Progress in Tunnel Ventilation – The Mont-Blanc Tunnel

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ABSTRACT: The requirements for tunnel ventilations are rapidly evolving, in particular because of an increased sensitivity towards safety in case of fire. A refined analysis of tunnel ventilation, for normal exploitation as well as for fire situations, is called for. New simulation tools are emerging and rapidly growing to standard design tools: 1-dimensional transient simulation and 3-dimensional simulation (CFD). These trends are illustrated based on the studies carried out for the restoration and modernization the Mont Blanc Tunnel after the catastrophic fire of 24th March 1999.

1. INTRODUCTION AND SCOPE

The requirements on tunnel ventilation systems are rapidly evolving. One observes in particular a clear shift in relative importance between the traditional general requirements:

- Reliable and inexpensive function for normal operation.
- Safety in case of fire.
- Minimization of environmental impact.

In recent years the sensitivity towards the environmental implications of tunnel ventilation increased steadily (e.g. Bettelini et al. 2001). A more prominent trend is however related to the increasing importance of safety in case of fire. On one side, the gratifying reduction of motor-vehicle emissions, driven by increasingly stringent national and international regulations, allows for a drastic reduction of the fresh-air requirements as compared to the recent past. On the other side, partly as a consequence of the tragic accidents in the Mont Blanc and Tauern tunnels, the sensitivity towards tunnel safety is growing. One consequence of this trend is a growing gap between the requirements on the ventilation for normal exploitation and in case of fire. As an additional effect, increasing economic pressure demands a reduction of the design-safety margins, which has to be achieved without endangering the overall safety level.

A refined analysis of tunnel ventilation, for normal exploitation as well as for emergency situations, is called for. New simulation tools are emerging and rapidly growing to standard design tools: 1-dimensional transient simulation and 3-dimensional simulation (CFD – Computational Fluid Dynamics). These trends are illustrated based on the studies carried out for the restoration and modernization the Mont Blanc Tunnel after the catastrophic fire of 24th March 1999.

2. THE VENTILATION OF THE MONT-BLANC TUNNEL

After 34 years of successful operation, the tragic fire of 24th March 1999 in the Mont Blanc Tunnel shook the tunnel community and the broad public. 39 persons died and the tunnel equipments and structure were seriously damaged.

A few months after the fire an interdisciplinary project team was charged with the mission of evaluating the damages and developing the concepts for the restoration and modernization of the Mont Blanc Tunnel, on the basis of the 41 recommendations formulated by the French-Italian Commission of investigation (Duffé, Marec & Cialdini 1999). Within this team HBI was in charge of the installations, with particular regard to the ventilation. The final elaboration of this team was a complex and demanding action program, which was definitively approved by the inter-government control commission for the Mont Blanc Tunnel on 14 December 1999 in Paris. The technical solutions retained, which are now being implemented by a project team led by SCETAUROUTE/SPEA, are exposed in AAVV (2000).

The main characteristics of the Mont Blanc tunnel can be summarized as follows:

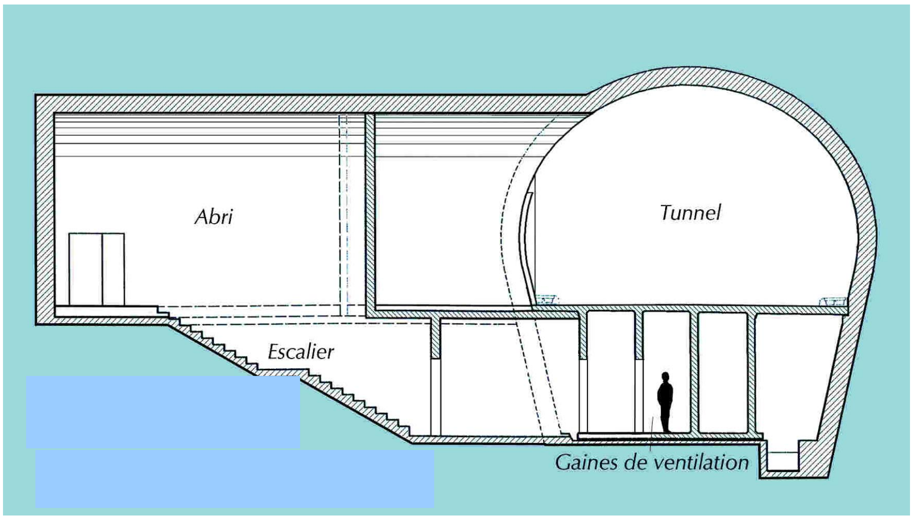
Length	11’600 m	
Slope (Italy → France)	+ 0.25%	(0 - 5’800 m)
	- 1.2%	(5’800 – 8’700 m)
	- 2.4%	(8’700 – 11’600 m)
Cross-section	46 m^2	

The ventilation is of the semi-transversal type, with a maximum fresh-air supply of originally 75m^3/s for each of the 8 sectors. Smoke extraction occurred through openings arranged at a distance of 300 m, partially equipped with dampers. The nominal extraction capacity could originally reach up to 2 x 150 m^3/s, but was significantly lower in case of local aspiration.

3. TUNNEL VENTILATION FOR NORMAL OPERATION

The ventilation system must guarantee under all circumstances a sufficient visibility level and sufficiently low concentrations of all pollutants. The fresh-air requirement of a tunnel depends, besides on its geometric characteristics, on traffic volume, composition and characteristics and on the specific motor-vehicle emissions.

In recent years motor-vehicle emissions diminished rapidly, owing to technical improvements and increasingly stringent regulations, and the trend is enduring. This is best illustrated by a few representative figures, based on the electronic handbook for motor-vehicle emission developed by the German UBA and the Swiss BUWAL (1999). In the coming 10 years in Germany the CO emissions of gasoline engines and the smoke emissions of Diesel engines are expected to diminish by over a factor 2 for cars. The improvements in the HGV segment are expected to be even more important, with an expected reduction of smoke emissions by about a factor 4. The combined effect of increasing traffic volumes and diminishing specific emissions results usually in reduced fresh-air requirements for normal operation. This effect is in many cases sufficiently strong, that the time scales of tunnel ventilation become too long. Consequently, the ventilation reacts too slowly to isolated "pollutant episodes", such as the transit of a particularly pollutant vehicle. This aspect is discussed in Riess et al. (1999).



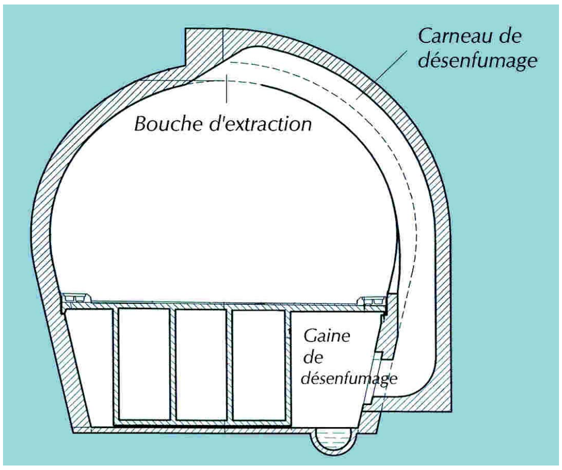


Figure 1

Cross sections of the tunnel.

Top: new shelter and connection with the fresh-air ducts.

Bottom: smoke-extraction duct ("carneau").

The situation in the Mont Blanc Tunnel is atypical in several ways. The traffic volume is relatively modest, with roughly 2 millions vehicles per year and hourly peaks of the order of 1'000 vehicles. For comparison, the traffic volume through the St. Gotthard road tunnel, about 21'000 vehicles/day, is larger by almost a factor 4. However, while the overall traffic volume has doubled compared with the original expectations, the flux of HGV has increased by a factor 17. Roughly 40% of the vehicles traveling through the Mont Blanc Tunnel are HGV. The fresh-air requirement increased therefore significantly in the past. For this reason after 1979 the smoke-extraction system was modified and could be used in a reversible way, for increasing the fresh-air supply.

The reversibility of the smoke-extraction system is now being eliminated, as recommended by Duffé et al. (1999). Owing to the intrinsic limitation of the fresh-air system, characterized by extremely long ducts with limited cross-sectional area, the available fresh-air supply could only be slightly increased by means of a substantial augmentation of the installed ventilation power. Compared to the situation with reversible smoke-extraction system, a significant reduction of the fresh-air supply cannot be avoided.

4. TUNNEL VENTILATION FOR FIRE SAFETY

Among the 41 recommendations formulated by Duffé et al. (1999), several concern the smoke-extraction system. The most important requirements in connection with ventilation are:

- Realization of smoke extraction openings equipped with motorized, remotely controlled dampers at a distance of 100 m (instead of 300 m for the original system).
- Extraction of at least 110 m^3/s over 600 m.
- Realization of a connection between the two smoke extraction ducts on the Italian and French side.
- Limitation of the longitudinal velocity to about 1.5 m/s within about 5 minutes.
- Realization of an automated and technically advanced tunnel management system.
- Optimization of the emergency procedures.

5. SMOKE EXTRACTION SYSTEM

Three main issues arise with the modified smoke-extraction system:

- The pressure loss in the smoke-extraction duct, characterized by a cross-section of only 4.4 to 8 m^2 and a total length of 5'800 m, is extremely high and could generate significant leakages.
- The realization of smoke-extraction openings at a distance of 100 m is extremely time and cost intensive.
- The stability of the smoke-extraction fans for all operating conditions had to be verified.

In spite of the obvious technical difficulties it was decided to increase the safety level well over the requirements by Duffé et al. (1999), and the smoke-extraction rate was increased from 110 m^3/s to 150 m^3/s. Transient simulations showed significant improvements in terms of smoke containment and control of fire exceeding 30 MW.

Several technical options were investigated in order to identify the best solution:

- Realization of connections in the upper part of the tunnel between the existing smoke-extraction openings and the new ones.
- Realization of a continuous false ceiling, connected with the smoke-extraction duct through the existing secondary smoke-extraction ducts ("carneaux").
- Realization or modification of the existing carneaux connecting the extraction openings in the upper part of the tunnel with the exhaust duct located under the road.
- Realization of "pumping" or "relais" stations, equipped with axial fans, along the smoke-extraction duct, in order to reduce the underpressure relative to the tunnel and the fresh-air ducts.

The hypothesis of connecting three aspiration openings to a single carneau had to be rejected because it offered no significant advantages compared with the more radical alternatives, whether in terms of quality nor in terms of cost.

6. CONTROL OF LONGITUDINAL VELOCITY

The main effects affecting the longitudinal velocity in the Mont Blanc tunnel are, in order of importance, meteorological pressure differences between the portals, traffic and aerothermal effects due to the higher temperature inside the tunnel.

The pressure difference between the two portals is illustrated in Figure 2. While the pressure is mostly higher in France, the largest pressure differences are in the opposite direction and can reach up to 1000 Pa under very particular conditions. If the aerothermal effects are taken into account, the resulting pressure difference will typically lay in the range of ±300 Pa. It is important that the "chimney effect" due the temperature rise caused by the fire is taken properly into account, as discussed in Riess et al. (2001).

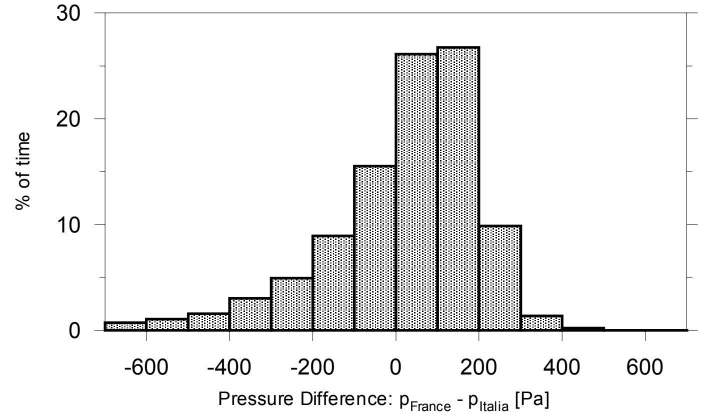


Figure 2 Meteorological pressure difference between the entrances.

In case of normal operation the longitudinal velocity vanishes in the central part of the tunnel and grows linearly towards the entrances (Figure 6), where a value of the order of 6-7 m/s is usually observed. In the past values up to 15 m/s were observed. In case of fire this velocity has to be reduced very quickly to values lower than 1-2 m/s, to avoid destratification of the fumes and improve the effectiveness of the smoke-extraction system. A precise goal was defined for this effort: a longitudinal velocity smaller than 1.5 m/s at the fire location has to be reached in less than 5 minutes. This is consistent with the more recent recommendations formulated by AIPCR/PIARC (1999).

Three possible paths were identified for the control of the longitudinal velocity:

- The realization of a reversible portal exhaust extraction system ("extractor") in proximity of each entrance (this device already existed on the French side, but was not yet reversible).
- The more conventional solution of installing a sufficient number of jet fans.
- The use of different fresh-air injection rates in the different ventilation sectors.

Quantitative analysis shows that the third path is only viable as a complement to the first or second alternative, since its effectiveness is limited, notably in case of fire in proximity of the low-pressure entrance.

7. POSSIBLE SOLUTIONS

The exigencies formulated in the previous sections led to three basic concepts:

1. Realization of carneaux similar to the existing ones at a distance of 100 m with “relais” stations in the smoke-extraction duct and control of longitudinal velocity by means of jet fans.
2. Realization of an intermediate ceiling over the whole length of the tunnel, where the dampers are installed at a distance of 100 m. Smoke extraction occurs through the existing and the new exhaust duct in parallel, which are connected through the existing carneaux. The control of the longitudinal velocity is carried out by means of reversible extractors on both sides. Because of the significant increase of the total cross section available for smoke extraction, intermediate exhaust “relais” stations are not necessary.
3. As a compromise between both solutions, the intermediate ceiling could be installed only in the central part, and a number of jet fans installed in proximity of both entrances, over a distance of roughly 2 x 1’500-2’000 m. This solution would not require the realization of the portal extraction systems and “relais” stations.

While several aspects influenced the final choice, a large number of transient simulations hat to be carried out in order to assess the effectiveness of the different alternatives in term of smoke extraction and containment.

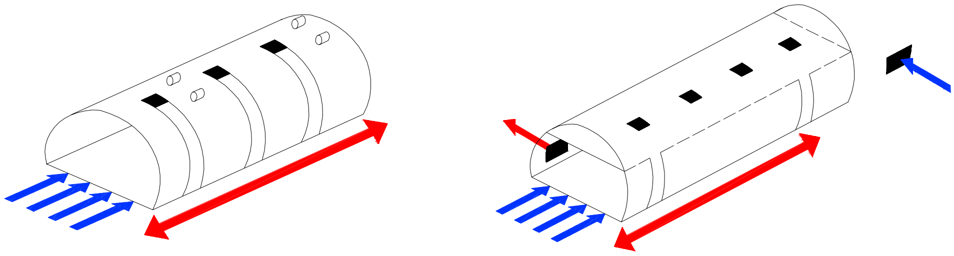


Figure 3 Left: Solution 1, with carneaux every 100 m and jet fans.
Right: Solution 2, with intermediate ceiling and extractors.

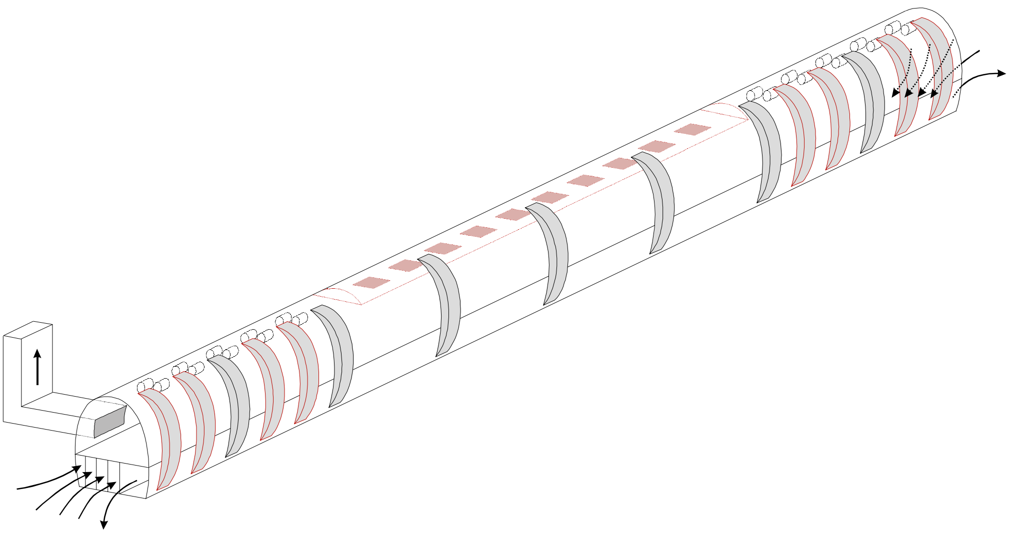


Figure 4 Solution 3, with intermediate ceiling in the central part and jet fans at the entrances.

8. TRANSIENT ANALYSIS - SPRINT

The newly developed simulation code SPRINT (Riess et al. 1999 and 2000) allows for the transient simulations of fire scenarios in tunnels with high accuracy. A unique feature of this code is its capability of simulating smoke propagation within the tunnel in a very realistic manner. Moreover, owing to its computational efficiency, the model can be applied in short time for analyzing a very large number of fire scenarios.

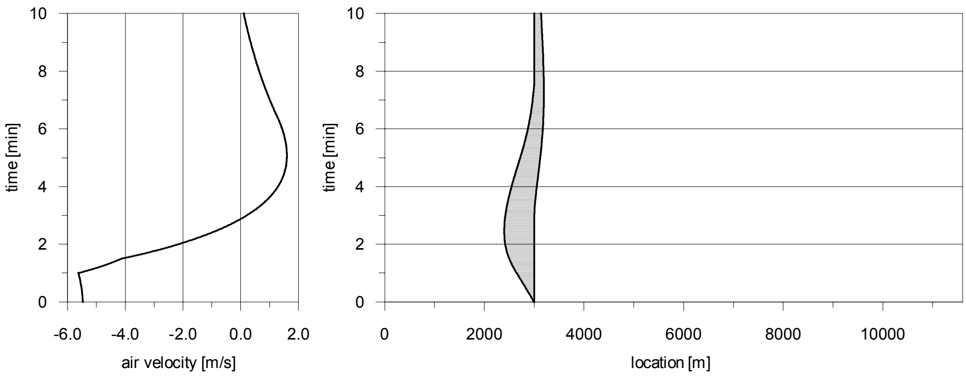


Figure 5 Left: evolution of longitudinal velocity at the fire location.
Right: limits of smoke propagation.

The large number fire scenarios analyzed can only be illustrated by example. The Figures 5 and 6 illustrate the results for a 30 MW fire located 3 km from the Italian entrance (on the left-hand side, x = 0). The longitudinal velocity is controlled by means of 24 jet fans, which are started 1 minute after fire ignition. It should be noted that at the same time the fresh-air supply is reduced from 100% to 20% for all ventilation sectors. The smoke-extraction rate is 150 m^3/s.

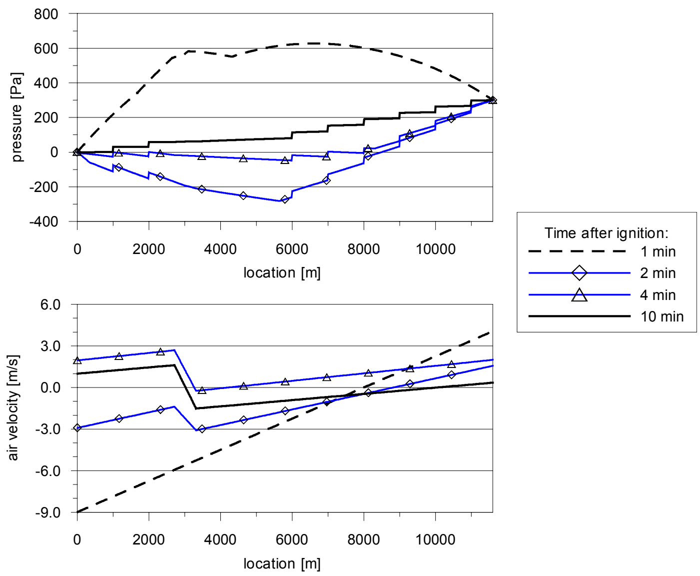


Figure 6 Top: pressure distribution in the tunnel.
Bottom: axial velocity distribution in the tunnel.

It should be noted that the results obtained with SPRINT could be validated based on own measurements carried out in the tunnel during November 1999.

The simulations showed that both extractors and jet fans could master adverse meteorological conditions. However the extractors could not cope with exceptional situations, when the pressure difference exceeds approximately 300 Pa (roughly 10% of the time). The solution with jet fans is more flexible, since their number can be increased almost arbitrarily. The goals set in terms of control of the longitudinal can be achieved, provided that the ventilation is controlled in the proper way.

9. FINAL SOLUTION

A comparative evaluation of the alternatives was carried out based on a combination of criteria, which included functionality for normal operation and safety in case of fire, implications in terms of civil engineering and equipments, maintenance, costs and delays of realization an possible technological risks.

It was finally opted for the more conventional solution, with carneaux at a distance of 100 m and "relais" stations in the exhaust duct for limiting the underpressure. The longitudinal velocity will be controlled by means of jet fans. The safety level of the solution that is now being implemented exceeds significantly the requirements formulated by the French-Italian Commission of investigation (Duffé et al. 1999), notably in terms of smoke-extraction capacity.

10. CONCLUSIONS

Evolving goals for ventilation systems call for the use of new tools and techniques of investigation. These include in particular 1-dimensional transient simulation. The design of the new ventilation system for the Mont Blanc Tunnel illustrates very well the necessity of an appropriate mix of "conventional" and "modern" tools. In this particular case transient analysis was the key element.

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