Bi-national Bielsa-Aragnouet tunnel
Intelligent traffic and ventilation system enabling alternate bidirectional and unidirectional traffic flow

Patrick Personna
Consortium Tunnel Bielsa-Aragnouet

Fernando Portugués, Daniel Octavio, Rafael Sánchez, Luis M. Gonzalo
Geocontrol

ABSTRACT
The Bielsa Tunnel renewal project includes a complete renovation of the ventilation and traffic management systems in order to increase travel between France and Spain. In order to meet the expected traffic demands, alternative traffic modes and ventilation system modes had to be modeled and validated. Extensive risk analysis and ventilation cases have been studied.
1. BACKGROUND

Bielsa Tunnel, which connects France and Spain through the High Pyrenees, opened in 1976. The 3070-meter-long single-tube tunnel has a cross section of 65 m². Its two lanes allow bidirectional traffic flow (one lane in each direction.) The traffic volume is approximately 1,000 veh/day, 3% of which are heavy vehicles (HVs). Circulation of Heavy Good Vehicles (HGVs) is not allowed.

After four decades of use, the tunnel is still working with virtually the same systems for which it was designed, which, according to twenty-first century safety standards, is very low.

For this reason, and to encourage the use of this route between France and Spain, a partnership was established between the two countries in order to modernize the facilities and equipment serving the tunnel. The project has been extended from 2007 until 2013.

Total renovation of the tunnel facilities was carried out in addition to repair of drainage networks, sidewalks and leaks in the tunnel resulting from age.

The possibility of drilling a parallel tube in order to alleviate traffic and create emergency exits was considered, but eliminated from the initial phase of the project due to the high associated cost.

One of the main design requirements is to have the ability to operate the tunnel in a unidirectional traffic mode whenever an HV is in the tunnel, yet convert to bidirectional traffic whenever HVs are not present. This dictated the need for a traffic management system to control vehicles entering both tunnel portals, as well as a ventilation control system to activate the appropriate ventilation fans to respond to various fire scenarios in order to reduce the associated risks.

This paper describes the design process of the ventilation system and the methods that were followed to validate its functionality under different operational scenarios within the tunnel.

2. VENTILATION SYSTEM SELECTION

During the design phase of the project it became clear that the only feasible ventilation system for the tunnel was jet fan-based longitudinal. The depth of the tunnel ruled out the possibility of using intermediate ventilation shafts for air supply and/or exhaust. It was determined that full transverse or semi-transverse ventilation systems would require tunnel extensions, which were neither technically nor economically feasible.

Thus, the mechanical ventilation system selected for the tunnel was longitudinal. However, the relatively tight tunnel cross section required selection of small diameter jet fans.
2.1. Sizing of the ventilation system

Temporary conditions unrelated to the scope of this article forced the project to be validated by the National Security Assessment of Tunnels France (CNESOR).

The design constraints were not 100% defined at this project phase because the CNESOR had to approve the exploitation possibilities proposed by the Bielsa tunnel consortium.

For this reason, a number of initial parameters were assumed for the purpose of furthering the project, including the possibility of bidirectional traffic and a design fire of 30 MW, a reasonable Heat Release Rate for non HGV vehicles.

Starting with these parameters, the longitudinal ventilation system was sized at 55 15-kW jet fans, each with a thrust of 428 N.

The assessment obtained by the CNESOR indicated the need to conduct a 30 MW fire ventilation simulation accounting for the actual natural ventilation conditions in the tunnel in order to verify the design criteria and the sizing of the ventilation system.
3. VERIFICATION OF VENTILATION SYSTEM SIZE

3.1. Measurement of natural ventilation

During the refurbishment of the tunnel, velocity measurements using fixed anemometers with continuous data recording were taken in order to determine the precise speed of the natural airflow inside the tunnel in the absence of a mechanical ventilation system.

This data was required to determine how close the natural air velocity in the tunnel was to that used in the design calculations, and thus to determine the adequacy of the estimated ventilation system capacities.

The natural ventilation velocity and direction measurements were taken and recorded every minute for over an entire year, from February 9, 2011 through February 21, 2012.

Because readings were collected during both daytime and nighttime periods, the data represented tunnel air velocities affected by the piston effect of travelling vehicles as well as in the absence of vehicles, respectively.

Five (5) wall-mounted ultrasonic anemometers, distributed along 3 km of the tunnel were used to carry out the air velocity measurements.

Figure 2.- Ultrasonic Anemometer

Post-processing data filtering was necessary to eliminate reading errors, such as those caused by the piston effect of passing vehicles.

It also was necessary to make adjustments to account for the differences in tunnel cross section in which each anemometer was installed. "k" factor multipliers were developed in order to obtain the average airflow rate in each section.

Once all of the natural ventilation values within the tunnel were obtained, it was decided that the 95th percentile speed value should be used as the boundary condition to determine the ventilation system capacity. This methodology is in accordance with the CETU "Dossier Pilote des Tunnels: Ventilation " (1) as shown below in Table 1.
### 95th Percentiles of Velocity Values (m/s)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towards France</td>
<td>3.46</td>
</tr>
<tr>
<td>Towards Spain</td>
<td>4.06</td>
</tr>
<tr>
<td>Absolute value</td>
<td>3.86</td>
</tr>
</tbody>
</table>

Table 1. 95th Percentiles of Velocity Values

Thus, the value chosen for validation by numerical simulation, corresponding to the 95th percentile without distinguishing schedule is 3.86 m/s. This air velocity value was used as the natural ventilation boundary condition in the calculation program.

### 3.2. Ventilation modes

Various ventilation modes are available for each mode of tunnel operation, as described below.

#### 3.2.1. Night schedule - mode M1

During the nighttime, the tunnel is operated for unidirectional traffic for all the vehicles, with alternating directions managed by traffic lights at the portals.

The ventilation system only operates if the pre-established concentrations of carbon monoxide (CO), oxides of nitrogen (NO\textsubscript{x}) or opacity are exceeded.

In the event of a fire, the ventilation system operates in the direction of traffic.

#### 3.2.2. Bidirectional mode - mode M2

Whenever there are no heavy vehicles (HVs) in the tunnel, the tunnel is operated with bidirectional traffic.

The ventilation system only operates if the pre-established concentrations of CO, NO\textsubscript{x} or opacity are exceeded.

In the event of a fire, the ventilation system operates in the direction occupied by the lower amount of people confined in their vehicles. This calculation is made by using inductive loops, which produce the number, location and type of vehicles inside the tunnel; and 1.5 people/vehicle, as stated in “Guide des dossiers de sécurité des tunnels routiers. Fascicule 4. Les etudes spécifiques des dangers (ESD)” (2).

If a fire occurs within the first 500 meters of either portal, the ventilation direction is towards that portal.

#### 3.2.3. Unidirectional mode - mode M3

Whenever there is an HV in the tunnel, all vehicles travel through the tunnel unidirectional in the same direction as the HV. Once the HV has exited, traffic lights at the portals are used to alternate the traffic direction.

In this case, the ventilation system is activated once the HV approaches the tunnel, reaching an air velocity of 1.5 m/s in the direction of the traffic. This figure was obtained through previous calculations, as a suggestion from CNESOR.

In the event of a fire, the ventilation system is operated at maximum capacity in the direction of the traffic.
3.2.4. **Bidirectional mode during the summer season - mode M4**

During the summer season, a crew of firemen is located in Spain, at the southern portal of the tunnel.

For this reason, bidirectional traffic flow is allowed. The ventilation system is maintained at a speed of 1.5 m/s in the direction toward France, to ensure that the firemen can safely enter the tunnel and extinguish the fire before it grows.

3.3. **Computer validation of the ventilation system**

Once the wind speed measurements were taken, the data was validated with specific tunnel ventilation programs capable of taking into account the effects of fire.

The calculations were performed using a one-dimensional program, Camatt (3), that models tunnel air speeds, temperatures and pressures in the event of a fire, while taking into account the existing boundary conditions.

3.3.1. **Calculation criteria**

According to the criteria established by the CNESOR, the calculation hypothesis considered for the validation of the ventilation system is as follows: a 30 MW fire occurs near the northern entrance while the ventilation flow is in the northern direction. The ventilation direction must be reversed in order to control the spread of smoke in the northern direction.

![Figure 3.- Worst case scenario for the ventilation system](image)

The fire, as indicated above, is in the vicinity of the north portal near the highest point of the tunnel. This is the worst case with respect to tunnel gradient, as the ventilation system must overcome the natural chimney effect of the smoke flume.

The air velocity of 3.86 m/s obtained during the measurement campaign was imposed as a pressure differential between the portals of 126 Pa.

In the calculations, all 55 jet fans are operated, with a thrust of 428 N, a jet velocity of 36.4 m/s, and a yield of 0.8.

The fire development curve as shown below in Figure 4 is linear up to 30 MW, requiring 10 minutes to achieve this power, maintained at 30 MW for 50 minutes, then lowered to 0 MW over the next 30 minutes (1).
3.3.2. Results
The air and smoke velocity, pressure and temperature have been calculated with the one-dimensional program Camatt (3).

The fire is located 300 m from the north portal, or at $x = 300$ m in the velocity graph below. The results show that the air velocity is always higher than the critical velocity of 2.54 m/s, which ensures that no back-layering of smoke to the north portal will occur.

Figure 4.- Fire growth curve for a 30 MW HRR fire.

Figure 5.- Results of Longitudinal Velocity in the Tunnel with a 30 MW Fire

The pressure diagram below takes into account the measured effect of natural ventilation in the Bielsa Tunnel, expressed as a pressure differential between the portals of 126 Pascals.

The pressure increases are due to operation of the tunnel fans, and the decrease that occurs directly after the 300 meter mark is due to the smoke generated by the fire.
4. **RISKS ANALYSIS USING COMPUTATIONAL FLUID DYNAMICS (CFD)**

The CNESOR, applying French tunnel safety legislation, determined that three-dimensional CFD analyses were required in order to expand the scope of the one-dimensional Camatt calculations and model the smoke concentration and temperature along the tunnel as a function of time.

It was recognized that CFD modeling could also be used to do a risk analysis to estimate the number of expected injuries and/or deaths in each scenario, thus providing a decision-making tool for the tunnel operator.

4.1. **Analyzed scenarios**

The methodology described by the CETU in the document “Guide des dossiers de sécurité des tunnels, Fascicule 4, Les études spécifiques des dangers (ESD)” (2) was followed.

As shown in the table 2, nine (9) scenarios combining various fire sizes, fire locations, traffic densities and directions, and fan operating modes were selected.

The CFD program Solvent was used to create models of the entire tunnel, including representative boundary conditions.

Transient simulations, following the growth curve of each type of fire and sequencing of fans were performed.

4.2. **Risk analysis criteria**

The CFD simulation results were used to verify that a tenable environment along the evacuation routes was maintained.

Acceptable risk levels, evacuation times and other criteria are described below:
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>105</td>
<td>1.5 Esp</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>105</td>
<td>1.5 Esp</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0+767</td>
<td>400, bidirectional</td>
<td>0</td>
<td>1.5 Fra</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>2+302</td>
<td>400, bidirectional</td>
<td>0</td>
<td>1.5 Fra</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>1+023</td>
<td>400, bidirectional</td>
<td>105</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>105</td>
<td>1.5 Esp</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>105</td>
<td>1.5 Esp</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>200</td>
<td>1.5 Esp</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>1+535</td>
<td>271, unidirectional</td>
<td>200</td>
<td>1.5 Esp</td>
</tr>
</tbody>
</table>

Table 2.- Risk Analysis Scenarios

Opacity and visibility
The opacity value of a tunnel allows one to estimate visibility distances and to evaluate the evacuation speed of tunnel users. The following formula estimates the visibility distance \(d\), in meters, depending on the opacity \(K\), expressed in m\(^{-1}\) and the visibility coefficient \(C\).

\[
d = \frac{C}{K}
\]

The coefficient \(C\) can range from 2 to 6, and in the absence of specific tests, it can be taken as an average value of 4, as shown in the Table 3.

<table>
<thead>
<tr>
<th>K [m(^{-1})]</th>
<th>0.1</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>d [m]</td>
<td>40</td>
<td>20</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.- Opacity and visibility distances

Opacity values below 0.2 represent good visibility (i.e., normal conditions), corresponding to an evacuation speed of 1 m/s.

For opacity values between 0.2 and 0.8, it can be assumed that tunnel users evacuate at 0.5 m/s. Above this value, the evacuation speed is reduced to 0.3 m/s (2).

Further, it has been assumed that half of tunnel occupants who are in areas with opacity values greater than 0.8 may get confused as to which direction is the one to follow to evacuate the tunnel.

Definition of risk areas
Risk areas caused by the propagation of fumes during a fire are defined by the following parameters:
• Smoke behavior: stratified or not
• Opacity
• Toxicity
• Smoke temperature

Risk areas can fall into one of three (3) categories:

• Safe Zone
• Danger Zone
• Lethal Zone

Safe Zone
A safe zone is one in which users can safely evacuate at an average evacuation speed of 1 m/s. The smoke has no impact on visibility, and the carbon monoxide (CO) concentration has no impact on respiration.

All other areas of the tunnel are defined as either danger zones or lethal zones.

Danger Zone
The following table 4 shows criteria corresponding to danger zones (2).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>CO Concentration</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-80ºC - &lt;15 minutes</td>
<td>400 ppm</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>800 ppm</td>
<td>1 hours</td>
</tr>
<tr>
<td></td>
<td>1500 ppm</td>
<td>30 minutes</td>
</tr>
<tr>
<td></td>
<td>1800 ppm</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>2600 ppm</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

Table 4.- Danger Zone Criteria

Lethal zone
A lethal zone is one corresponding to severe incidents, such as situations that can cause death of the tunnel users. The following table 5 shows reference values corresponding to lethal zones (2):

<table>
<thead>
<tr>
<th>Temperature</th>
<th>CO Concentration</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-80ºC - &gt;15 minutes &gt;80ºC</td>
<td>2 300 ppm</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>3 200 ppm</td>
<td>1 hours</td>
</tr>
<tr>
<td></td>
<td>4 200 ppm</td>
<td>30 minutes</td>
</tr>
<tr>
<td></td>
<td>5 000 ppm</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>7 000 ppm</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

Table 5.- Lethal zone criteria
4.3. Results

Each fire scenario was analyzed in conjunction with the evacuation processes of the tunnel users in order to estimate the number of people wounded and killed.

The following figure 7 shows the temperature diagram for Scenario 2, in which the Bielsa Tunnel is operated with an airflow of 1.5 m/s in the direction of traffic, protecting tunnel users from adverse conditions with the exception of those right next to the fire.

![Temperature diagram for Scenario 2](image)

**Figure 7.- Temperature analysis for Scenario 2**

The severity level of each scenario was classified according to the following table 6, included in Part 4, Annex B2 of the CETU’s ESD:

<table>
<thead>
<tr>
<th>Severity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Minor</td>
<td>Damages</td>
</tr>
<tr>
<td>II. Significant</td>
<td>Minor injuries</td>
</tr>
<tr>
<td>III. Critical</td>
<td>Seriously injured or &lt; 5 deaths</td>
</tr>
<tr>
<td>IV. Catastrophic</td>
<td>5 &gt; # deaths &lt; 50</td>
</tr>
<tr>
<td>V. Major Catastrophe</td>
<td>&gt; 50 deaths</td>
</tr>
</tbody>
</table>

**Table 6.- Severity levels**

At the same time, the frequency of occurrence was studied for each scenario, based on the definition of occurrence in the following table 7.
### Table 7.- Frequency of occurrence

<table>
<thead>
<tr>
<th>Severity</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A- Very Common</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>B- Frequent</td>
<td>&lt; 10 years</td>
</tr>
<tr>
<td>C- Occasional</td>
<td>10 to 100 years</td>
</tr>
<tr>
<td>D- Rare</td>
<td>100 to 1,000 years</td>
</tr>
<tr>
<td>E- Very Rare</td>
<td>1,000 to 10,000 years</td>
</tr>
<tr>
<td>F- Extremely Rare</td>
<td>&gt;10,000 years</td>
</tr>
</tbody>
</table>

Given the likelihood of each scenario, calculated from the data of accidents in the road network of France, the probabilities of occurrence were obtained:

### Table 8.- Risk Matrix

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>GRAVITY</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>ZONE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>ZONE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>ACCEPTABLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>ACCEPTABLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 5. VENTILATION TEST

Once all of the ventilation calculations and risk analyses were performed, a cold smoke test was carried out to check the capacity of the ventilation system installed, and to simultaneously verify proper functioning of other equipment and operations such as anemometers, opacity sensors, vehicle detection systems and road signs, proper transmission of information to the control center, and control algorithms.

Two tests reflecting possible situations that can occur in the tunnel were performed:

- Critical situation of the ventilation system in normal operation: This involves the need to reverse the airflow by imposing a certain speed in a short time.
- Critical situation in case of fire: Consists of smoke control with unfavorable conditions from the point of view of ventilation.

#### 5.1. Ventilation inversion test

This test was conducted to reverse the direction of the airflow, in the shortest time possible, to accommodate passage of an HV in accordance with the following sequence:

1. Tunnel opened to two-way traffic and natural draft.
2. Identification of an HV near the French portal, and closure of the French portal.
3. Establishment of the ventilation in the tunnel in the direction of circulation of VP.
4. Exit of VP1 from the tunnel and inversion of the ventilation for the passage of VP2.
5. Entry of VP2 in the tunnel direction France, generating smoke trace for monitoring from the control center.
6. Exit of VP2 from the tunnel and restoring of the operating conditions in bidirectional mode.

In this test, the tunnel traffic management system is fundamentally responsible for detecting HVs approaching the tunnel, and the ventilation system is responsible for establishing the “preventive” ventilation, which is an air velocity of 1.5 m/s in the forward direction from HVs entering the tunnel.

---

**5.2. Fire ventilation test**

The fire test consists of imposing and maintaining the critical velocity associated with a 15 MW fire to overcome the natural draft and the buoyancy effects of the fire in accordance with the following sequence:

1. Tunnel opened to two-way traffic and natural draft.
2. Accident of two light vehicles 600 m from the French portal.
3. Operation of the ventilation system in the direction from France to Spain.
4. Air velocity established above the critical speed.

This test simulates the effect of a fire-causing accident between two light vehicles circulating in the opposite direction 600 m from the French portal. Three vehicles traveling behind the crash are forced to stop, two in the direction toward Spain and one in the direction toward France.

The control system must detect the fire, close the tunnel to additional traffic, and manage the tunnel ventilation system according to the location of the fire and the affected users.

For effective ventilation management, the traffic control system must first assess the number of affected vehicles in each direction, and then ventilate the smoke past the lower number of users. In this particular scenario, the smoke should be vented in the direction from France to Spain since that would affect only two vehicles, while the opposite ventilation mode would affect three vehicles.
After determining the direction of the ventilation, the ventilation control system, through the linear fire detection system deployed in the ceiling of the tunnel, must manage the number of fans required to maintain the critical velocity.

The test is performed immediately after ventilation inversion, maintaining the traffic cut and handling the control system clock.

With a cold smoke test, it isn’t possible to generate smoke equivalent to that from a 15 MW fire or to imitate the stratification properties of such hot smoke. Thus, the key feature of this test was to simulate the maximum flow of smoke possible.

According to the CETU "Dossier Pilote des Tunnels: Ventilation (1), the volume of smoke generated by this size fire, when 100% developed, is 45 m$^3$/s.
6. CONCLUSIONS

The ventilation system of the Bielsa Tunnel, due to the tunnel constraints and the adaptation project, is a longitudinal type with 55 jet fans.

This system, which is currently valid for a unidirectional tunnel, has certain limitations if operated for bidirectional traffic, as is the case for the Bielsa Tunnel.

However, an automated traffic management and ventilation management system that can activate controls depending on traffic needs and the time of year allows this to be accomplished. For example, the system can be used to activate preventive ventilation in the traffic direction when HVs are present, or to stop opposing traffic from entering the tunnel in the direction opposite to that of the HV.

All tunnel modes have been studied by means of risk analysis as well as ventilation simulations to ensure that possible risks are kept to the minimum while traffic volumes are kept to a maximum.

7. REFERENCES

(1) Dossier Pilote des Tunnels: Ventilation. CETU (Centre d'Études des Tunnels)
(2) Guide des dossiers de sécurité des tunnels, Fascicule 4, Les études spécifiques des dangers (ESD). CETU (Centre d'Études des Tunnels)
(3) Camatt. Logiciel de calcul monodimensionnel anisotherme transitoire en tunnel. Tunnel monodimensional anisotherme transitory calculation software. Enables modelisation of ventilation and fire simulation in road tunnels, and evaluation of smoke cleaning strategies. It is distributed by CETU (Centre d'Études des Tunnels)