Regulations and risk analysis methods for bi-national road tunnels: application of a combined scenario-based and system-based method for the Grand Saint Bernard tunnel

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ABSTRACT

For a bi-national tunnel, application of regulations and risk management from different countries makes it necessary to develop specific and consistent methodologies. For example, risk management for the Grand Saint Bernard tunnel (a 5,798 m bidirectional tunnel) has to be consistent with requirements from:

- Italy (implementation of European Directive 2004/54 EC in Italian law, which imposes quantitative risk assessment for fires and comparison with absolute acceptability criteria);
- Switzerland (which is not in the European Union).

In this paper, the following topics are presented:

- What are the Grand Saint Bernard tunnel’s specific safety issues (traffic, operation, safety devices, emergency services, etc.)?
- What are the risk analysis requirements that need to be taken into account (from Switzerland/Italy)?
- What are the methodologies that have been specifically developed and applied to this tunnel?
- What are the results of these studies for the Grand Saint Bernard tunnel and what has been learned?

KEYWORDS: risk analysis, quantitative risk assessment, bi-national tunnel, European Directive

INTRODUCTION

The Grand Saint Bernard alpine tunnel was inaugurated and opened to the public in 1964. It was constructed as a single 5,798-meter-long bi-directional tunnel. The entry portal on the Italian side is 1,875 metres above sea level, while the Swiss entrance is at 1,918 metres.
As set forth in Article 13 of Decreto Legislativo n°264, the Italian Decree dated October 5, 2006 implementing European Directive 2004/54 EC in national law, a risk analysis must be done to quantify the risks associated with accidental events that could occur in tunnels. These risks must then be compared to the acceptability criteria set by this Decree.

To meet these requirements, the following two-stage methodology was used for risk analysis in the Grand Saint Bernard tunnel:

- The method initially used consists in applying a transversal approach (incorporating the tunnel’s safety features, operation and intervention resources, traffic load, etc.), and is scenario-based. The aim of this method is to analyse the development of some fire scenarios and their consequences (with the help of simulation software), in order to evaluate whether the tunnel measures ensure safe conditions.
- Subsequently, the findings from studying the fire scenarios (in terms of consequences) and a probability-based analysis of key parameters (Heat Release Rate of fire, location where scenario occurs, etc.) allow the risks to be fully quantified. Quantification of the “frequency” and “severity” components of the risks then make it possible to determine the frequency/severity curves, which can be compared to the acceptability criteria defined in Italian Decree n°264.

In compliance with the Decree, the methodology takes into account only those events considered to be critical within a confined space, such as fires or accidents involving hazardous materials.

Since events associated with traffic accidents are not specific to the tunnel environment, they are considered elsewhere; victims of incidents that, strictly speaking, are traffic accidents, should therefore be counted in the traffic accidents category. For this reason, such events are excluded from the scope of this study.

This article covers the following topics in succession:

- A description of the Grand Saint Bernard tunnel and its operation;
- Stage 1 of risk analysis: study of fire scenarios;
- Stage 2 of risk analysis: complete quantification of risks;
- Conclusions;
- Recommendations.
DESCRIPTION OF THE GRAND SAINT BERNARD TUNNEL

The diagrams below show cross-sections of the Swiss and Italian parts of the tunnel.

![Cross-sections of the tunnel](image)

**Figure 2** Cross-sections of the tunnel

The tunnel has a transverse ventilation system, with smoke extraction through smoke extraction dampers about every 80 m. There are five ventilation plants, and the air intake duct is divided into four sections, each about 1,500 m long, so that the extraction flow will be higher in the area where the fire occurs.

There are toll booths at each end of the tunnel (in Switzerland and Italy).

![Italian toll booth](image)

**Figure 3** Italian toll booth

**Operator Setup**

The facilities and traffic are managed from two control rooms, which are located at the ends of the tunnel, one on the Italian side and the other on the Swiss side. In these premises, which are staffed 24 hours a day, all information from the various facilities, alarms, and emergency calls is available. The tunnel is controlled alternately by one room or the other (with control changing weekly).
**Intervention**

If an incident occurs, each control room alerts its own emergency response team. The teams, which are located at each end of the tunnel, are then deployed immediately. They are operational 24 hours a day and have special vehicles with firefighting and first-aid equipment.

**Traffic**

In 2008, the annual average daily traffic (AADT) was approximately 1,600 veh./day (both directions). About 10% of these vehicles were heavy trucks, while 1.3% were buses.

It should be noted that under European Directive 2004/54 EC and Italian Decree n°264 of October 5, 2006, the tunnel is considered to be low-traffic (less than 2,000 vehicles per lane per day).

There is no particular peak traffic time in the tunnel during the day. In summer (the busiest time of the year due to tourism), average peak traffic is about 190 veh./h.
STAGE I OF RISK ANALYSIS: STUDY OF FIRE SCENARIOS

The objectives of the first stage of risk analysis are as follows:

- Consideration of dangerous situations that might occur in the tunnel.
- Determination of their frequency of occurrence (average number of occurrences per year).
- Selection a small number of scenarios corresponding to events of a specific type to the confined tunnel environment and arising from these dangerous situations. The scenarios are then analysed in more detail in terms of their possible consequences.

In accordance with Italian Decree n°264, only events considered to be critical within a confined space, such as fires or accidents involving hazardous materials, were considered.

First, the theoretical frequency of occurrence of possible adverse events (fires) was determined.

Table 1 Theoretical frequency of the occurrence of fires in the Grand Saint Bernard tunnel

<table>
<thead>
<tr>
<th>Frequency of occurrence of various event categories in the tunnel</th>
<th>Number of events per year for the tunnel</th>
<th>Time between occurrences (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car fires</td>
<td>6.4E-03</td>
<td>150</td>
</tr>
<tr>
<td>Heavy truck fires</td>
<td>5.3E-04</td>
<td>1 900</td>
</tr>
<tr>
<td>Hazardous materials fires</td>
<td>8.9E-07</td>
<td>1 126 000</td>
</tr>
<tr>
<td>Bus fires</td>
<td>6.8E-05</td>
<td>14 700</td>
</tr>
</tbody>
</table>

To determine the frequency of occurrence of events such as fires, it is essential to make use of a broader statistical base that goes beyond incidents for this tunnel only (as no major fire has occurred since the tunnel began operating in 1964), given the very long repeat cycle for this type of event.

The statistics for heavy truck fires were taken from the CETU (French Tunnel Studies Centre) report entitled “Pannes, accidents et incendies dans les tunnels routiers français” (Breakdowns, Accidents and Fires in French Highway Tunnels), with reference to fire rates observed in a family of tunnels similar to the Grand Saint Bernard. However, these rates were corrected to take two important characteristics of the Grand Saint Bernard tunnel into account:

1. The checking of heavy trucks when they enter the tunnel (which allows technical problems or overheating to be spotted).
2. The presence at each end of the tunnel of permanent emergency response services that can intervene quickly if a fire starts.

Choice of Scenarios

If there is a fire, many contextual factors can influence its severity: traffic levels, location of the event in the tunnel, fire Heat Release Rate, etc.

In the interest of simplification, the number of circumstances studied was voluntarily limited to the “envelope” events or the most probable events (depending on the case), so as to make possible a good analysis of the tunnel’s safety level.

Heat Release Rate of Fire

With reference to part 4 of the Guide to road tunnel safety documentation (CETU – France), and in accordance with the reference fires used in dimensioning the ventilation system, the standardised source terms of 30 MW and 100 MW were used in considering heavy truck fires. It can be noted that action by the emergency response services, which can help limiting the Heat Release Rate of the fire
source in some scenarios, was not taken into account (due to the difficulty of quantifying the impact of extinguishing the fire), making this an “upper limit” type of approach.

**List of the Fire Scenarios Studied**

The criteria stated above led to the selection of a list of scenarios using crossed parameters. For a given fire Heat Release Rate, only one parameter at a time is changed, in such a way that the results can be compared to each other. The results of such crossing of the variables make it possible to develop a list of scenarios such as the one in the table below.

**Table 2 List of scenarios chosen**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Heat Release Rate (MW)</th>
<th>Source Position</th>
<th>Extracting Section</th>
<th>Extraction Stations</th>
<th>Ventilator Loss</th>
<th>DeltaP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>2585</td>
<td>2</td>
<td>B + C + D</td>
<td>NO</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>4600</td>
<td>4</td>
<td>E</td>
<td>NO</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>4600</td>
<td>4</td>
<td>E</td>
<td>NO</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>2585</td>
<td>2</td>
<td>B + C + D</td>
<td>YES</td>
<td>100</td>
</tr>
</tbody>
</table>

By comparing the results of the scenario studies two by two, it is possible to measure the sensitivity of the consequences to:

- fire’s location in the tunnel;
- fire’s Heat Release Rate;
- external weather conditions;
- losing or not losing smoke extraction plants (100 MW fire at MP 2585).
The fire simulations created for risk analysis are based on the use of a model for 3-D simulation of fire scenarios.

It will be noted that for all selected scenarios, the differences in pressure from one end of the tunnel to the other lead to uneven extraction of air. In some scenarios, the speed of the air is sufficient to cause smoke destratification. The following diagram illustrates this phenomenon.

Figure 7 Illustration of the phenomenon of destratification

The consequence of this phenomenon is to “protect” users on the side where the natural air flow originates, to the detriment of users on the other side, who find themselves in the smoke (smoke at the height of a person).

Aside from its effects on conditions inside the tunnel, the 100 MW fire can result in high smoke temperatures in the air extraction duct. So the assumption was that after ten minutes, the ventilators in extraction stations B, C and D could provide only 50% of their nominal extraction capacity (Stations B and C are not protected by a sprinkler system in the duct to limit smoke temperatures.)

In studying the scenarios, working hypotheses were used for the following items:
- time of intervention by rescue services;
- survival criteria (temperatures, CO concentration, and visibility);
- assumptions related to traffic and operation;
- user behaviour;
- fire Heat Release Rate.

The methodology used to evaluate the consequences of fire on the users was as follows:
- modelling of the ambient conditions in the tunnel over time: change in visibility, temperatures, etc. (3-D simulation);
- determination of user movements and superposition on the ambient conditions;
- comparisons of the conditions encountered by users with survival criteria.

As an illustration, the two graphs below show the temperatures varying with space (abscissas) and time (ordinates) for two different fire Heat Release Rates:
- 30 MW (heavy truck, empty);
- 100 MW (heavy truck, filled with combustible goods).
It can be seen on this comparison that the fire Heat Release Rate has a considerable influence on the conditions in the tunnel:

- In the case of the 30 MW fire (scenario 1), most users pass through areas where the temperature is limited to 80°C, which is acceptable.
- In the case of the 100 MW fire, the temperatures on the Swiss side (taking the Italy-to-Switzerland air current into account) quickly rise above 100°C, which corresponds to the survival threshold for users caught in the smoke.

N.B.: the user routes for the 100 MW fire are theoretical to the extent that the users might encounter fatal conditions at a given time (depending on their ability to withstand those conditions) and become unable to continue on their way.
STAGE 2 OF RISK ANALYSIS: COMPLETE QUANTIFICATION OF RISKS

Risk has two components:
- frequency of occurrence;
- severity.

A common representation of risk, based on these two components, is the frequency/severity (F/S) curve. This is a curve showing the annual frequency of occurrence (F) of a scenario likely to cause an effect (usually number of deaths) greater than or equal to S.

In the context of Italian Decree n°264, the number of deaths was used as the main criteria for quantifying risk.

A complete evaluation of the risk of a tunnel fire would require a study of all possible weather conditions, all possible fire Heat Release Rates, all possible traffic situations, etc. Since such an evaluation is totally unrealistic, simplifications were introduced.

The F/S curve was developed using the following methodology:
- Select a limited number of parameters that influence the fire’s severity.
  Example: fire Heat Release Rate.
- For each of these parameters, select a limited number of possible states of these parameters. Example for fire Heat Release Rate: 30 MW or 100 MW.
- Calculate the conditional probabilities associated with each state. Example for fire Heat Release Rates: 54% for 30 MW fire and 46% for 100 MW fire.
- Cross-correlate all parameters to determine “basic” situations: Example: 30 MW fire, with a favourable air current, peak traffic, etc.
- For each basic situation identified: calculate the related frequency (by means of the corresponding conditional probabilities) and determine the number of victims (based on a study of the fire scenarios).
- Adjust, then construct the F/S curve from all of the basic (frequency, severity) pairs that have been determined.

Context Parameters Selected and Their Associated Conditional Probabilities

The main parameters affecting fire severity were selected as follows.

*Table 3 Main parameters influencing the severity of the scenarios*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Possible States</th>
</tr>
</thead>
</table>
| Fire Heat Release Rate                                         | 30 MW  
|                                                               | 100 MW                                               |
| Natural air current                                            | Favourable  
|                                                               | Unfavourable (smoke destratification)                 |
| Traffic                                                        | Peak  
|                                                               | Normal                                               |
| Presence of a bus near the fire                                | Yes  
|                                                               | No                                                   |
| Fire at the end of the tunnel (maximise the number of users on one side of the fire) | Yes  
|                                                               | No                                                   |
| User behaviour at red lights in tunnel                         | Users stop at red lights  
|                                                               | Users do not stop at red lights                       |

The probability of each possible state must be known for each parameter listed above.
A probability-based analysis was carried out for each of these parameters and the following summary table constructed:

**Table 4**  Probabilities associated with the parameters influencing the severity of the scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Conditional Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Release Rate</td>
<td>30</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.46</td>
</tr>
<tr>
<td>Unfavourable air current</td>
<td>Yes</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.67</td>
</tr>
<tr>
<td>Peak traffic</td>
<td>Yes</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.67</td>
</tr>
<tr>
<td>Bus present</td>
<td>Yes</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.94</td>
</tr>
<tr>
<td>Fire at end of tunnel on unfavourable side</td>
<td>Yes</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.83</td>
</tr>
<tr>
<td>Drivers stop at red lights</td>
<td>Yes</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Next, all possible “basic situations” were listed and each parameter was changed, one by one. The frequency and severity were calculated or estimated for each of these basic situations. The frequency of occurrence for each situation is based on:
- the “base” frequency of heavy truck fires;
- the conditional probabilities corresponding to the situation in question (contextual factors).

Example: “Situation A” is defined by:
- a Heat Release Rate of 30 MW;
- unfavourable air current;
- peak traffic;
- the presence of a bus;
- fire at the end of the tunnel;
- drivers stop at red lights.

The frequency for Situation A is calculated as follows:
- Annual frequency of unsuppressed fires = 5.98 x 10^-4 fires/year
- Conditional probabilities (see above table):
  - P(Heat Release Rate 30 MW) = 0.54
  - P(unfavourable air current) = 0.33
  - P(peak traffic) = 0.33
  - P(bus present) = 0.06
  - P(fire at end of tunnel) = 0.17
  - P(drivers stop at red lights) = 0.66

Frequency of Situation A = (5.98 x 10^-4) x 0.54 x 0.33 x 0.33 x 0.06 x 0.17 x 0.66 = 2.37 x 10^-7/year.

**Estimating Severity**

The number of victims was estimated for each situation identified, taking into account all parameters relevant to the situation in question. In particular, the estimates are based on the study of the four fire scenarios discussed above, through extrapolation of the results.
Constructing the F/S Curve

The F/S curve is calculated from the (frequency, severity) pairs from all the situations.

This set of points yields the F/S curve, which can then be compared with the acceptability limits set in Italian Decree n°264.

It must be noted that because the set of calculations defining the F/S curve are complex and are based on a large number of parameters and assumptions, the final result is necessarily associated with significant uncertainty.

![Frequency/Severity Matrix for the Grand Saint Bernard tunnel](image)

**Figure 9** Frequency/Severity matrix for the Grand Saint Bernard tunnel

The grey area corresponds to the uncertainty of the F/S curve.

The corresponding expected value, i.e., the theoretical number of deaths per year due to fires, is $1.60 \times 10^{-3}$ deaths/year (this number does not include deaths due to traffic accidents).

CONCLUSIONS

The progression of the fire scenarios studied, and their generalisation to broader scenarios, led to the following conclusions:

- The relatively light traffic in the Grand Saint Bernard tunnel, along with specific provisions that have a favourable effect on fire prevention (heavy trucks stopped and checked during customs inspections, emergency response teams ready to intervene as soon as a fire starts, etc.), help limiting the frequency of fires.
- In the scenarios in which a natural air flow leads to smoke destratification, survival conditions for the users depend on the fire Heat Release Rate. As a point of reference, a 30 MW fire would not necessarily cause fatal conditions for most users, while a 100 MW fire probably would.
Limiting the air current favours smoke stratification, and ambient conditions should allow users to evacuate under acceptable conditions in most situations.

The number of users involved depends on several parameters. The relatively light traffic in the Grand Saint Bernard tunnel and quick closure of the tunnel significantly limit the number of users.

The presence at the tunnel’s ends of emergency response teams that can be mobilised and respond quickly facilitates user evacuation and limits fire progression.

Additionally, the F/S curve calculated for the Grand Saint Bernard tunnel showed that the level of risk is relatively close to the lower limit of acceptability set in Italian Decree n°264.

Still, it is essential to take into consideration the significant uncertainties inherent in this type of quantitative evaluation.

**RECOMMENDATIONS**

In view of these analyses, the following can be recommended:

- Controlling the longitudinal air current would help limit the risks of smoke destratification and so improve evacuation conditions for the users.
- Given the age of some of the ventilating fans and their lack of specific fire resistance, it would be wise to plan to bring them up to standard or replace them.
- Installation of luminous road studs would improve evacuation conditions for the users.
- Augmenting the traffic stop signals in the tunnel (red lights) with illuminated panels, flashing lights, etc. would increase the chance of the users seeing and obeying the red lights. It would be worthwhile to study the installation of traffic-stopping barriers in the tunnel.
- It would be worthwhile to consider specific operating mechanisms that would avoid the presence in the tunnel of a bus behind a heavy truck—for example, by delaying the entry of a bus into the tunnel following the entrance of a heavy truck.
- Giving operators the ability to send radio messages to the users from their control rooms is a measure that would allow users in the tunnel to be warned earlier if an event were to occur.
- The fire resistance of the pavement and the cables that traverse the tunnel in ducts (especially those providing power to certain extraction stations) should be checked.

Construction of the emergency access tunnel parallel to the existing tunnel will allow some of the above recommendations to be met.

*Figure 10 Illustration of the emergency access tunnel*

Once the emergency tunnel is completed, a new risk analysis can be done based on this tunnel configuration with the new safety facilities.