal plate in the train windows. They were placed in the middle of the driving head, in the central train car and in the other driving head, all of them outside.

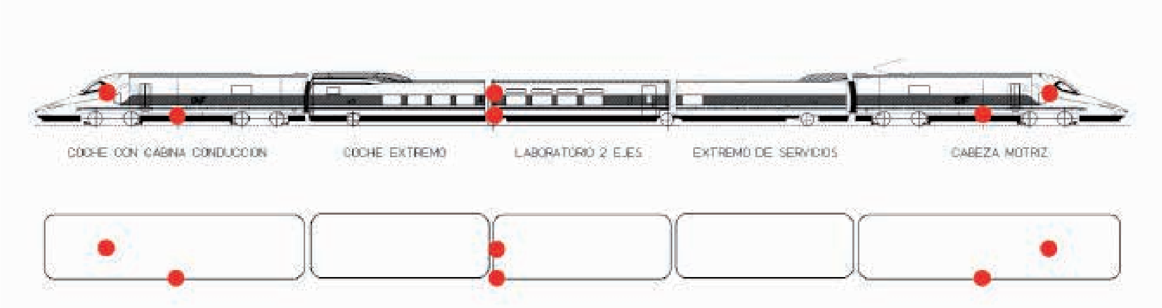


Figure 2 Control sections included in the inspection train

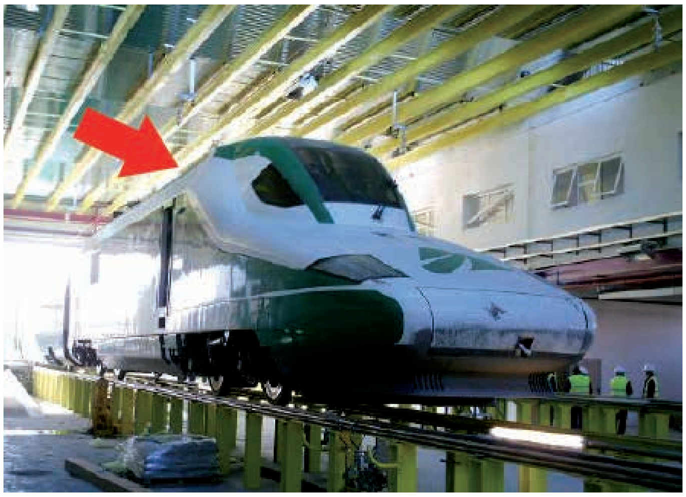


Figure 3. Inspection train from ADIF

The auscultation of the tunnels was carried out from late 2007 to early 2008. The obtained data presented a great similarity with real-scale tests data and simulations carried out with ThermoTun, which meant the use of Thermotun software in Spain as calculation software was authorized by ADIF.

The following is an example of one of the graphs that were obtained by comparison between the auscultation and the full scale tests. It belongs to instrumentation section S1 of the Castejón tunnel at a speed of 278km/h and the S -103.

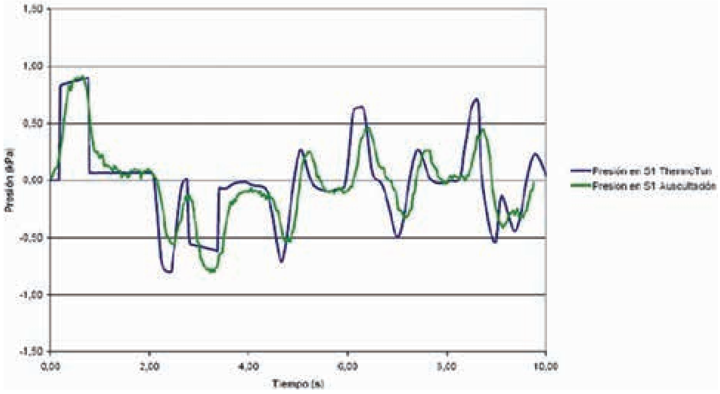


Figure 4. Comparison ThermoTun and full-scale test in Castejón Tunnel.

5. Aerodynamic calculations

Different aerodynamic studies have been carried out at INECO over the years looking for improving the circulation conditions of the infrastructure and the design of tunnels in general. The studies have been carried out working with ADIF and other private entities in a collaborative approach improving the circulation conditions of these infrastructures and the design of tunnels in general.

5.1 Tunnel cross-sections optimization

From 2008 until the end of 2012, a study was developed that enabled the analysis of almost 50 tunnels included in the High Speed Railway Network of Spain. The objectives are summarized in the following aspects:

- Analyse compliance with aerodynamic regulations in terms of health and comfort criteria. At that time the 2008 ETI was in force, which was used for dimensioning of the health criterion. The ADIF IGP-4.1 standard was used for the analysis of the comfort criterion.
- In the case of compliance with the initial data (type of cross- section, longitudinal profile and speed), a section optimization was carried out, resulting in section reductions that were implemented for the following project phases.
- If these criteria were not met, two alternatives were considered: a bigger cross-section was analysed or, if considered appropriate, a possible reduction of speed was contemplated assessing reductions of 5km/h at a time with the aim of not penalizing in excess the final exploitation of the line.

It should not be forgotten that the objective of the development of the High Speed Railway Network was and still is to obtain a High Speed Railway Network that allows acceptable travel times at a relatively inexpensive cost.

With all these premises, the following are the most important results obtained in the project:

- A large majority of the proposed tunnel cross-sections were optimized. There was only one tunnel in which it was not possible, (3rd Tunnel of the Pancorbo - Ameyugo section) in which the section had to be increased by 10m2.
- There were very specific tunnels in which it was only a question of checking compliance with both health and comfort criteria since the starting sections were the minimum stipulated by ADIF in the IGP-4.1. This suggests that the minimums established by ADIF in its regulations are optimised to the aerodynamic needs. These values were 85m2 for the case of double track section and 52m2 for the single track case.
- Given the great versatility of the calculation code used (ThermoTun), it was possible to model the tunnels in different situations. For example, in the case of the Temerosa tunnel, the actual conditions of the analysed tunnel was modelled. In this tunnel three specific narrower sections exist due to constructive needs and were analysed with detail.

It is noteworthy that with the UIC 779-11 Code it is not possible to reflect this situation of the tunnel, which means that the results obtained when using these leaflets are not completely accurate.

The works carried out solved situations during the execution of the tunnels, demonstrating a great adaptability of the calculations to real situations. In this way, it was possible to update the aerodynamic study to the existing conditions of the infrastructure and to introduce changes of speed during the stage of exploitation.

In view of the conclusions drawn in the study, the following points are highlighted:

- The optimization of the free cross-sections of the tunnels has allowed to achieve savings in construction costs derived from the reduction in the concepts of excavation, support system and lining.

- In cases where the section could not be reduced, either because it was the minimum section according to the IGF 4.1 of ADIF, or because it was not possible to reduce it due to other reasons, it was possible to carry out a speed sensitivity study, to determine the maximum speed of circulation of the trains inside the tunnels with the conditions imposed. This improves and optimises the operating conditions.

- ThermoTun's great versatility and flexibility against the UIC 779-11 tokens. This type of calculations allows to implement changes in the layout of tunnels, trains, speeds that the chips do not allow, so it is not possible to quickly adapt them to a construction situation in which changes can occur suddenly.

However, over the years, the following must be taken into account:

- During the last years there have been changes in the characteristics of the rolling stock. This means an improvement of the conditions of the tightness of the trains, as well as the geometrical and aerodynamic characteristics thereof, which make the results obtained from the aerodynamic calculations with the current trains better and better. This makes possible, from the point of view of the operation, to increase speeds while meeting the criteria of health and comfort. Therefore, it is recommended that, if you want to increase travelling speeds, these aerodynamic studies are performed.

- Currently there are many tunnels in Spain that were built without carrying out this type of studies. In many cases, conducting a study of these characteristics could provide with circulation guidelines for trains that improve operating conditions.

5.2 Interoperability certifications. High speed lines to levante and Barcelona

Another relevant piece of work carried out has been the certifications of interoperability, have been carried out for two reasons. On one hand, to demonstrate compliance with the Infrastructure TSI under the supervision of the NoBo (Notify Body). On the other hand, to assess how fast it is possible to circulate complying with such regulations.

With that purpose, studies have been carried out for the Levante High Speed line and the Barcelona - Figueras line.

In the case of the Levante line, S-130 and S-112 trains were considered as well as a generic interoperable train that complied with the Rolling Stock TSI. The calculation speed was 300km/h for a total of 22 tunnels.

In the study of the Barcelona line, the studies were carried out with two types of trains, a S-103 circulating at 350 km/h, and an S-112 circulating at 330 km/h.

In all cases, trains of 200 and 400m long were analyzed. For the case of double track tunnels the following train crossings were considered: 200-200m, 200-400m and 400-400m.

5.3 Construction stage. Aerodynamic studies

On many occasions, one of the problems that a contractor deals during the execution of a tunnel is the "entry into section", or, in other words, the occurrence of convergences and closure of the section. In these cases, it is considered appropriate to carry out an aerodynamic effect study in which introducing the new characteristics of the tunnel, including the location and length of the existing narrowing, demonstrates that aerodynamic health and comfort criteria are still met, or if these are not met, determine the speed value that makes these compliances possible

5.4 New explotaition speeds

Another benefit of aerodynamic studies is the analysis of the possibility of increasing the speed of circulation aiming to achieve improvements in the operating conditions. In these cases, the infrastructure is actually built and takes some time in service, so just the parameter of speed is studied in these cases

As it can be observed, aerodynamic studies are an increasingly important tool for the development of high-speed rail tunnels, since it is a typology of studies that can be carried out over the entire life of the tunnel. It has influence on parameters as diverse as size and type of the section and trains speed.

6. Sonic boom

6.1 Introduction

A major evolutionary step has been that the European high-speed networks are gradually increasing traffic speeds as signaling and security systems allow. In both Asia and Europe, highspeed tunnel networks with speeds in excess of 250km/h have developed considerably in recent decades. Most of these tunnels were designed as a double track monotube since they were more economical and because the tunnel lengths were lower than the current ones.

The construction of tunnels with one type or another of cross-section greatly conditions the aerodynamic effects (overpressures, depressions and sonic boom) that occur in these tunnels. However, there is a tendency for the design and construction of bitube tunnels.

Currently, due to the development that is taking place in the High Speed Railway, tunnels are being built increasingly longer, so there is a generalized tendency to design the tunnels as single track tubes. The main reasons are:

- They are considered safer due to the reduced probability of collision of trains, and due to the better evacuation and rescue conditions.

- Maintenance is performed in better conditions of safety as it is possible to use one tube while the other is closed to traffic.

The main disadvantages are the higher costs of construction and operation.

Switching from dual track sections to single track tunnel sections involves the following aerodynamic considerations.

- Due to the existence of a smaller cross-section in the case of single track tunnels, the pressure fluctuations are greater.

- However, interference with other trains is lower, which implies better compliance with the required comfort criteria.

- In relation to micro - pressure waves (sonic boom), the probabilities of occurrence increase due to a smaller section.

- On the other hand, the presence of slab track instead of a ballasted superstructure, which is very common nowadays given its lower maintenance cost, increases the probability of the sonic boom phenomenon.

Since 2005 - 2006 the existence of the sonic boom phenomenon in Europe has been observed when the lines are put in service or when the speed increases. Until then it had not been observed due to the preference of double-track tunnels versus single-track tunnels.

- In Germany in 2005, this phenomenon was observed on the Nuremberg - Ingolstadt line in the first start - up tests in several bitube tunnels of about 7.2 and 7.7km respectively.

- Here in Spain, in the High Speed line Madrid – Valencia it has been detected in the tunnel of La Cabrera, bitube and about 7km in length. Also in the LAV Madrid - Valladolid / Medina del Campo this effect has been detected in the bitube tunnel of San Pedro of about 8.7km in length.

- In Japan, in 1975, the presence of this phenomenon was detected in the tests of the Okayama - Hakata line of the San - Yo section of the Shinkansen. Until that time, in Japan there was not any legislation limiting the phenomenon.

6.2 Decription of the sonic boom phenomenon

As it was mentioned above, when a high-speed train enters a tunnel, there is an overpressure and depression in head and tail that propagate along the same at the speed of sound, reflecting each time they reach the portals of the tunnel.

At the outlet portal of the tunnel, most of the pressure wave is reflected as an expansion wave propagating in the opposite direction towards the inlet portal. However, part of this wave is emitted in all directions outside the tunnel in the form of impulse-type micro-pressure waves, which generate a detonating sound in the vicinity of the outlet of negative environmental effects.

Thus, the phenomenon of micro - pressure waves has three phases:

- Generation of the compression wave by the entrance of the train in the tunnel. The shape of the compression wave generated depends on different parameters such as: areas of the train and tunnel, geometry of the nose of the train and speed of the train among others.
- Propagation of the wave through the tunnel. The propagation of this wave occurs at the speed of sound, and is affected by the inner structure of the tunnel: tracks, platform ...
- Radiation of part of the micro - pressure wave to the outside (sonic boom). As the velocity of the train increases at the entrance to the tunnel, the amplitude of the pressure wave grows cubically

The effect called "Sonic Boom" is characterized by a sound similar to an explosion in some cases. It can be detected even at distances of 1km, and it can cause vibrations in doors and windows of nearby buildings. In addition, the strong sound generated causes a generally unacceptable noise pollution.

The maximum value of these micro - pressure waves is approximately proportional to the pressure gradient of the wave arriving at the exit portal (generated by the entrance of the train in the tunnel) and inversely proportional to the distance to which the train is located of said portal.

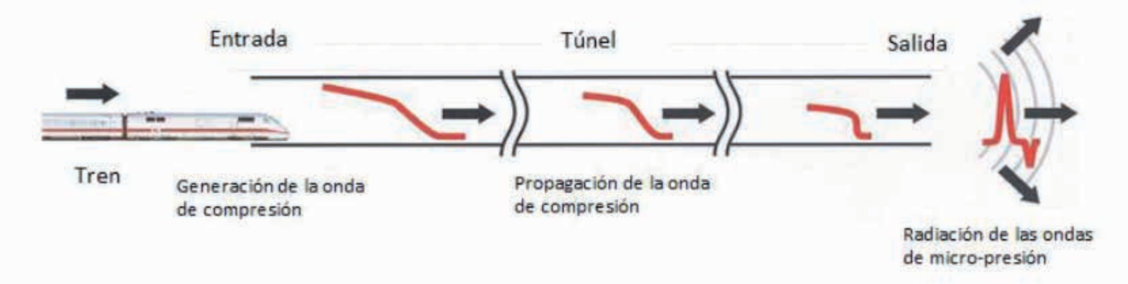


Figure 5 Sonic Boom generation

Currently, from different countries, and mainly at European level, measures are contemplated dissipating this effect once it has been proven to occur. However, there are still few actions that arise at the construction project level, since this effect can not be reliably calculated with the computer tools available today.

The most important measures used to mitigate this effect are detailed below. Some of them can only be included in the drafting phase of the project since these are measures that affect the construction of the tunnel. Other measures may be incorporated later, even if the tunnel is in operation.

As a main measure to mitigate the effect of the "Sonic Boom" is considered the reduction of the pressure gradient of the wave that reaches the exit portal of the tunnel once the train enters the same. This is achieved mainly by reducing the speed at the entrance of the tunnel and optimizing the aerodynamics of the nose of the train. These two measures can be implemented even if the tunnel is in operation.

On the other hand, structural measures can be applied that help reduce the effects of the sonic boom phenomenon. These measures could be:

- Increase the free cross- section of the tunnel which is only possible in the design phase.
- Modification of the design of the packaging: inclusion of "windows" or pores (also called porous or perforated packaging). These "pores" act as pressure sinks. Another measure is to modify the outer geometry of the portals making them flared, as well as to increase the length of the same.
- Use of ballasted track instead of slab track, since ballast, not being a continuous medium, has gaps between the edges that act as "pressure absorbers".
- Use of absorbent materials inside the lining (porous panels). This measure is very innovative and it has detractors because of fire safety and durability.
- Double track tunnel instead of two single track tubes with the aim of presenting a larger cross-section, only applicable in the project phase.
- Inclusion of connecting galleries between tubes, as long as the doors of the same are open and thus act the galleries as fireplaces. It must be taken into account that this aspect should

not go against the safety regulations of evacuation in case of emergency (propagation of smoke in case of fire).

- Inclusion of ventilation wells inside the tunnel near the portal area.

Figure 6. North Porous Portal. Perthus Tunnel.

Due to the great development of the Shinkansen over the years, a regulation has been considered that limits the value of the micro-pressures to 20Pa in the vicinity of tunnels.

Until 2013, this was the only existing regulation regarding the sonic boom effect and was also assumed by much of the world in the civil design of tunnels. In September 2013 a new German standard introduced as a module of the already existing DB Ril 853 was presented at the 15th International Symposium "Aerodynamics, Ventilation and Fire in Tunnels" which limits the value of the decibels produced by the sonic boom. This limitation has two variants:

- In the vicinity of buildings, the decibels in C-weighting (evaluation of high sound level sounds) are limited to the following values:
    - Residential areas: 70dB (C).
    - Parks and Gardens: 85dB (C).
    - Industrial Zones: 95dB (C).
- On the other hand, in the case of non-proximity to the previous elements, the decibels are limited to a distance of 25m from the portal to 115dB (C).

This regulation has been presented after carrying out a comparative study between actual measurements and a numerical model in the Katzenberg tunnel (Karlsruhe - Basel line) of about 9.4km in length, bitube and single track. This comparative study is currently being used in the analysis of the German high-speed rail network.

This limitation of C - weighted "noise" production is based on the fact that most of the energy produced by micro - pressure waves is at low frequencies (<100Hz) and even in the infrasound region (<20Hz). As it will be seen later, the frequency weights "clean" the sound pressure level (SPL), let us call it "raw noise", leaving only the noise produced in the desired frequency ranges so that it can be analyzed better. This cleaning is done by subtracting from the SPL noise a value

(WC) of "decibels" for each frequency. This Wc value is determined by a formula that depends on the frequency at which it is found (f).

Therefore, using the "noise" produced in C-weighting allows the clear analysis of noise produced only by micro-pressure waves.

6.3 Innovative project

In INECO, a tool called PROTAV has been developed, through the Innovation Directorate and thanks to the collaboration of the Ignacio Da Riba Institute of the UPM (Polytechnic University of Madrid) in Madrid, able to predict and attenuate the effect of the sonic boom.

To carry out this project the following steps were developed:

- Instrumentation of a tunnel in which sonic boom was produced
- Modelling of this tunnel and checking in the tool.
- Check using the tool if this effect occurred in tunnels in which the effect of micropressures does not occur.

The following parameters were measured:

- Distribution of pressure and air velocities in the tunnel.
- Static sound produced by the impact of the shock wave generated at the tunnel entrance when Mach 1 speed is reached.

The main objective of these measurements has been the evaluation of the Sonic Boom that produces the pressure wave generated by the trains at their entrance to the tunnel when it reaches the exit portal.

6.4 Cabrera tunnel features

The La Cabrera tunnel belongs to the LAV Madrid - Valencia / Albacete. It is a single-track twintunnel. Its most important characteristics are the following:

- Length: 7229m
- Cross-Section Type: Circular - Bitube of 53m2
- Input Line ch: 351 + 277 at 624m height
- Output Line ch: 358 + 506 at the 461m height
- As for the longitudinal profile according to increasing chainage is characterized by a slope of -30 ‰ during the initial 2.3km, then changes its slope to -8 ‰ for 1.1km, to finish with a slope of -25 ‰ rest of the tunnel.

Figure 7. North Portal of La Cabrera Tunnel.

Figure 8. Inner of North Portal of La Cabrera Tunnel.

6.5 Location of control sections for auscultation

The instrumentation arranged in the tunnel of La Cabrera has been very varied and with very different objectives.

Due to the intention to evaluate the effect of the sonic boom, two sonometers were installed in the vicinity of the portals to record the decibels corresponding to each generated pressure wave, in order to obtain the frequency spectrum of the burst in bands of thirds of octave. The La Cabrera tunnel presents ideal conditions to measure this effect since, as mentioned, it has been verified with a field visit that this effect occurs. Sound level sonometers have been placed 50m from the portal of the Valencia side.

As it has been necessary to measure pressure variations and wind speed inside the tunnel, pressure sensors and triaxial anemometers have been installed.

At the entrance and exit of the tunnel displacement sensors or strain gauges have been installed to record the passage of trains and to determine the speed, composition and type of train that circulates.

Likewise, the pressure, air velocity in the longitudinal component, temperature, humidity and environmental pressure, as well as the passage of the train have been recorded.

The central section of the train has been instrumented with pressure sensors, anemometers and train passage detectors. This section is located towards the middle of the tunnel and has sought the proximity to a connecting gallery in the tunnel of La Cabrera, in order to instrument in and out of the gallery with pressure sensors.

Figure 9. Instrumentation set in La Cabrera Tunnel

To summarize, the scheme of installation of the sensors in the tunnel of La Cabrera was the following one:

- A sensor to measure pressure, temperature and humidity outside the tunnel at ch 351 + 277 (tunnel entrance) and 358 + 450 (section 3).
- Two sound level meters on the outside of the outlet with the corresponding data acquisition equipment and separated by one meter and placed at 50m from the portal (section 4).

- Pressure sensors in ch 354 + 825 (in the middle of the tunnel, section 1) arranged in a tunnel and in the vicinity of the nearest gallery (ch 354 + 885, section 2), as well as inside the tunnel and as far away as possible from the entrance door to the tunnel. These sensors are accompanied by their corresponding data acquisition equipment and also records the temperature and humidity of the air.
- Triaxial anemometers inside the tunnel at ch 354 + 825 (section 1) and section 3 (ch 358 + 450) at the point where the plate is located with strain gauges. This is accompanied by a corresponding data acquisition team.
- Train pass detection sensors have been added inside the tunnel in the central section ch 354 + 825 (instrumentation section 1).

To summarize the instrumentation by sections arranged is as follows:

- Section 1, located at ch 354 + 825: tunnel pressure sensors, triaxial anemometers and strain gauges.
- Section 2, at ch 354 + 885: pressure sensors in a gallery near the central section. Arranged on the outside and inside of it.
- Section 3, in ch 358 + 450, has pressure sensors and triaxial anemometers.
- Section 4, at ch 358 + 568 (outside of the tunnel), in this section two sonometers separate from each other 1m and at a distance of 50m from the outlet portal are arranged.

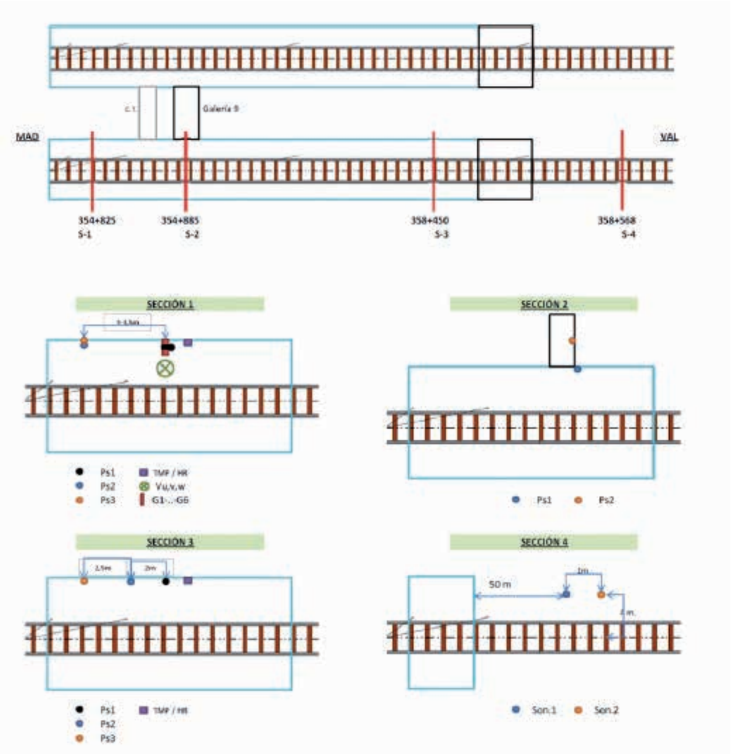


Figure 10. Scheme of the distribution of control sections in tunnel

The detail of the plate on which the gauges are located can be seen in the following diagram. It is possible also to see the position of the pressure sensor on one side of the plate in the next photo:

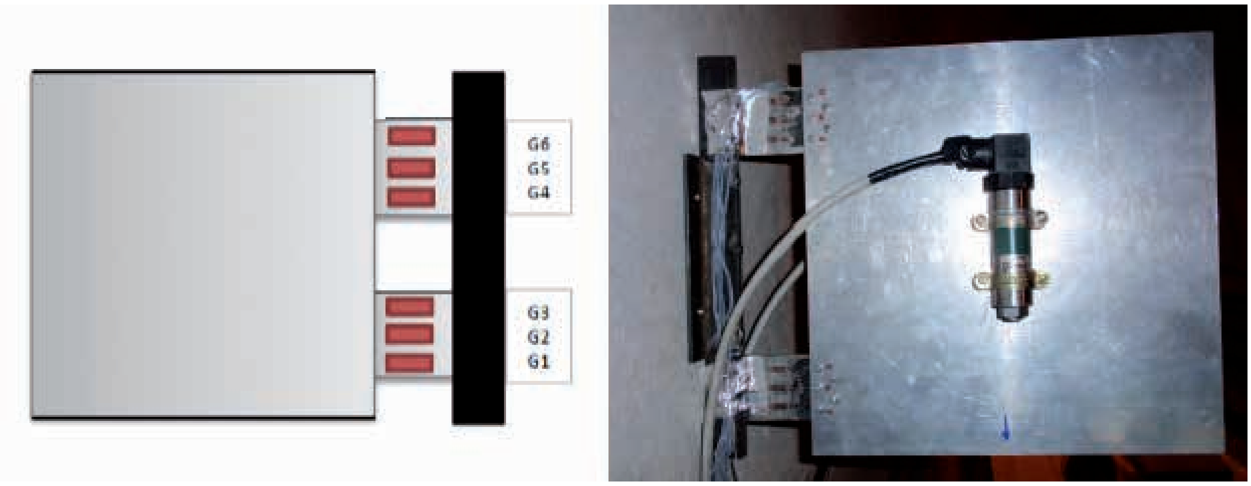


Figure 11. Pressure sensor location

For the installation of the sensors it has been necessary the use of a vehicle in the tunnel of The Cabrera and the existence of energy that feed the equipment to which the instrumentation has been connected.

For the installation of the sensors it has been necessary the use of a vehicle in the The Cabrera tunnel and to provide electricity to feed the equipment to which the instrumentation has been connected.

The instrumentation and start-up of the sensors was performed during the night and the measurements were carried out during the day. Three nights were used for the placement of the instrumentation and two nights to uninstall equipment.

The data of the circulations of these days: schedules, train typology, length, speed ..., were provided by RENFE to be able to compare with the arranged instrumentation.

Once the measurements were made in July 2013, work began on the processing of the same, which materialized in a series of Excel files for each of the circulations analyzed.

Then, a comparative work was started between the field data and the data obtained through the tool finalizing the innovation project with the generation of the PROTAV tool.

7. Protav

PROTAV (PRopagación de Onda en Túnel de Alta Velocidad,) tool has been developed in collaboration with the Institute of Microgravity "Ignacio da Riva", hereinafter IDR of the Universidad Politécnica de Madrid.

PROTAV has been developed as a tool that reflects more or less faithfully the behavior of pressure waves in tunnels, as well as the introduction of dissipating elements of overpressures. The main features of the PROTAV tool are as follows:

- It is an INECO´s proprietary software developed in-house. It allows the analysis and engineering calculations that were not approached with confidence. (Functionality of the sonic boom).

- PROTAV performs an analysis of the generation and propagation of pressure waves inside a tunnel with a higher degree of accuracy than other existing tools and also at a very low computational cost.
- In order to ensure greater accuracy of the studied phenomenon, PROTAV allows to define a multitude of parameters identified as relevant in the calculation of the aerodynamic phenomenon: velocity, length, perimeter and train area, tightness, tunnel geometry, existence of pressure dissipating elements ...
- PROTAV is a tool with a relatively simple and intuitive operation.

In long tunnels with low friction (slab track), the nonlinear effects of wave propagation produce a steepness of the pressure wave front and can form a shock wave. Increasing the pressure gradient of the wavefront increases the wave's ability to radiate energy out of the tunnel by impacting the output.

The method selected by IDR and proposed for the study of radiation is based on the wave separation process proposed by Kikuchi in 2009. This method consists of placing two microphones within the tunnel, whose relative position must be accurately known and placed at some distance from the exit of the tunnel. Another microphone is placed outside the tunnel at such a distance that the flat wave hypothesis can be assured to capture the radiated wave and calculate the transfer function of the tunnel exit.

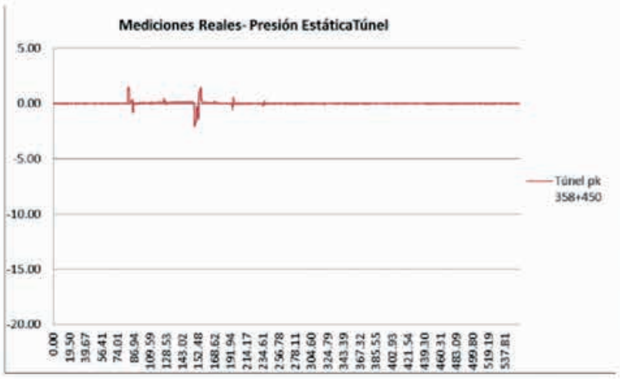
7.1 Protav validation

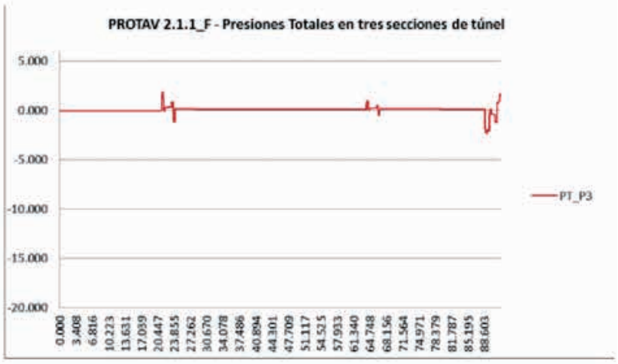
As can be seen in previous sections, four sections were instrumented, three inside the tunnel, and the fourth on the outside with the sonometers.

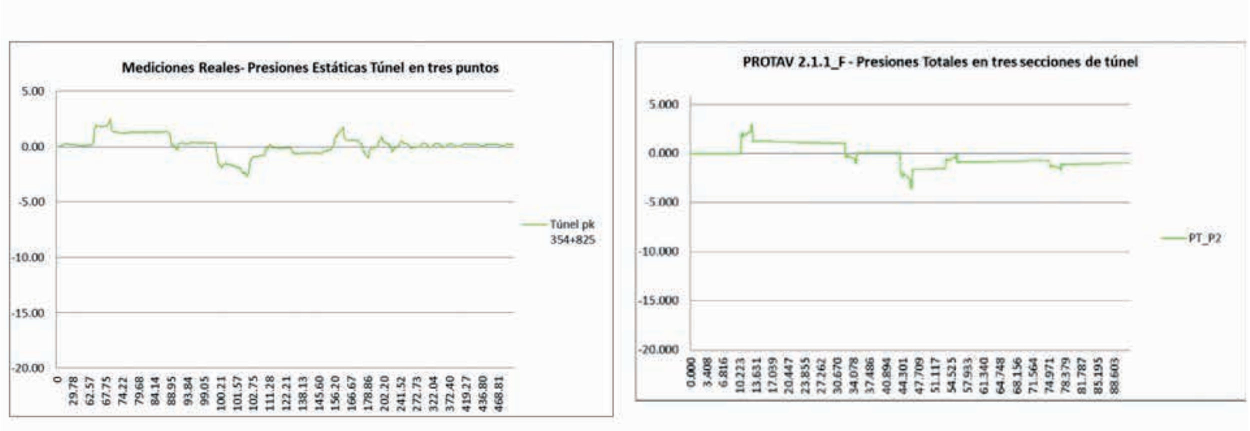
Sections 1 have been considered as comparison sections located at ch 354 + 825 and section 3 located at ch 358 + 450 direction Valencia. The comparison pass is the T-02, an S-112 train that is detected in the tunnel at 8:44 h at 291 km/h and is detected at the exit section at 8:45 h at 296 km/h. This train has been taken as a comparison train, since in this case the sonometers of section 4 detected a sonic boom.

The comparative graphs of these measurements with PROTAV are shown below. In the graphs:

- For PROTAV, the abscissa represents the time in seconds (s), and the ordinate axis represents pressures in kilopascals (kPa).
- In the Full scale measure graphs, the abscissa axis represents the available data number and the ordinate axis represents pressures in kilopascals (kPa).






Mediciones Reales- Presiones Estáticas Túnel en tres puntos

PROTAV 2.1.1_F - Presiones Totales en tres secciones de túnel

Figure 12. Comparison full-scale test vs PROTAV

As can be seen in the graphs, two aspects to comment are observed:

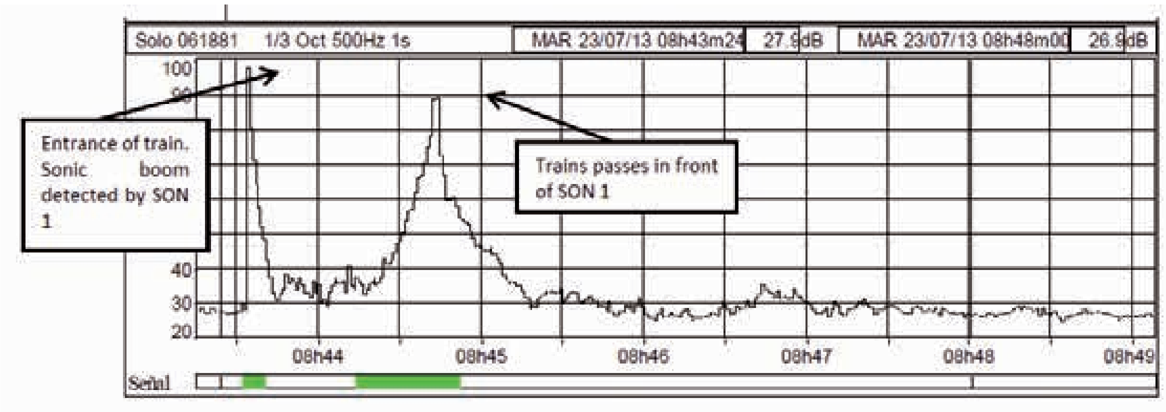
1. PROTAV does not consider atmospheric pressure values when it measures instantaneous pressures. This results in the results obtained starting at 0 kPa as is done in the case of measuring devices.
2. There is a certain difference between the graphs. This is due to the volume of data. To make the graphs in the case of the actual measurements have been counted with about 550 data, which are provided by the pressure sensors. To realize the graphs of PROTAV have obtained something more than 8800 data which explains the small existing distortions.

There is a certain difference between the graphs. This is due to the volume of data. To make the graphs 550 readings provided by the pressure sensors have been considered. To produce the PROTAV graphs more than 8800 readings have been used, which explains the small existing distortions.

7.2 Sonic boom calculations

To determine the validity of the sonic boom several of the passes of the real measurements of July 2013 have been compared against the simulation of the same conditions in PROTAV in order to evaluate this new functionality of the tool. One of them is shown as illustration.

The data provided by the SON 1 sonometer of instrumentation section 4 include a maximum of 122.6dB Overall at 100Hz. The SON 1 sound level meter is at a distance of 50m from the exit portal to Valencia. This is the graph of the sound level meter that illustrates this data:


Entrance of train. Sonic boom detected by SON 1

Trains passes in front of SON 1

Figure 13. Relation between frequencies and time of the train T-02

As shown in the above chart, SON 1 located in the opposite portal of the entrance detects a very steep rise after 8:43 p.m., time of entrance of the train in the tunnel, so that this peak reflects the sonic boom. Very close to 8:45 a second peak is detected again indicating that the train is passing in front of the sound level meter 1 once it has left the tunnel. Both rises occur in the frequency range of 100Hz or 90Hz (low frequencies) as seen in the chart above.

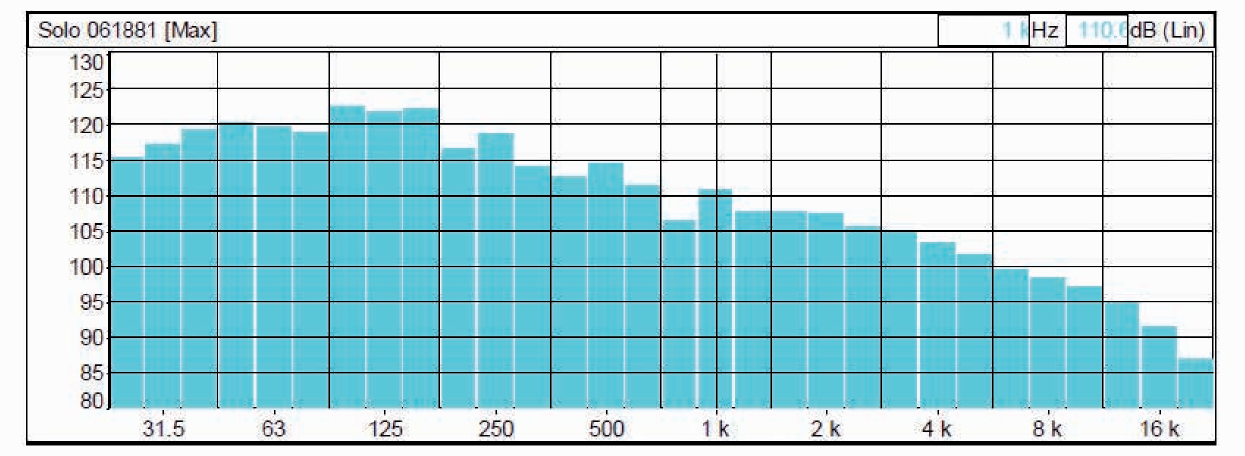
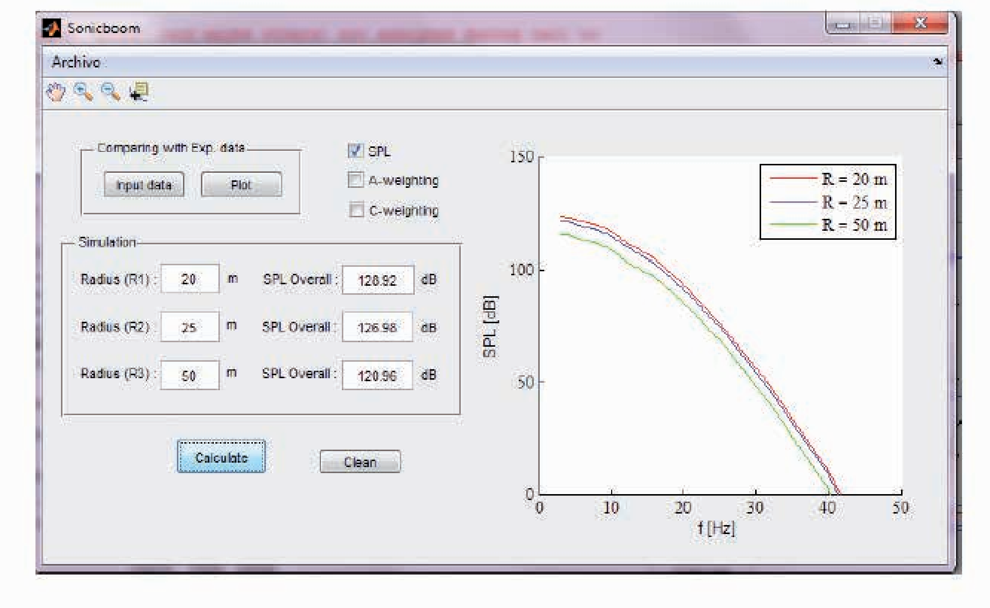


Figure 14. Relation between frequencies and decibels overall of the train T-02

The above image shows the Overall decibels produced with the frequencies at which the sound is produced. In this graph is possible to see that at approximately 100Hz there are more than 120dB, specifically 122.6dB Overall.

With this data, the simulation in PROTAV of the same conditions of this pass was carried out, and it was measured the Overall decibels produced at 50m from the portal (position of SON 1):



☑ SPL
☐ A-weighting
☐ C-weighting

Radius (R1) : 20 m SPL Overall : 128.92 dB
Radius (R2) : 25 m SPL Overall : 126.98 dB
Radius (R3) : 50 m SPL Overall : 120.96 dB

Distance R [m]	20	25	50
SPL Overal [dB]	128.9154544	126.9772541	120.966578

Figure 15. Results obtained with PROTAV in the T-02 train

As shown in the table above, at 50m distance PROTAV detects 120.966dB. This value is less than detected even though it is in the same order magnitude and is only 1.33% lower. Therefore, and in view of the results obtained after several analyzes, it can be concluded the great reliability of the tool in the calculation of this phenomenon

8. Conclusions

Throughout this article a revision of the possibilities of aerodynamic studies in high speed rail tunnels has been performed, including the opportunities offered to the designer and the possibilities of optimization of the free cross- section, as well as the possibility of analysis of variations of speed to improve the operating regimes.

Additionally, it has been presented the PROTAV tool of sonic boom calculation done by INECO in collaboration with the Instituto Ignacio Da Riba (IDR) of the Polytechnic University of Madrid. This new tool represents a new possibility of design and calculation of a growing phenomenon caused by the gradual train speed increments.

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