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Safety in Road Tunnels: Accident Data Analysis of the Italian Motorway A24 and A25

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This paper illustrates the accidents data observed in 14 road tunnels of the Italian motorway A24 and A25, with particular emphasis on two top events such as fires and release of dangerous goods. Consistent data regarding this kind of events are essential to improve the reliability of quantitative risk analysis models for road tunnels. According to the European Directive 2004/54/EC, a quantitative risk analysis (based on accidents data) is required for tunnels belonging to the Trans-European Road Network and longer than 500 m. This work illustrates the accidents occurred inside the 14 tunnels of the A24 and A25 motorway in the years 2012-2018 (7 years), taking into account the different length of the tunnels and the specific traffic of each section of the track. These data can be used by analysts and researchers for quantitative risk analysis purposes using the Event Tree Analysis (ETA) technique. In particular, the observed data are useful to make a comparison with results estimated using analytical models. Finally, the consistency of the estimated accident rates is evaluated by a comparison with literature results.

1. Aim of the accident data analysis

Road tunnels allow on the one hand to improve the plane-altimetry coordination of road sections, reducing slopes, at times even lengths (distances) and fuel consumption, but on the other hand they can be a serious problem for the safety of users in case of a relevant accidental event (Borghetti et al., 2019). The main purpose of this paper is to analyze traffic and accident data of the A24 and A25 motorway in Italy and evaluate the expected frequency of events for each of its 14 tunnels longer than 500 m managed by Strada dei Parchi S.p.A. These new data, collected and provided by Strada dei Parchi S.p.A, can be used to implement tunnel risk analysis where statistical data are not available (e.g. new tunnels) or to compare results with those from other sources. Moreover, the observed data represent a valued and updated database in literature. The probability of occurrence of an accident and the probability of being injured is lower in tunnels (approximately half) than on open sections of roads (Bassan, 2016). However, if an accident does happen in a tunnel, the severity of injuries sustained is significantly higher than on open stretches of motorways, as reported also by Nussbaumer (2007) and Caliendo et al. (2012). Drivers in road tunnels generally reduce their speed and increase their distance from the tunnel wall while driving. In short tunnels, with reduced driving speed, driver vigilance and attention are higher than in longer tunnels, because monotonous driving can lead to boredom and fatigue (Bassan, 2016; Ma et al., 2009; Amundsen et al., 2001). The aim of the Quantitative Risk Analysis (QRA) for road tunnels, performed in accordance with the European Directive (2004) on minimum safety requirements for tunnels belonging to the Trans-European Road Network, is to evaluate the risk for the specific “tunnel system”. This means that several parameters such as accident rate, traffic characteristics, tunnel geometry, as well as infrastructure measures, equipment and management procedures have to be considered. A critical phase in the risk analysis is the evaluation of the frequencies of the accidental events. For this reason, it is in general desirable to use reliable statistical data for the specific tunnel or for similar tunnels of the same motorway/road. On the contrary, the study of the consequences is considered less subject to macroscopic errors.

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Risk analysis is therefore an analytical method that fundamentally consists of identifying the answers to the following three questions (Kaplan and Garrick, 1981): *what could happen inside the tunnel system?, what is the probability of occurrence?, having established that it occurs, what are the possible consequences?* Starting from the top event, the evaluation of the frequencies of each accidental scenario is performed using an approach based on Event Tree Analysis techniques (Beard and Carvel, 2005; PIARC, 2007; Gehandler, 2015). The risk model, in accordance with the European Directive and the Italian Legislative Decree, provides the F-N (Cumulated Frequency – Number of Casualties) curves of the societal risk, in other words functions that relate the frequency of occurrence of an accidental scenario (F) with the expected consequences in terms of potential fatalities (N) (Derudi et al., 2018; Borghetti et al., 2019).

2. Motorways description

The A24 and A25 motorways are located in central Italy and are currently managed by Strada dei Parchi S.p.A.. The total length is about 280 km (160 km of A24 and 120 km of A25), and the road is characterized by long bridges, viaducts and tunnels: 14 of these tunnels are longer than 500 m, while 4 of them are longer than 2,000 m, reaching ~ 10,000 m in the case of the Gran Sasso tunnel. Each tunnel has a double-tube configuration. The two motorways have in the open-air section two carriageways with two lanes plus an emergency lane (not present inside the tunnels). Tunnels longer than 500 m are subjected to the Directive 2004/54/EC on minimum safety requirements. Thus, 14 tunnels are considered in this work. Table 1 contains the main features of the 28 tubes, including main geometrical and traffic data (Average Daily Traffic – ADT, Light Vehicle - LV, Heavy Good Vehicle - HGV).

Table 1: List of the 28 tunnel tubes subjected to the EU Directive 2004/54/EC. Transverse sections of these tunnels range between 54 and 56 m^2, only S. Rocco has section of 70 m^2

Tube name [R=right; L= left]	Length [m]	ADT [vehicle/day]	LV [%]	HGV [%]	Slope [%]	Speed limit [km/h]
ARA SALERE R	606	13695	88	12	+1	130
ARA SALERE L	589	13503	88	12	-1	130
ROVIANO R	805	11006	87	13	+1.7	130
ROVIANO L	807	10771	87	13	-1.8	130
GENZANO R	741	6648	85	15	-2.01	130
GENZANO L	738	6544	86	14	+2.1	130
COLLE CASTIGLIONE R	863	5891	82	18	-1.15	130
COLLE CASTIGLIONE L	878	5933	83	17	+1.2	130
COLLEDARA R	910	5684	84	16	-3.3	130
COLLEDARA L	916	5636	85	15	+3.4	130
COLLE MULINO R	1110	9480	86	14	+0.7	130
COLLE MULINO L	1023	9328	87	13	-0.96	130
S. GIACOMO R	1029	5403	84	16	+0.36	130
S. GIACOMO L	1025	5423	86	14	-0.36	130
PIETRASECCA R	1132	10065	87	13	+3.03	130
PIETRASECCA L	1133	9869	87	13	-3.03	130
STONIO R	1243	15739	88	12	+2.6	130
STONIO L	1191	15510	88	12	-2.6	130
MONTE S. ANGELO R	1585	9480	86	14	-2.16	130
MONTE S. ANGELO L	1573	9328	87	13	+1.7	130
COLLURANIA R	2088	8516	84	16	+1.4	130
COLLURANIA L	2108	8233	85	15	-1.4	110
S. ROCCO R	4183	7223	86	14	+2.2	130
S. ROCCO L	4176	7089	87	13	-2.2	130
S. DOMENICO R	4547	5096	81	19	-1.01	130
S. DOMENICO L	4557	5067	82	18	+1.01	130
GRAN SASSO R	10121	5328	84	16	-0.55	130
GRAN SASSO L	10116	5196	85	15	+0.55	110*

*Gran Sasso Left tube has variable speed limits due to the presence of the Laboratories access inside the tube

It is important to note that inside all tunnels, except the Gran Sasso one, the transit of vehicles carrying dangerous goods substances is allowed, while overtaking is forbidden for heavy vehicles (with mass>3.5 t).

The tunnel lengths are between 589 m and 10121 m and the ADT ranges between 5067 and 15739 vehicle/day. This means that the set of analyzed tunnels is heterogeneous. Another important feature is the percentage of Heavy Goods Vehicles-HGV: the variability is between 11% and 19%. Generally, the frequency of accidents was positively associated with length, Average Daily Traffic, and percentage of Heavy Goods Vehicles (Caliendo et al., 2019). The importance of the presence of Heavy Goods Vehicles is shown in Figure 1 with the characteristics of some typical fires associated with light vehicles (cars), buses, heavy vehicles and vehicles used to transport dangerous goods (e.g. oil tankers or trailers). An indication of the maximum fire intensity that can be reached is given for each type of fire, in terms of Heat Release Rate (HRR) and the corresponding estimated smoke flowrate (Borghetti et al., 2019).

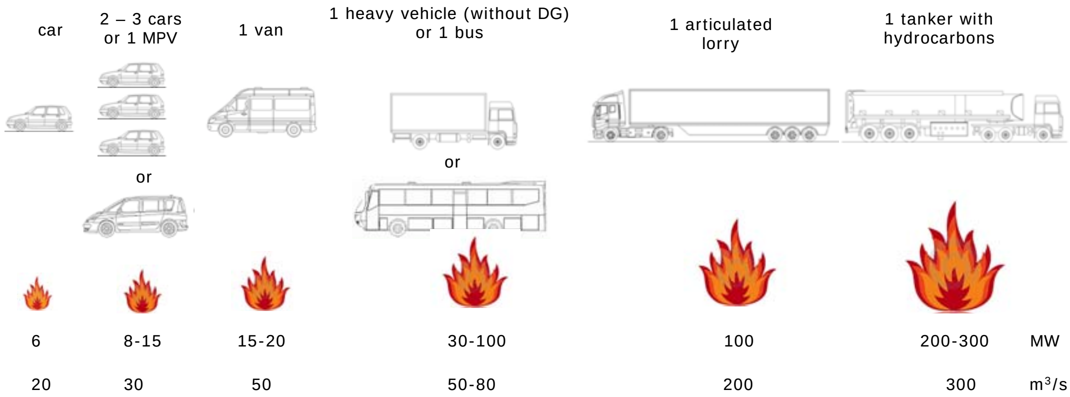

Figure 1: Estimation of fire Heat Release Rate [MW] and smoke production rate [m^3/s] for different types of vehicles, from Borghetti et al. (2019)

3. Accidental events considered in the analysis

Generally, a tunnel quantitative risk analysis takes into account two kind of observed accidental events in a specific time period: fire events and release of Dangerous Goods (DG). These events are typical and representative of the potential dangers inside the tunnel system as a confined environment (Borghetti et al., 2017). On the other hand, non-relevant events are accidents that were observed in the tunnels but are considered not critical for the specific purpose of this analysis, i.e. the risk analysis in the confined environment of the tunnel. In fact, these events, not leading to fires or DG release can be associated to the typical accident rates that are also observed in the open-air sections of the motorway. Indeed, in agreement with what is indicated in the European Directive 2004/54/EC and the Italian Legislative Decree 264/2006, the events of road accidents connected with the geometric characteristics of the infrastructure and not induced by the specific tunnel environment (confined), should not be considered in the tunnel risk analysis. In fact, this kind of events does not cause risks other than those already connected with road circulation, and thus are to be considered only for prevention in the traffic regulation and road design context. For this reason, the victims of this type of accident are recorded as caused by ordinary road accidents (Borghetti et al., 2019). Examples of these non-relevant events are: failure of the vehicle and collision between vehicles without fire or DG release, collision of a vehicle with tunnel elements (pavements, walls, guard rails, etc.), collision with animals without consequences, other events. For this reason, the analysis presented in this work takes into consideration two initial events, a fire and a Dangerous Good (DG) release in the time period 2012-2018 (Borghetti et al., 2018; Derudi et al., 2018; Borghetti et al., 2019) using a Bow-Tie diagram (PIARC, 2007) for each top (initiating) event.

4. Observed frequencies and rates of accidental events

The analysis refers to a total time period of seven years: 2012-2018. Figure 2 shows the average frequencies observed for each tunnel tube: no release of DG occurred, and 8 tubes was involved in fire/fire principles events. The dotted lines represent the average values of fires (red line) and non-relevant events (blue line) for the 28 tubes. It is possible to observe that the tubes are characterized by different accident frequencies. However, it has to be considered that the seven-year period, despite being quite long, is not sufficient to completely characterize the accident frequencies of all the tubes. This is important especially if the number of accidents is low or equal to 0 (in the case of DG release events) and would require using rather long time-series. Thus, starting from these data recorded, a proper analysis is required to allow estimating plausible event frequencies for all the tubes to evaluate risks according to the European Directive.

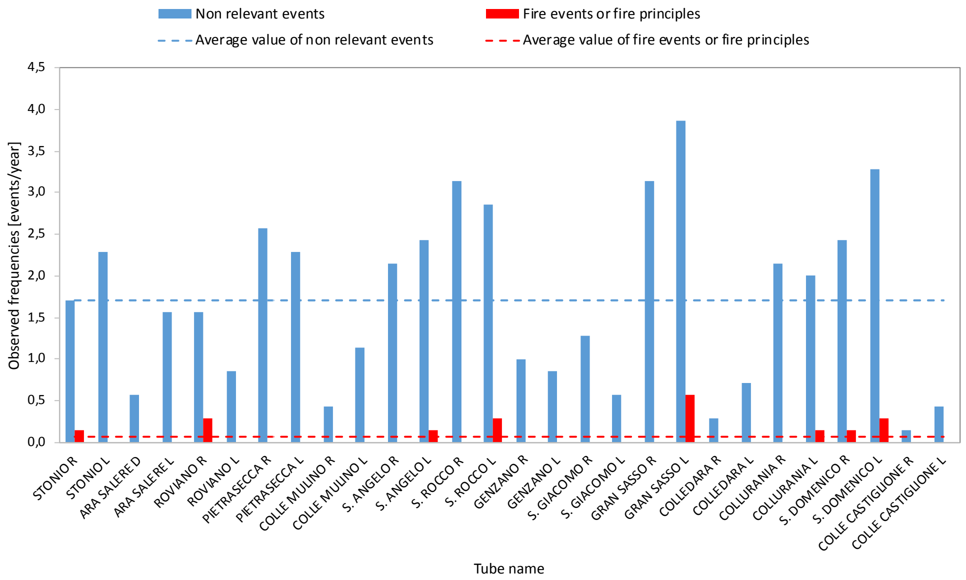

Figure 2: Representation of the observed frequencies of occurrence (average values in years 2012-2018)

The analysis included the estimation of the occurrence rate of accidental events in order to make the comparison with literature data. Figure 3 shows the three categories of events: non-relevant events, fire events (or fires principles) and DG release for each single tube, in terms of events per 100 million vehicle-kilometers. These values are the average events observed in the years 2012-2018 and are calculated using the tube length and the average daily traffic data over the same time period (2012-2018). It can be observed that the rates are significantly different for the 28 tubes due to length and traffic. In some cases, the frequencies of fire events are zero. Moreover, no DG releases were observed during the seven years (2012-2018).

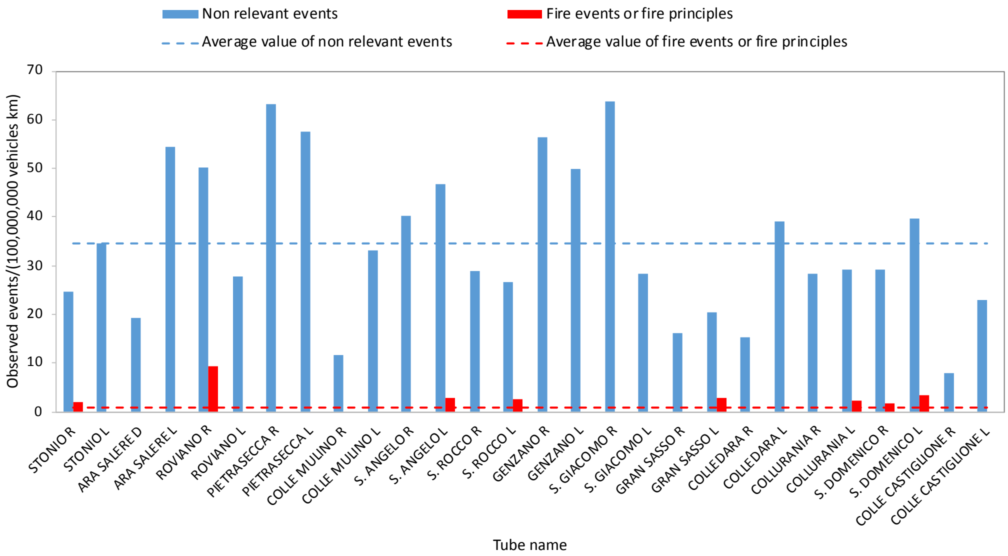

Figure 3: Representation of the observed events/100,000,000 vehicles km (average values in years 2012-2018)

A preliminary analysis showed that most fires were caused by vehicle failure and no deaths were observed as indicated in Figure 4. These percentage distributions are consistent with the work of Kim et al. (2010) and Ren et al. (2019).

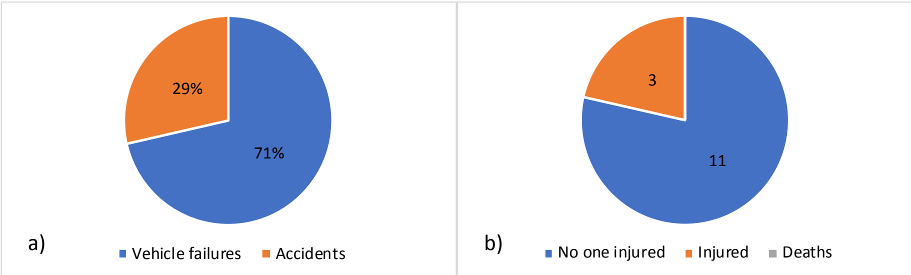

Figure 4: (a) causes of fires observed; (b) consequences of fires observed; Source: Strada Dei Parchi S.p.A.

Moreover, for each tunnel an evaluation was performed to compare the literature reference values (Rattei et al., 2014; CETU, 2003; PIARC, 1995; Pálsson, 2004) and the observed/predicted frequencies of fire events. As already said, only 8 tubes involved fires. The available references are data collected on Austrian motorways (ASFINAG) (Rattei et al., 2014), which have an average fire frequency of 0.67 events/100,000,000 vehicle-km. Another reference is the French CETU guidelines (CETU, 2003), which recommend a value of 2 events/100,000,000 vehicle-km. PIARC data suggest a value between 0 and 10, while Pálsson (2004) suggests a value of 4 events/100,000,000,000 vehicle-km. Table 2 and Figure 5 show a comparison between frequencies (in terms of events/year) based on the literature (Rattei et al., 2014; CETU, 2003), and the specific analysis presented in this paper. The frequencies have been calculated from the accident rate, tunnel length and traffic provided by Strada Dei Parchi S.p.A.

Table 2: Comparison among average observed fire frequencies in year 2012-2018 and literature data

Tube name	Average frequencies observed [yr^{-1}]	Estimated frequencies with CETU values [yr^{-1}]	Estimated frequencies with ASFINAG values [yr^{-1}]
STONIO R	1.43E-01	1.40E-01	4.54E-02
ROVIANO R	2.86E-01	6.37E-02	2.07E-02
S. ANGELO L	1.43E-01	1.06E-01	3.43E-02
S. ROCCO L	2.86E-01	2.14E-01	6.95E-02
GRAN SASSO L	5.71E-01	3.79E-01	1.23E-01
COLLURANIA L	1.43E-01	1.51E-01	4.90E-02
S. DOMENICO R	1.43E-01	1.66E-01	5.40E-02
S. DOMENICO L	2.86E-01	1.65E-01	5.38E-02

In Figure 5 it is possible to observe that there is a reasonable agreement between the observed frequencies in this work and the CETU data (orange bar). In two cases, Collurania L and S. Domenico R, the frequencies calculated using the CETU rate are slightly larger than the frequencies observed. On the contrary, the ASFINAG frequencies (green bar) are characterized by systematically lower values than the ones observed in this work and by CETU. As we said before, it is fundamental to implement a methodology able to estimate the frequencies of occurrence especially for the tubes without recorded events in time period (2012-2018). In fact, this obviously does not automatically mean that in these tubes fires cannot occur in the future.

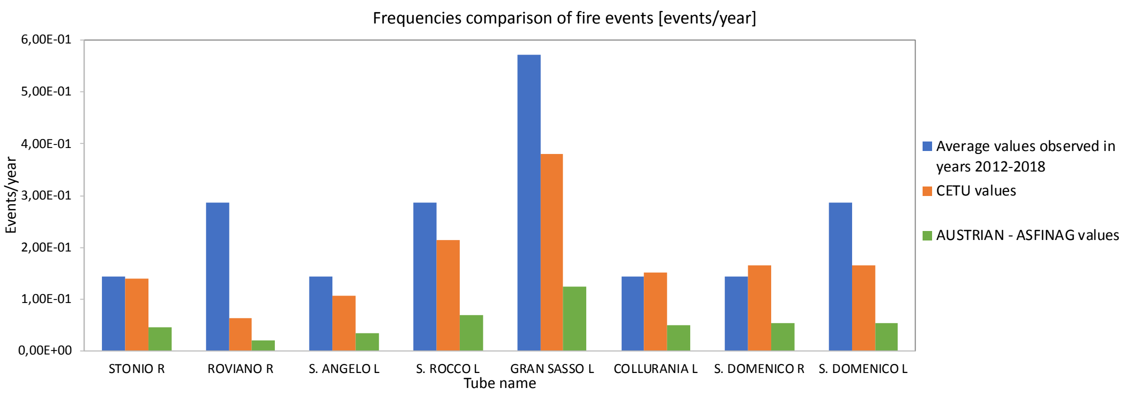

Figure 5: Comparison among average observed frequencies in year 2012-2018 and literature data for fire events

5. Conclusions

The aim of the work is to analyze the accidents of road tunnels belonging to the A24 and A25 motorways located in Italy in accordance with European Directive 2004/54/EC. 14 motorway tunnels have been taken into consideration for a total of 28 tubes between 500 m and 10,000 m in length. These data can be used by the analyst to implement the risk analysis of tunnels where statistical data are not available (e.g. new tunnels) or to compare the results with other works or research. For each tube two types of events, fire and DG release were analyzed in the years 2012-2018. The observed data refer to a relatively short period of time (7 years) and it is necessary to implement a methodology to estimate the frequency of occurrence from these data. In the coming years it will be possible to expand the database and carry out more accurate analyses. For fire events, a comparison has been made with the literature data taking into account the French CETU guidelines and the Austrian data - ASFINAG: there is a reasonable agreement between the frequencies observed in this work and the literature, in particular the CETU data. In two cases, Collurania L and S. Domenico R, the frequencies calculated with the CETU rate are higher than the observed frequencies. The Austrian - ASFINAG frequencies are instead characterized by a systematically lower value than the observed one. The next step of the research is to increase the database and to make a comparison with other researches and studies in order to develop an analytical methodology able to estimate the possible fire and the DG event for the tube in which non-events were observed.

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