THE COMPLEXITY TO DESIGN THE VENTILATION SYSTEM IN LONG RAILWAY TUNNELS WHERE LARGE HEIGHT VARIATIONS OCCUR

Sanz-Sacristán, Juan Manuel[1]; Peris-Sayol, Guillem[1]; Gago-Fernández, Constantino[1];

juan.sanz@sener.es

[1] Spain, SENER Ingeniería y Construcción.

ABSTRACT

The ventilation in railway tunnels has two main objectives: to dilute the pollutants generated by the normal operation of the trains and control the smoke in case of a fire. This paper shows the work carried out regarding the ventilation system design process in a 24.4 kilometers railway tunnel, which crosses a mountainous region connecting two different climatic areas with strong difference in barometric pressure between portals. The tunnel has two tubes with cross passages every 500 meters and having a constant slope during all its length, which implies a strong height difference between portals (420 meters). Under these geometric characteristics, it is very important to estimate appropriately the effects to be overcome by the ventilation system: difference in pressure between portals (barometric effect) and thermal effect due to difference in temperature between portals environment and air temperature inside the tunnel that depends on wall temperature. To calculate adequately those effects, meteorological data from 1961 to 2018 have been processed and analyzed. A measurement campaign of pressure, temperature and air speed has been carried out in order to calibrate the simulation model used to size the tunnel ventilation system. Additionally, it is important to remark the importance of air properties in the design process that are altitude-dependent. It should be noted that the simplified formulas usually used in tunnels are not valid in long tunnels in which large height variations occur, where complete formulation must be considered taking into account the variation in air pressure, temperature and density with the height along the tunnel.

Keywords: Ventilation System, long railway tunnel, portal altitude, mountain range

1. INTRODUCTION

The tunnel scope of this study is the Tunnel of Pajares, a railway tunnel of two tubes with cross passages located at maximum intervals of 500 m. The length of the tubes is 24.4 km with a constant slope of 1.69%, which implies a difference in height between both portals of 420 m. The North portal is located at 596 m above sea level and the South portal is located at 1,016 m above sea level. The cross section area of each tube is 50.3 m². The tunnel is in the northern Spain and crosses the Cantabrian mountain range that separates the central plateau from the coast area. The tunnel has two galleries outside connected for maintenance purposes and emergency access. The galleries are located 7.5 km and 10 km far from the South Portal and are closed in the connection to the main tunnel.

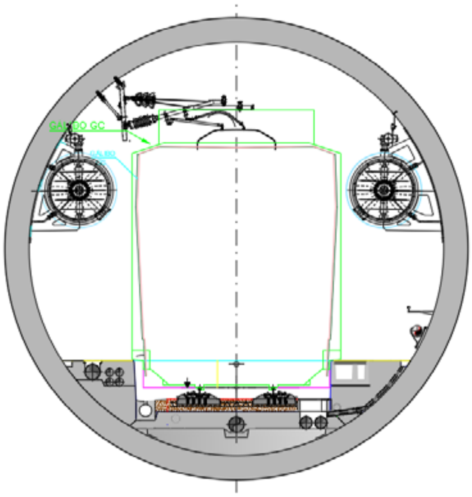


Figure 1: Cross section of the railway tunnel (the two tubes are symmetrical)

At the beginning of the tunnel ventilation system detailed design stage, the tunnel was drilled 8 years ago. Waterproofing, finishes and equipment works were still being carried out. This fact, together with the provisional construction ventilation and the natural forces, allows us to consider that the wall temperature of the tunnel will be close to a stable condition.

Even after 8 years of connection of the tunnel on both sides of the mountain range, there are no meteorological stations near the portals, so meteorological data from the portals is not available. Anemometers were installed inside the tunnel and continuous measurements have been made during these years showing an important airflow inside the tubes, which shows the importance of environmental conditions in the design of the ventilation system. The measurements showed air speed, due to atmospheric effects, of up to 5 m/s, both upwards and downwards, as well as continuous changes of the flow direction. For the execution of the field works, there is a provisional ventilation through the two intermediate galleries to avoid periods with air speed close to 0 m/s.

The previous studies defined a longitudinal ventilation system with jet fans without any intermediate ventilation shaft. Due to the difficulty of build new shafts in a tunnel practically completed and in order to avoid a significant delay at the time of operate the tunnel, a longitudinal ventilation system has been maintained at this design stage. The previous ventilation design was not valid because it had not taken into account the importance of natural forces, that exist in the tunnel due to atmospheric effects, as well as the fact of not having taken into account the variation of the density of the air with the height and the thermal effects. Normally, the ventilation of a tunnel is designed without considering the variation in air density with height. Only the variation in air density with temperature is considered. These simplified equations are valid for a short tunnels or tunnels with small height variation [PIARC, 2007]. In this case, with a tunnel of an important height difference between portals and large length it has been necessary to use the complete equations. These aspects have a special relevance when the density varies: (1) the variation of the air density in the tube increases the air speed and therefore the friction losses; (2) the thrust of the jet fans is directly proportional to the density of the air and therefore it implies that not all jet fans works in the same way, having better performance those installed at the lower portal.

2. VARIATION OF AIR CONDITIONS WITH HEIGHT

The equations of the ideal atmosphere consider that the temperature decreases linearly with the height (6.5 ºK/km) until 11 km height [U.S. Government, 1976]. The force of gravity is considered constant and the air is an ideal gas. With these considerations the variation of pressure and density of the air with the height are the following:

$$T(h) = T_0 + a\,(h - h_0)$$

$$P(h) = P_0 \left(\frac{T(h)}{T_0}\right)^{-\frac{g}{aR}}$$

$$\rho(h) = \rho_0 \left(\frac{T(h)}{T_0}\right)^{-1-\frac{g}{aR}}$$

Where a=-0.0065 ºK/m, R is the gas constant of the air, subscript 0 indicates the measurement level and h indicates the difference in height from the measurement level.

Therefore, in the standard atmosphere the density, temperature and pressure decrease with height, without involving driving forces, keeping the air in stable conditions. There will be fluctuations on these values that will induce an airflow in the tunnel (due to climatic conditions or temperature of the tunnel wall).

In a long tunnel, with a longitudinal slope, the air in its movement is subject to variations in density that involves, among other things, variation in air velocity. This condition prevents using the simplified equations for all the length of the tunnel, and it is necessary to solve the equations in small lengths of the tunnel or by a finite element method using the complete differential equations.

The natural forces that are normally considered in a short tunnel are wind at portals and temperature difference between the inside and outside of the tunnel, aspect normally neglected in short tunnels or tunnels with small slopes. In case of tunnels that crosses a mountain range, the pressure and temperature differences between portals must also be considered and, as we will show later, they can be decisive in the design of the tunnel ventilation system.

In any case, the climatic conditions between both portals (temperature and pressure) must be studied [CETU, 2003]. The height must be considered in the analysis in order to translate the conditions of temperature and pressure of each portal to a reference level. In this study the lower portal has been considered as the reference level. In addition, the temperature inside the tunnel must be considered to obtain the real natural forces due to atmospheric effects. All that forces must be overcome by the ventilation system.

3. MEASUREMENT CAMPAIGN

Since the tunnel drilling, continuous measurements of the airflow in the tunnel have been carried out, which have been a great help in the ventilation system design stage. The main drawback has been the fact, that these measurements are not supported by simultaneous information of the external conditions at the portals, so it has been necessary to obtain the data from the closest stations of the National Meteorological Agency (AEMET) that are located around 25 km far from the portals.

To check the correlation of the measurements of the meteorological stations with the values of the tunnel, several campaigns of simultaneous pressure, temperature, humidity and wind speed have been carried out at different points inside and outside the tunnel. These measurements have allowed to correlate the values of the meteorological stations with the real conditions in the tunnel. This information has been used to calibrate the 1D simulations model.

A thermal imaging camera measured the wall temperature. These measurements have some variability and do not allow to obtain the accurate value of wall temperature but have been useful to know the order of magnitude. It has been more practical and reliable to measure air temperatures along the tunnel in different conditions and periods in order to infer the real wall temperature.

From the campaign carried out, a variation in temperature has been shown in the first 3 kilometres from the portals due to the air intake in the tunnel at external temperature. Far from the first 3 kilometres a constant temperature around 13.5ºC has been shown. This value is slightly higher, between 2 and 3 ºC, than the average temperatures at the portal of the tunnel. It is important to remark that the temperature observed is lower than what it was expected due to the depth of the tunnel (maximum of around 1,000 meters). The average and extreme values of temperature at two portals are presented in the following figure:

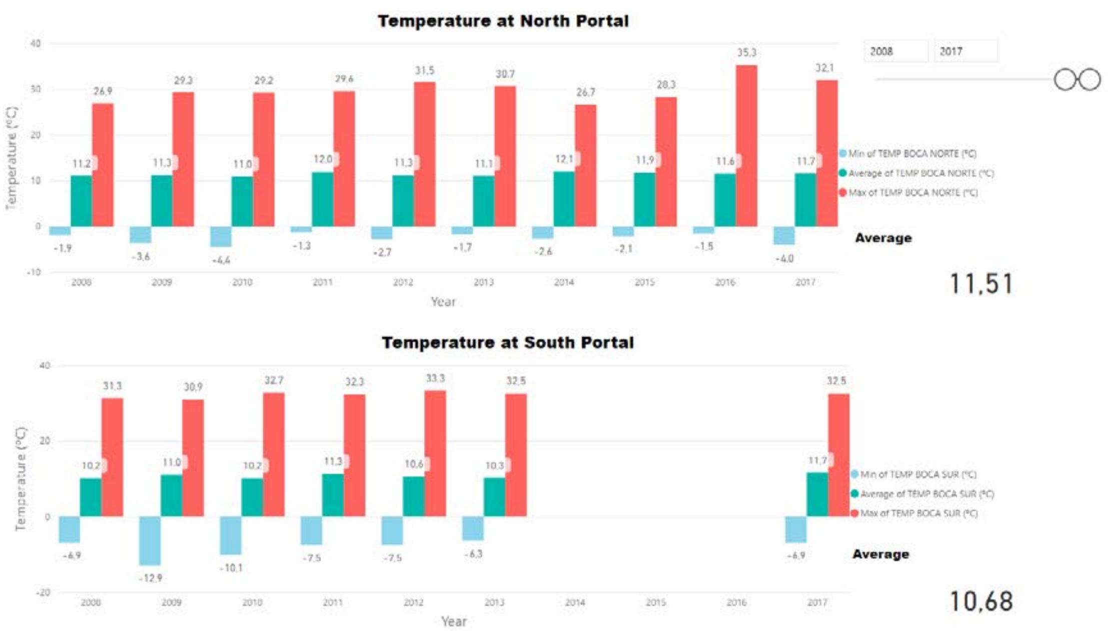


Figure 2: Temperatures registered at the portals of the tunnel. Note: values for years 2014-2016 at the South portal were missing

It is shown that in the period 2008-2017 (period where the tunnel was drilled) the North portal has a yearly average temperature of 11.51ºC and the South portal has 10.68ºC. Taking into account the height difference (420 m) which corresponds to 2.73ºC considering 6,5ºC/km, it could be shown that the difference in the yearly average value between portals is lower, so the South portal tends to have higher temperatures than the North portal.

4. CALCULATION OF THE EXTREME CONDITIONS AT PORTALS

In order to characterize the climatic conditions for the design of the ventilation in the tunnel, a treatment of the meteorological records provided by the National Meteorological Agency (AEMET) for four locations have been realized. These four locations are the closest meteorological stations to the portals that simultaneously register temperature, pressure, wind and humidity. Two of them are at one side of the mountain range close to Leon and the other two at the other side of the mountain close to Oviedo.

The data recorded by these weather stations range from 1961 to the present day, which allows to analyse with great accuracy the normal and extreme conditions, that can be reached at the tunnel portals. This data allows obtaining the velocity, pressure, temperature, humidity and density of the air at each portal at the same time. Therefore, the three natural forces that have an influence on the movement of the air inside the tunnel could be calculated: (1) difference in barometric pressure between portals, (2) thermal effect due to difference in temperature between inside and outside and (3) wind at portals.

Next figure represents the barometric pressure differences between both sides of the mountain range, values corrected to a reference level, for the different months of the year. The average and the percentiles 1% 5%, 95%, 99% are shown.

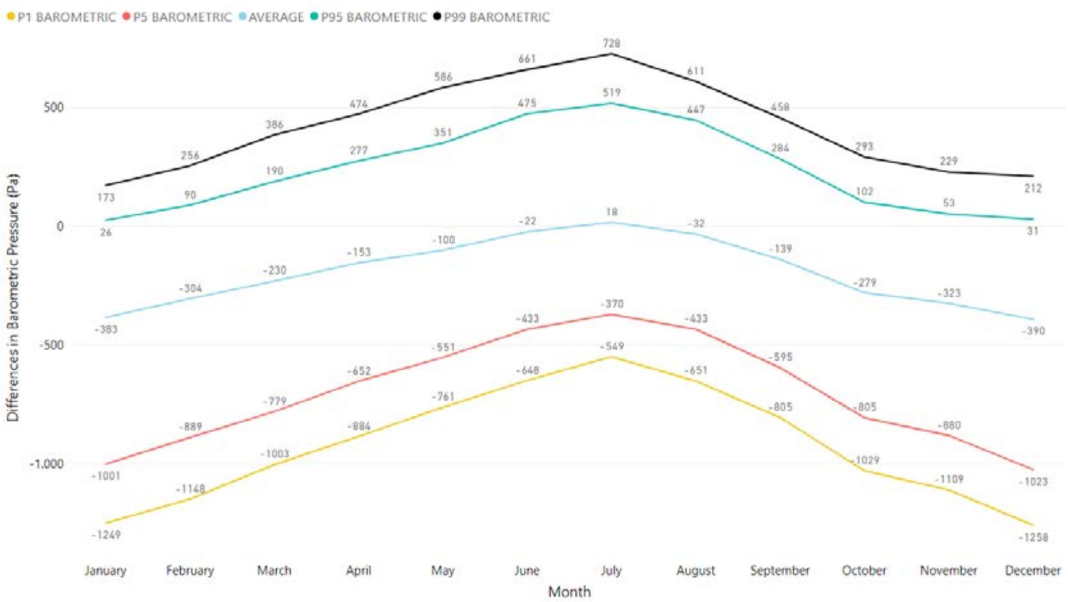


Figure 3: Difference in Barometric pressure between portals corrected with the height (North – South)

As can be observed throughout the year, negative values predominate, that would indicate that the airflow in the tunnel is predominantly from South to North, which is not observed in the tunnel. To obtain the real natural forces due to meteorological conditions, we must add the thermal effect due to temperature differences between inside and outside of the tunnel considering the temperature of the wall. This value is shown in the following figure and shows, for different percentiles, the natural forces that will have to be overcome by the ventilation system (excluding winds at portals):

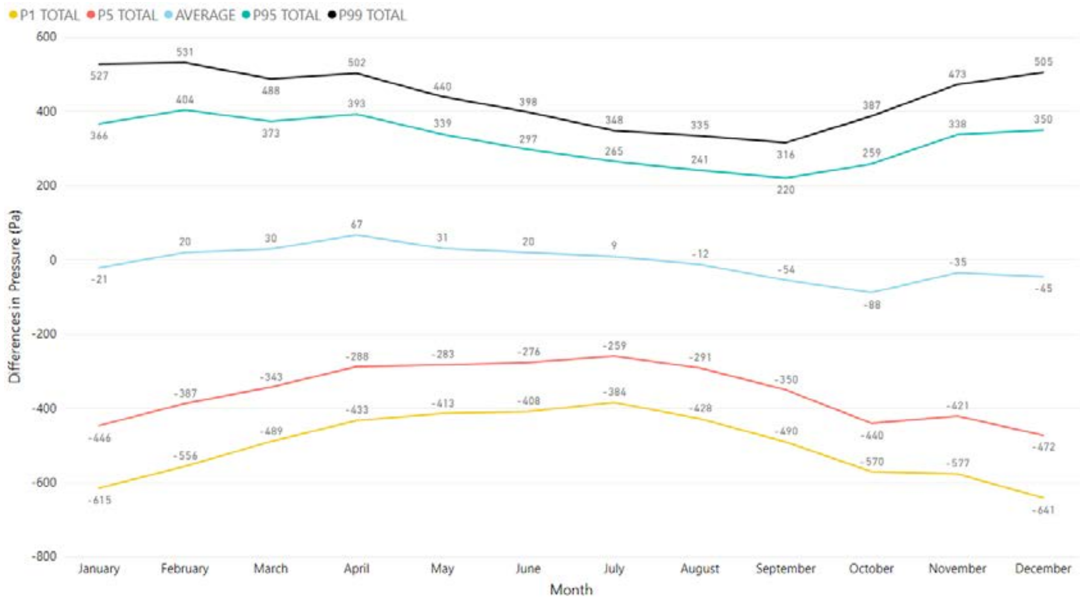
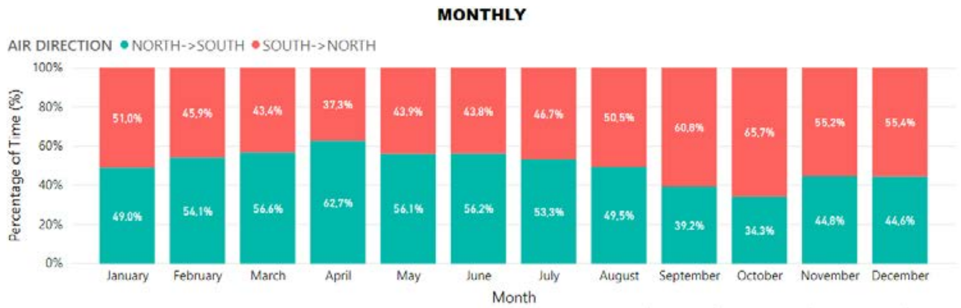
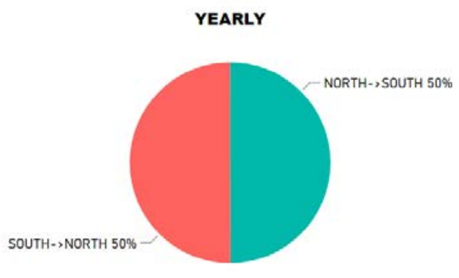


Figure 4: Natural pressure to be overcome by the ventilation in the tunnel (North – South). Note: Positive values indicate air from North to South

As can be observed throughout the year, the average it is close to zero, producing the highest values in autumn and winter (with higher values towards the North) and lower values in spring and summer (with predominant value towards the South). It can be observed better in the following figure, that shows the percentage of time of the air direction inside the tunnel due to natural forces for each month of the year. This information has been calculated for all the meteorological data available.





Month	NORTH->SOUTH	SOUTH->NORTH
January	48,96%	51,04%
February	54,06%	45,94%
March	56,63%	43,37%
April	62,67%	37,33%
May	56,07%	43,93%
June	56,19%	43,81%
July	53,30%	46,70%
August	49,50%	50,50%
September	39,21%	60,79%
October	34,27%	65,73%
November	44,78%	55,22%
December	44,64%	55,36%
Total	**49,93%**	**50,07%**

Figure 5: Air direction into the tunnel along the year

5. SIMULATION MODEL OF THE VENTILATION SYSTEM

For the detailed calculation of the ventilation and the analysis of the different stationary and transient situations of the tunnel, a complete model has been developed using the Ida Tunnel software. This model has been calibrated with the data measured in the tunnel in different situations, adjusting the various calculation parameters, such as losses due to roughness of walls, singularities, wall temperature, etc. The model considers the arrangement of the jet fans, the configuration of the cross passages between tubes and the meteorological conditions chosen.

The Ida Tunnel model of Pajares Tunnel is shown in the next figure, where the 58 cross passages and the two intermediate galleries are modelled:

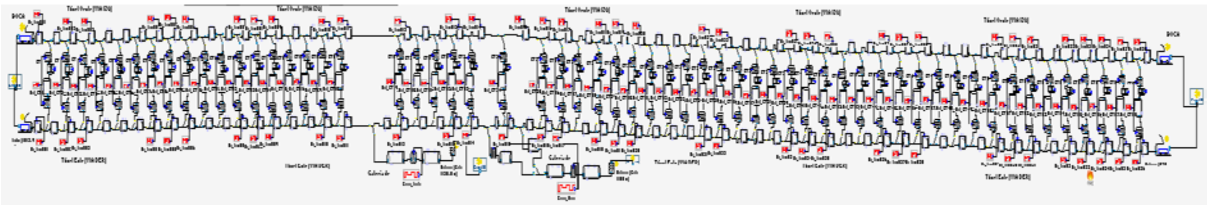


Figure 6: 1D Simulation model of the Tunnel of Pajares

In the following figures some results are shown as an example of how the air varies along the length of the tunnel. It can be seen how the outside air quickly reaches the temperature of the inner wall (around 3 kilometers) and how the variations in air pressure with height have an important effect on the speed of the air along the tunnel. This example shows a case with natural ventilation, with no barometric difference between portals, 25º C at both portals and the hypothesis of 15ºC internal wall. The air move from left to right (from high to low).

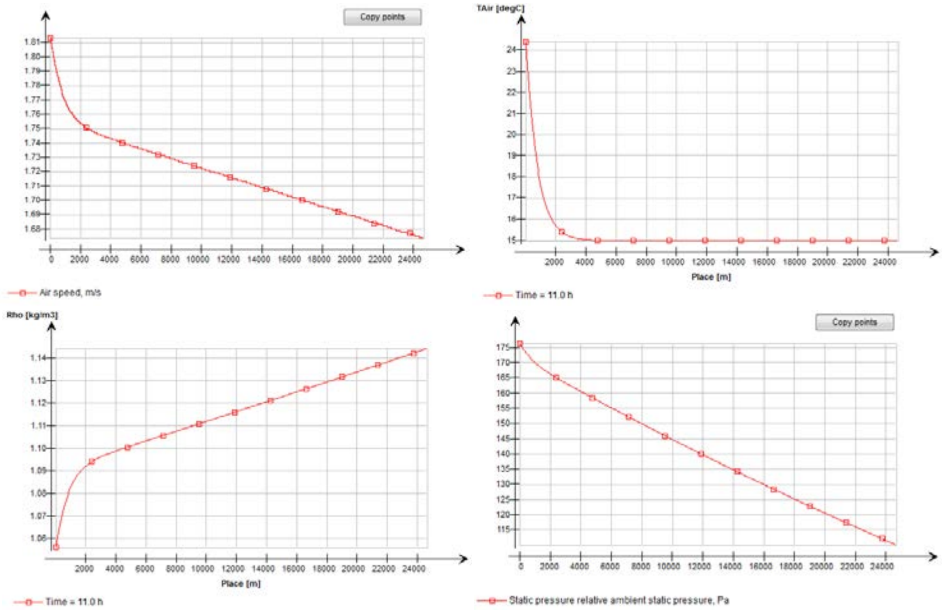


Figure 7: Example of a simulation with natural ventilation in a specific condition

6. SUMMARY AND CONCLUSIONS

For tunnels with high difference in height between portals, it is important to consider the variation of air density along the tunnel, which implies to apply the complete formulation to calculate all the pressure losses to design the ventilation system.

In cases, where the tunnel crosses a mountain range, it is important to study the temperature and pressure at both portals among the wall temperature inside the tunnel. In order to calculate the design extreme conditions at the portals, it is recommended to install meteorological stations at the portals.

In order to obtain a long-term data, it is necessary to analyze the meteorological data available close to the portals from Meteorological National Agency. It should be noted the importance in drilled tunnels to have measurement campaigns to calibrate the simulation model, correlate the meteorological stations to the real situation of the portals and obtain the wall temperature profile.

In the tunnel studied, it has been shown:

- The wall temperature is slightly higher than the average temperature at portals.
- The barometric effect has an important effect, but it is balanced by the thermal effect.
- The natural forces, due to barometric and thermal effect, are predominant compared to chimney effect due to fire and wind.
- The natural forces shown depend on the month of the year and varies in the range of 530 to -615 Pa for percentile 1% and 99%.

7. REFERENCES

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