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# Tunnel Risk Analysis: a Quantitative Evaluation of the Effectiveness of Emergency Teams Inside the A24 and A25 Motorway Tunnels

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The European Directive 2004/54/EC - concerning minimum safety requirements for tunnels on the trans-European road network - requires a quantitative risk analysis for tunnels belonging to the trans-European road network and longer than 500 m, based on accident data. Strada dei Parchi S.p.A. is a company that manages a large number of road tunnels belonging to the A24 and A25 motorways in central Italy. In the course of recent modernization work on several tunnels, Strada dei Parchi S.p.A. has decided to set up and train emergency teams as a measure to further reduce the risk to tunnel users.
This paper discusses the effectiveness of emergency teams during major events, in particular fire accidents. The effect of emergency teams on road tunnel risk is assessed through a quantitative model implemented by Politecnico di Milano: TRAM - Tunnel Risk Analysis Model. The TRAM risk analysis model is able to assess the societal risk for the different tunnel configurations also taking into account the presence of emergency teams. Starting from two types of initiating events, fire and DG (Dangerous Goods) release, TRAM can consider up to 18 accidental scenarios occurring in different positions inside the tunnel under investigation. The main goal of the work is to analyze the effect of the presence of emergency teams in terms of reduction of the societal risk index for a representative tunnel; the resulting F-N (Cumulated Frequency - Number of Casualties) curves are also compared with the ALARP acceptance criterion. This study is divided into three main parts. The first part of the study describes the tunnel infrastructure and the equipment of the emergency teams; the second part is related to the description of the risk model with respect to the effectiveness of the emergency teams and, finally, the third part describes an application of this model to a case study. The effectiveness of the emergency teams and, in particular, their ability to control or extinguish the fire principles is analyzed using observations made inside the tunnels of the A24/25 motorways which were recorded and provided by Strada dei Parchi S.p.A.

## 1. Introduction

Several international studies confirmed that the presence of fire-fighting teams located close to tunnel portals (able to react quickly) brings significant benefits in terms of effectiveness in the management of a tunnel fire (Beard et al., 2005; Kim et al., 2010). The analysis carried out within the work of Chen et al. (2013), concerning Japanese and European tunnels, as well as a computational fluid dynamics activity, has determined that the intervention of the fire-fighting teams should take place within 7 minutes. In the report "Fire Safe Design, Technical Report - Part 3" (FIT, 2005), it is indicated that the intervention of emergency teams is effective if it takes place within the first 10 minutes of the accidental event. It is also highlighted that fire-fighting teams should have a clear knowledge of the situation in order to perform their operations effectively. This knowledge can be obtained more easily if the teams are dedicated to a specific tunnel and communication is used with the control center, which supervises the evolution of the accidental scenario. In fact, the control center can communicate via radio with the teams to both support them and provide guidance.

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In addition, the control center is able to manage the ventilation system in order to move the smoke away from the area where the teams arrive, facilitating the rapid approach to the fire area and the related fire-fighting maneuvers. The added value of these teams, in addition to their speed of intervention, is that they have a detailed knowledge of the tunnel system with particular reference to infrastructure measures, equipment and management procedures. In this way the emergency teams are in a condition to operate in order to control or extinguish fire principles before they evolve into larger fires (Beard et al., 2005). In addition, emergency teams can support tunnel users in their evacuation process by quickly providing information about the direction of the nearest emergency exit to be reached (FIT, 2005). Thanks to the specific knowledge of the tunnel, teams can possibly support the intervention of other rescue teams (e.g. Fire Brigades) by providing information on the scenario and infrastructure also through continuous communication with the control center (Beard et al., 2005). In the work of Kim et al. (2010), several tunnel fires have analyzed in order to estimate the intervention time and the effectiveness of the teams in controlling or extinguishing the fire. The study also analyzed the intervention strategies of firefighting teams for different types of tunnels (e.g. one-way or two-way, with or without vehicle queues in the smoke zone and different ventilation strategies). In addition, the study provides a historical analysis of some fires that have occurred in road tunnels in order to analyze the dynamics, the possible number of victims and the effectiveness of the intervention teams. Finally, in the technical-scientific literature several authors have studied and calibrated models in order to investigate how occupants behave and respond when exposed to a fire emergency inside road tunnels (Bosco et al., 2018; Lovreglio et al., 2016a; Lovreglio et al., 2016b). From this point of view, the emergency teams could, therefore, support tunnel users in choosing the emergency exit to be used also according to the evolution of the scenario (e.g. smoke direction). More details about the egress model and related parameters are reported in Borghetti et al. (2019).

## 2. Emergency teams description

The fire service on the A24 and A25 motorways is composed of emergency rescue teams with special vehicles and equipment to control and extinguish fires. The personnel have specific qualifications such as, for example, that of "Emergency and first aid workers in tunnels/confined areas" (http://www.gsa-safety.it). The vicinity of the emergency teams allows them to quickly reach the location of the accidental event, and directly control/suppress a possible fire and support the egress process of the tunnel users. Figure 1 shows the location of the 9 tunnels on the A24 and A25 motorways and the position of fire-fighting teams.

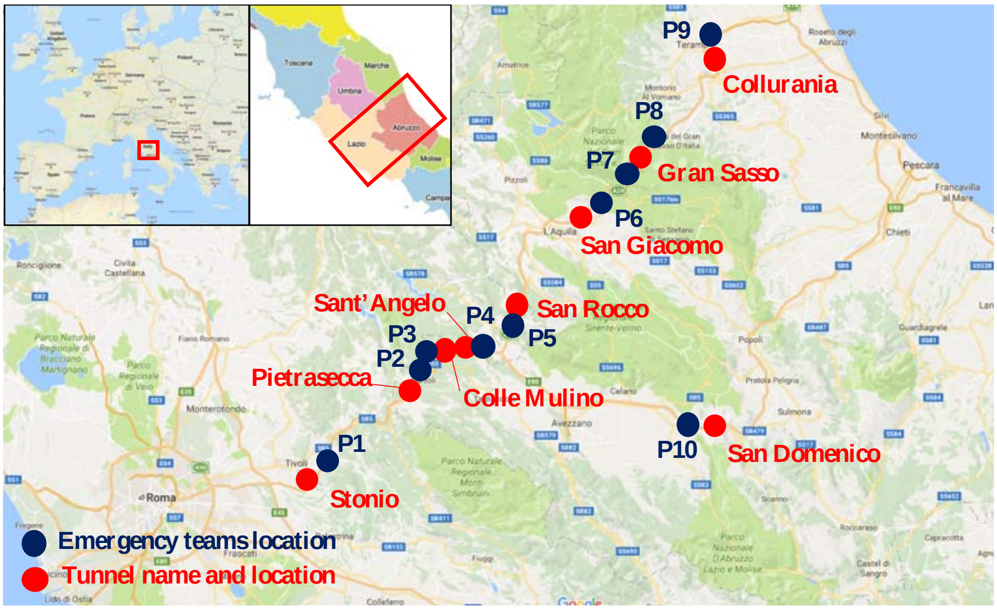


*Figure 1: Location of the 9 tunnels longer than 1000 m (red symbols). A fire-fighting service has been set up for each tunnel (blue symbols). For the Gran Sasso tunnel, having a length higher than 10000 m, two fire-fighting teams are located at the two entrances.*

Figure 2 shows the main vehicles and equipment used by the fire-fighting teams.


*Figure 2: Main vehicles and equipment; Source: Strada Dei Parchi S.p.A.*

Both vehicles are equipped with an emergency fire-fighting system using micronized water; the main technical features are shown in Table 1.

*Table 1: Main technical characteristics of vehicles used by fire-fighting teams*

| Vehicles | Description |
|---|---|
| SUZUKI BURGMAN | 1 stainless steel tank with a capacity of about 60 L of extinguishing liquid<br>2 compressed air cylinders of 9 L each at 300 bar<br>1 fire hose with a length of about 40 m<br>1 spray gun of 1 L |
| ISUZU D-MAX | 1 stainless steel tank with a capacity of about 400 L of extinguishing liquid<br>5 compressed air cylinders of 9 L each at 300 bar<br>1 fire hose with a length of about 40 m<br>1 spray gun of 1 L<br>1 high pressure pump<br>1 fractional Water Lance |

## 3. Effectiveness of emergency teams

The *TRAM* risk analysis model is described in detail by Derudi et al. (2018) and Borghetti et al. (2019). The role and the effectiveness of emergency teams is considered by *TRAM* in the Event Tree related to fire events at the question "Is the fire rapidly extinguished?" as illustrated in Figure 3, while emergency teams do not affect the Event Tree related to DG events. The right side of Figure 3 shows the typical fire Heat Release Rate (HRR) and corresponding estimated smoke production rates for different types of vehicles.

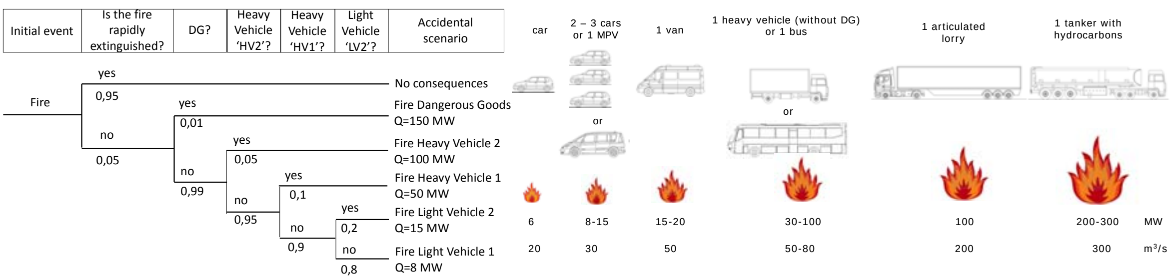


*Figure 3: Event tree (left panel) and fire HRR and smoke production rates for different types of vehicles (right panel) (Borghetti et al., 2017)*

According to the risk model, two safety measures influence the fire Event Tree: the presence of a fire-fighting specialized team and the availability of a water supply. For the fire scenarios it is therefore possible to distinguish four different cases, as shown in Figure 4, considering the presence of the two safety measures.

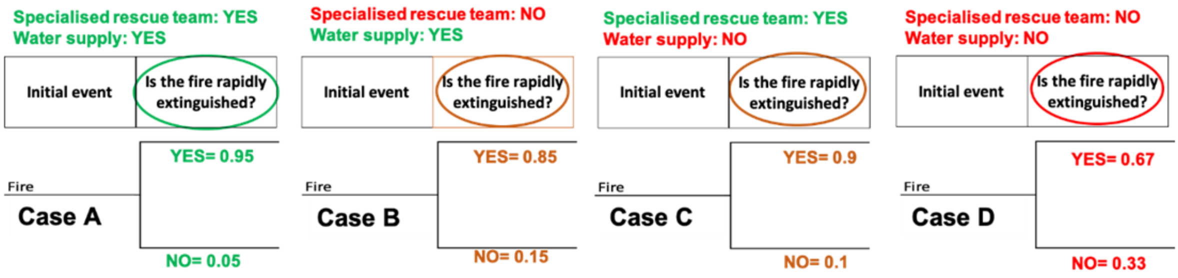


*Figure 4: Fire Event Tree (detail) used in the TRAM risk analysis model (Borghetti et al., 2019)*

Figure 4 shows that the probability of an initial fire event (fire principle) evolving into fires of relevant intensities, which can affect the tenability of the tunnel users, results:

- 0.05 (5%) when the fire-fighting specialized team and water supply are present (Case A);
- 0.15 (15%) when the fire-fighting specialized team is not present, but the water supply is available (Case B);
- 0.10 (10%) when the fire-fighting specialized team is present, but the water supply is not available (Case C);
- 0.33 (33%) when both safety measures are not present (Case D);

This means that if the fire-fighting team is present, the probability of controlling/extinguishing a fire principle is 95% if the water supply system is also available (case A) or 90% if the water supply system is unavailable (case C). In these two cases, only 5% and 10% of the initial fire principles are not controlled/extinguished and evolve into fires with a peak HRR of 8 MW, 15 MW, 50 MW, 100 MW, or 150 MW, respectively, as shown in Figure 3. In the risk analysis model, in the presence of the water supply system (cases A and B), the probability that the fire principle does not evolve in successive scenarios increases from 85% (case B) to 95% (case A). This corresponds, therefore, to an average effectiveness of emergency teams of about 70%: out of 100 fire principles, 15 fires develop without emergency teams. This number becomes 5 in the case of the presence of emergency teams. The fire-fighting specialized team is, therefore, able to control/extinguish 10 fires (difference between 15 and 5 fires) compared to 15 fires without a team.
The effectiveness of the fire-fighting team can therefore be estimated by comparing the situation with the water supply system ($E_{wsy}$) and without this system ($E_{wsn}$), as follows:

- effectiveness with water supply system (case A and case B)

$$\boldsymbol{E_{wsy} = \frac{fires\ without\ emergency\ team - fires\ with\ emergency\ team}{fires\ without\ emergency\ team} = \frac{15-5}{15} = \frac{10}{15} = 0,67 \approx 0,7} \qquad (1)$$

- effectiveness without water supply system (case C and case D)

$$E_{wsn} = \frac{fires\ without\ emergency\ team - fires\ with\ emergency\ team}{fires\ without\ emergency\ team} = \frac{33-10}{33} = \frac{23}{33} = 0{,}7 \qquad (2)$$

Thus, it is necessary to pay attention to the difference between the effectiveness of the fire-fighting specialized team (about 70%) and the probability that the initiating fire event will be controlled/extinguished in the presence of the team. The first one represents the ability of the team to control/extinguish a fire compared to the condition without a team (regardless of the presence of the water supply system); the second one represents, in the Event Tree, the probability that, in the presence of the fire-fighting specialized team, the event is controlled/extinguished and does not evolve into successive fires.
The effectiveness value associated with the fire-fighting team was adopted as a function of:

- intervention time at most equal to 10 minutes (the intervention time is given by the sum of the activation time and the travel time to reach the point of the event);
- presence of a control center and CCTVs;
- presence of devices to detect the event (e.g. Linear heat detectors, fibrolaser);
- ability to control/extinguish the fire (certified teams);
- personnel devices and equipment;
- vehicles used by operational personnel;
- preparation and operational procedures (training).

## 4. Case-study

As mentioned above, the TRAM model was applied to the A24 and A25 motorway tunnels during the modernization phase. In order to evaluate the effectiveness of the specialized emergency teams with reference to societal risk, the results of a representative tunnel in terms of F-N curve and *EDV - Expected Damage Value* are here reported. Table 2 presents the main features of the tunnel and table 3 shows a summary of the infrastructure measures, equipment and management procedures adopted for the tunnel.

*Table 2: Main features of the reference tunnel*

| ***Parameter*** | ***Value*** |
|---|---|
| Length [m] | 2100 |
| Section [$m^2$] | 56 |
| Number of lanes | 2 |
| Distance between the emergency exits [m] | 510; 1045; 1595 |
| ADT – Average Daily Traffic [vehicles/day] | 11600 |
| Peak time flow when the analysis was carried out [vehicles/h] | 1160 (10 % ADT) |
| Longitudinal slope [%] | -1.4 |
| Average number of people in a light vehicle [n. people/vehicle] | 2 |
| Average number of people in a heavy vehicle [n. people/vehicle] | 1.1 |
| Average number of people in a bus [n. people/vehicle] | 30 |
| Percentage of light vehicles [%] | 86 |
| Percentage of heavy vehicles [%] | 13 |
| Percentage of buses [%] | 1 |
| Average speed of the light vehicles [km/h] | 110 |
| Average speed of the heavy vehicles/buses [km/h] | 70 |

*Table 3: Main safety measures of the tunnel*

| ***Infrastructure measures, equipment and management procedures*** | ***Presence*** |
|---|---|
| Road signs | YES |
| Traffic lights and/or arrow-cross panels inside the tunnel | NO |
| Variable message panels inside the tunnel | NO |
| Emergency messages by radio for tunnel users | NO |
| Speakers in shelters and at emergency exits | NO |
| Emergency lighting | YES |
| Emergency pedestrian platforms | YES |
| Emergency team | YES |
| Emergency ventilation | NO |
| Control center | YES |
| TVCC with AID (Automatic Incident Detection) | YES |
| Fibrolaser | YES |
| Traffic lights and/or arrow-cross panels at the tunnel entrance | YES |
| GSM coverage | YES |
| Emergency stations | YES |
| Fixed Fire-fighting system | NO |
| Flammable liquid drainage | NO |
| Water supply | YES |

Figure 5 shows the comparison in terms of F-N curve which allows to represent the societal risk and subsequently verify its acceptance with respect to the *ALARP - As Low As Reasonably Practicable* criterion. The F-N curves are evaluated starting from the frequencies of occurrence of the accidental events and the number of fatalities determined for each accidental scenario. The right side of Figure 5 shows the estimation of the expected damage value of each F-N curve. The four F-N curves have been developed for the 4 cases of Figure 4. The dashed lines represent the two cases with water supply (case A and B).
It is possible to observe that the presence of emergency teams has a considerable effect on the F-N curves, and thus also on the EDV value. A reduction of about ~75% can be observed, which is higher than the efficiency of the emergency teams in controlling the accidental fire. This is due to the fact that these teams are also able to ease the users' egress from the tunnel, thus improving the overall reduction of the risk score. From the F-N curves it is also possible to notice that the effect of the emergency teams only affects the frequency of the fire events and not the frequency of DG events. This effect corresponds to a vertical shift of the left part of the F-N curves, while the frequencies of the DG releases (which are characterized by a large number of fatalities and low frequencies) are not affected by the presence of specialized rescue teams.

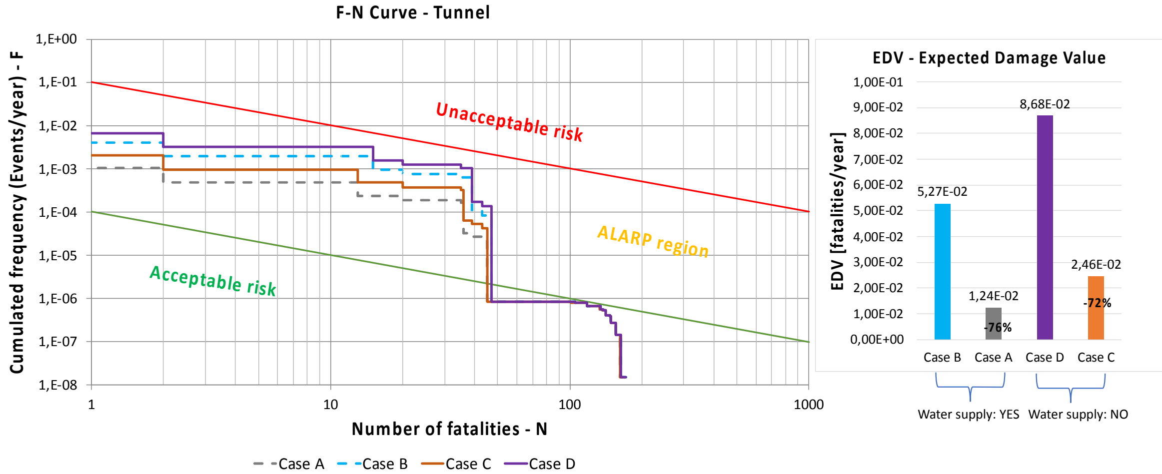


*Figure 5: F-N curves and EDV calculated with TRAM model in order to evaluate the effectiveness of emergency teams in terms of societal risk mitigation. The chart on the right shows the % decrease associated with the presence of emergency teams when the water supply is available (case A vs B) or not available (case C vs D).*

## 5. Conclusions

This paper illustrates and describes the effectiveness of specialized emergency teams during relevant events in road tunnels. In particular, the role of these emergency teams was evaluated for a reference tunnel, with several other mitigation measures, by means of the quantitative risk analysis model TRAM (Tunnel Risk Analysis Model) developed by Politecnico di Milano; model predictions highlighted the strong effect that specialized emergency teams have in reducing all the societal risk indicators of the investigated tunnel. These results were also confirmed by the observations made inside the tunnels of the A24 and A25 motorways by Strada dei Parchi S.p.A. for some unwanted fire events, which were successfully controlled/extinguished with the help of the emergency teams.

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