RISK-BASED TUNNEL DESIGN FOR CONSEQUENCES OF ROAD ACCIDENTS: THE ROLE OF TUNNEL LENGTH

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ABSTRACT

Tunnel extension is an under-analysed variable in road tunnel accidents despite being a dimensioning parameter for the purposes of users' safety according to Directive 2004/54/EC. Recent studies have shown a correlation between the tunnel length and consequences of accidents. The analysis of fire events which occurred in tunnels indicates that in many cases fires are triggered by road accidents. By analysing the road accidents in Italy, the study aims to assess the relative risk of accidents with serious consequences for different classes of road tunnels. The second objective was to assess, using a vehicle type (or size) approach, the corresponding probability of accidents involving vehicles or trucks and special vehicles resulting in serious consequences (domino effect). We analysed the Italian National Institute of Statistics (Istat) dataset on tunnel accidents which occurred between 2018 and 2020 on Italian public roads, involving at least one vehicle. Of these, we extracted tunnel accidents, classified by tunnel length and estimated the corresponding probability of serious consequences. The analysis identified 1,885 case studies of tunnel accidents that occurred in approximately 265 long tunnels and 450 short tunnels and underpasses. Compared with "controls", "size" was found to be more than double in long tunnels where the related probability of serious accident consequences exceeded 50% more than those of short tunnels. We found that the related probability associated with serious accident consequences in tunnels over 500 m in length was higher than in short tunnels, except for trucks and special vehicles. Road accidents and research on risk evaluation of the effects associated with long and short tunnels are rare. The study aims to fill these gaps.

Keywords: road tunnel safety, tunnel length, vehicle, risk exposition, work-related road risk, risk based design.

1 INTRODUCTION

Studies are not consistent in regards to the impact of tunnel length on safety indicators. However the length effect was indirectly considered in Directive 2004/54/CE, as a parameter for defining classes of minimum safety requirements. A road accident occurs when two or more vehicles collide or when a vehicle hits a pedestrian, an animal or an object such as a tunnel wall, traffic sign, etc. Amundsen [1], carried out a series of tunnel traffic accident analyses on Norwegian road tunnels from 1994 to 2009. They observed that the risk of accidents in tunnels was lower than on open roads, but that the severity of accidents was much higher (Amundsen [1], Amundsen and Engebretsen [2] and Amundsen and Ranes [3]). In general, it was found that the frequency of tunnel accidents is lower than on straight sections, curves, roundabouts and intersections. Tunnel extension is an under-analysed variable in road tunnel accidents although being a dimensioning parameter for the purposes of users' safety according to Directive 2004/54/EC [4]. Recent studies have found a positive correlation with the length and consequences of tunnel accidents (Caliendo et al. [5]), other studies have shown a higher absolute and relative frequency of road accidents and injuries in the shortest tunnels (Pireddu and Bruzzone [6]).

However, such studies have not yet demonstrated a clear correlation between the risk of accident and the length of the fornix tunnel. This is probably the result of the unavailability of sufficiently comprehensive case studies to draw reliable conclusions. According to

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previous simulation and psychological studies, the analytic results indicate that the different types of tunnel have distinct accident characteristics and therefore should be considered separately for safety analysis (Pervez et al. [7], PIARC [8]).

Based on recent findings, fire in tunnels are in many cases caused by road accidents that do not occur in the same conditions as the open roads. Although less frequent than in open sections, road accidents in tunnels can cause serious fires. A notorious example is the fire in the Gotthard Tunnel on 24 October 2001 where, at the entrance to the tunnel, the driver of a truck carrying tyres lost control of the vehicle, invading the other lane and hitting a truck that ran through the tunnel in the opposite direction. The frontal collision between the two vehicles caused the fire, whose flames extended for about 300 m, raising the temperature to 1,200°C. This event highlights the importance of empirical analyses of road accidents and related variables in the accident scenario. The information derived from case studies is a useful tool in road safety design to identify appropriate measures (or safety minimum requirements, according to Directive 2004/54/CE) to prevent accidents in tunnels. Consequently, these analyses are useful in assessing the risk of road accidents and the risk of fire triggered by a domino effect, in road tunnels.

Therefore, the main purpose of this study, based on road accidents in Italian tunnels, was to assess the relative risk of road accidents resulting in serious consequences for road users and workers, in various types of road tunnels. A second objective was to assess, using a vehicle type approach, the relative risk of accidents resulting in serious consequences, in terms of deaths or serious injuries, when vehicles or truck and special vehicles are involved.

2 MATERIAL AND METHODS

Case studies on road accidents are provided by Istat [9]–[13], based on the "Survey on road accidents resulting in death or injury" that includes all road accidents involving deaths within 30 days or injuries. This archives contain accidents occurred throughout the country in public roads where "at least one vehicle is involved and where at least one injured person is recorded by a police authority" (Vienna Convention on Road Traffic, 1968). The detection data refers to the time which the accident occurred (Istat data warehouse, I. Stat, 2018–2020).

The Istat dataset, provided the following information: the accident circumstances (European Commission [14]), the accident type, the carriageway, the consequences (fatalities or injuries), the involvement of pedestrian, the geographical coordinates (Cima et al. [15], Costabile et al. [16]), the road type, the time of the accident, the journey purpose (work-related or not work-related) [17], the vehicle type. By geo-processing, we integrated the Istat dataset with the OpenStreetMap (OSM) road information to obtain the tunnel section geometry involved in the accidents. According to Directive 2004/54/EC [4], tunnels were grouped into two length classes: up to 500 m (underpasses included), over 500 m, more suitable for our investigation (Fig. 1 and Table 1) because equipped with minimum requirements according to the tunnel length. The tunnels involved in at the least one accident in 2018–2020 were then ordered by frequencies, accident variable and classes. This first step of study missed variables such as the characteristics of road sections, the tunnel route and traffic intensity-composition. We implemented a case-control design for the estimation of the association between the tunnel length and severity of road accident consequences. We compared population exposure for two clusters: accidents resulting in serious consequences occurred in long tunnels and remaining accidents without consequences (control cases). The dichotomous dependent variable Y assumed 0 value in case of non-serious accident consequences and 1 in case of serious consequences. Among the risk factors (regressors X_i, $i = 1 \dots n$ in the $n \cdot m$ matrix), we have taken the ones affecting the response of the variable Y. Then, by means of logistic regression (Breiman et al. [18]) and R applications, we estimated the incidence risk ratio. The relation between the severity of consequences Y and the other independent variables Xi is explained by eqn (1):

$$= \ln \frac{p}{(1-p)} = \beta0 + \beta1 \cdot X1 + \beta2 \cdot X2 + \ldots \beta n \cdot Xn + \varepsilon. \quad (1)$$

Probability of serious consequences Y is provided by eqn (2). The coefficients βi of exponentials associated with independent variables Xi, represent the event occurrence odds ratio (OR) corresponding to the increment of the independent variable (e.g. the length), net of other ones

$$p = \frac{1}{e^{-(\beta0 + \beta1 \cdot X1 + \beta2 \cdot X2 + \ldots \beta n \cdot Xn + \varepsilon)}} + \varepsilon. \quad (2)$$

The exp (βi) provided a measure of the relative risk (probability of serious consequence in case of road accident) Yi, compared to the exposure to the risk factor Xi, represented by the length of the tunnel over 500 m. We implemented eqns (1) and (2), the "glm" function and the "family = binomial" to the following subsets including: (i) accidents involving all vehicle type; (ii) accidents involving all vehicle type excluded trucks or special vehicles; (iii) accidents involving at least one truck or special vehicle. As a result, we obtained a cross validated model that estimates, for each subset, the "size" of severity of accident consequences by length classes. Within the subsets (ii) and (iii), using kernel density, which is a non-parametric method, we estimated the density and the probability that a certain class of accident consequences belonged to a given class of tunnel length (Fig. 2).

Figure 1: Location of the studied tunnels. Long tunnel accidents (blue) and short tunnel accidents (red), Italy, 2018–2020. *(Source: Author's processing from Istat and OSM dataset. QGIS.)*

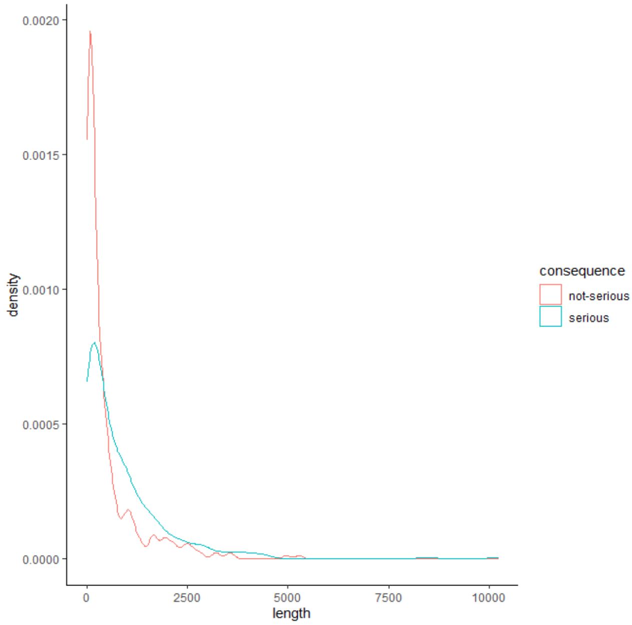
Table 1: Attributes and labels resulting from the Istat data, Italy, 2018–2020. *(Source: Author's processing from Istat data, QGIS and R Studio.)*

Variables (attribute)	Classes (label)
Accident circumstances	distance (not keeping distance between vehicles); distraction; normal driving; speeding; other_circ (unspecified and other circumstances); corresponding to driver behaviour recorded when the accident occurred (Amundsen [1], Amundsen and Engebretsen [2], Pireddu and Bruzzone [6], Gariazzo et al. [19], [20])
Accident type	rear-end; collision, impact (impact with other vehicles, frontal or lateral collisions); other (pedestrians or obstacles, skidding or off-road, etc.)
Carriageway	carr1 (one-way lane); carr2 (two-way lanes); carr3 (two carriageways); carr4 (more than two carriageways)
Consequence	serious (accidents with more than three injuries and/or one or more fatalities); not-serious (accidents with up to three injuries and no fatalities)
Journey purpose	work-related 1 (driving for duty); work-related 2 (as part of commuting); not work-related (journey purpose not work-related) (Pireddu and Bruzzone [6], [21]) The journey purpose resulted often not filled due to the difficulty of recording this information at the scene of the accident
Pedestrian	0 (accident not involving pedestrian); 1 (accident involving at least one pedestrian)
Road tunnel location (road type)	motorway (road inside or outside urban areas, reserved to certain categories of vehicles); rural (road outside urban areas and not motorway); urban (road in urban areas and not motorway) (Italian Road Traffic Law [22])
Time of accident	morning (06:00–12:00); afternoon (13:00–18:00); evening (19:00–21:00); night (22:00–05:00); defined according to a conventional interval
Tunnel length (class)	short tunnels and underpasses; (up to 500 m in length or "0–500"); long tunnel (over 500 m in length or ">500"); unclassified (when the tunnel location were not available)
Vehicle type	car; truck or special vehicle (heavy goods vehicle); motorcycle; otherV (other vehicle); bicycle, scooter; (bicycle, electric bicycle and scooter)

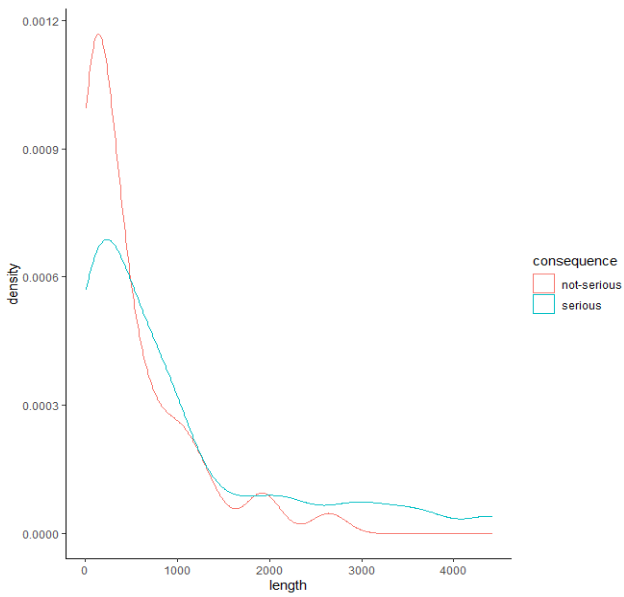
3 RESULTS

The 1,885 cases selected from the Italian road accidents dataset, complete with information on the accident scenario, tunnel geometry and traffic information, included 2,999 injured people and 60 deaths. The accident dataset provided about 715 tunnels (Fig. 1) exactly classified: 37% long tunnels (>500 m) and 63% short tunnels (0–500 m).

Table 1 shows a classification of accident variables, used in the n·m matrix on accident frequencies where the rows are the tunnels studied and columns the classes.



(a)



(b)

Figure 2: Kernel density estimation. Consequences of serious (turquoise) and not serious (red) accidents by tunnel length (m). (a) Accidents including all vehicle type trucks and special vehicles excluded; and (b) Accidents involving at least one truck or special vehicle. Italy, 2018–2020. *(Source: Author's elaboration from Istat data.)*

3.1 Association between accident consequences and tunnel length by vehicle class

Applying eqns (1) and (2), the “glm” function and the “family=binomial” in R to the three subsets (i), (ii), (iii), we obtain the probability of serious consequences associated to long tunnel exposure or relative risk (Tables 2 and 3).

3.2 The risk ratio and the relative risk attributable to exposure to tunnels longer than 500 m

The incidence relative risk ratio allows comparison of accident rates between two different groups. Attributable relative risk is the increase or decrease in the probability of serious consequences (outcome) that is attributable to road users’ exposure in long tunnels (Table 3). This parameter provides a measure of the absolute frequency of the outcome associated with exposure. Considering the outcomes per 100 population units, Table 3 lists the confidence intervals.

As reported in Table 2, the odds reached values of 1.7, 1.9 and 2.9 for subsets (i), (ii) and (iii). The odds ratio reached for the same subsets 2.69, 2.70 and 2.45 while the incidence relative risk ratio 1.58, 1.62 and 1.37 respectively, with a 95% confidence interval. For the subset (i), the incidence relative risk ratio (RR) falls within a confidence interval of 1.37 ÷ 1.82 and thus is always greater than 1, indicating that the incidence rate is higher in the group exposed to long tunnels (+) than in the control group (−). The result indicates that for vehicles as a whole (i), exposure to long tunnels is a factor that increases the probability of serious accident consequences by 58%. This result is even higher in the subset where no trucks or special vehicles are involved, where exposure to long tunnels leads to a 62% increase in relative risk (C.I. 1.38 ÷ 1.90). On the other hand, in the case where each accident involves at least 1 among trucks or special vehicles, the incidence relative risk ratio is lower than the previous ones (1.37) and falls in the confidence interval between 1.04 and 1.79. This means that the incidence relative risk ratio can reach as high as 1, thus indicating that the severity of accident consequences in long tunnels can be very close to that observed in short tunnels. For subset (iii), unlike subsets (i) and (ii), we have accepted RR = 1 and the null hypothesis associated with the probability that the severity of accident consequences in the long tunnels coincides with that observed in the short tunnels.

3.3 The consequences of road tunnel accidents referring to the length of the tunnel and the type of vehicle involved

Not serious consequences (up to three injuries in the 3-year period) affected 354 tunnels out of the total, while serious consequences (more than three injuries and/or at least one death in three years) affected 361 tunnels (64% long tunnels and 36% short tunnels).

The Kernel graphs in Fig. 2 present density curves by tunnel length expressed in metres (x-axes) for severe and not serious consequences. When heavy vehicles were not involved in accidents (ii), the density graph reaches 0.0020 for not serious consequences and 0.0008 for serious consequences. The curve reverses between 500 m and 5,000 m, when severe consequences exceed not serious consequences (Fig. 2(a)).

If heavy vehicles are involved in accidents (iii), the density reaches 0.00012 for non-serious consequences and 0.0008 for serious consequences. The curve reverses between 500 m and about 1,000 m in length, where serious consequences exceed not serious consequences (Fig. 2(b)).

Table 2: The accident outcomes. Long tunnels exposure. Probability and relative risk associated to accidents involving (i) all type of vehicles; (ii) trucks or special vehicles excluded; and (iii); trucks or special vehicles. Italy, 2018–2020. *(Source: Author's processing from Istat and OSM data on road accidents, QGIS and R Studio.)*

Tunnel type and consequence	The accident outcomes for accidents involving all type of vehicles (i)				
	Serious consequences (Outcome +)	Not serious consequences (Outcome −)	Total consequences	Incidence probability	Odds
>500 m (exposed +)	174	91	265	65.7	1.9
≤500 m (exposed −)	187	263	450	41.6	0.7
Total	361	354	715	50.5	1.0

Tunnel type and consequence	The accident outcomes for accidents involving all type of vehicles, trucks or special vehicles excluded (ii)				
	Serious consequences (Outcome +)	Not serious consequences (Outcome −)	Total consequences	Incidence probability	Odds
>500 m (exposed +)	136	75	214	63.6	1.7
≤500 m (exposed −)	150	232	382	39.3	0.6
Total	286	310	596	48.0	0.9

Tunnel type and consequence	The accident outcomes for accidents where trucks or special vehicles are involved (iii)				
	Serious consequences (Outcome +)	Not serious consequences (Outcome −)	Total consequences	Incidence probability	Odds
>500 m (exposed +)	38	13	51	74.5	2.9
≤500 m (exposed −)	37	31	68	54.4	1.2
Total	45	74	119	63.0	1.7

Table 3: The accident consequences. Exposure to long tunnels. Point estimates for accidents involving (i) all type of vehicles; (ii) trucks or special vehicles excluded; and (iii) accidents where trucks or special vehicles are involved (95% CI). Italy, 2018–2020. *(Source: Author's processing from Istat and OSM data on road accidents, QGIS and R Studio.)*

Accidents involving all type of vehicles (i)	Point estimates	Confidence interval 95%
Incidence relative risk ratio	1.58	(1.37 ÷ 1.82)
Odds ratio	2.69	(1.96 ÷ 3.69)
Attributable relative risk in the exposed	24.10	(16.80 ÷ 31.41)
Attributable fraction in the exposed (%)	36.71	(27.20 ÷ 44.98)
Attributable relative risk in the population	8.93	(3.09 ÷ 14.78)
Attributable fraction in the population (%)	17.69	(11.77 ÷ 23.22)

For subset (i), uncorrected $\chi 2$ test that OR = 1: $\chi 2$ (1) = 38.767. Pr> $\chi 2$ = <0.001. Fisher exact test that OR = 1: Pr> $\chi 2$ = <0.001. Wald confidence limits.

Accidents involving all type of vehicles trucks or special vehicles excluded (ii)	Point estimates	Confidence interval 95%
Incidence relative risk ratio	1.62	(1.38 ÷ 1.90)
Odds ratio	2.70	(1.91 ÷ 3.81)
Attributable relative risk in the exposed	24.28	(16.19 ÷ 32.38)
Attributable fraction in the exposed (%)	38.21	(27.44 ÷ 47.39)
Attributable relative risk in the population	8.72	(2.39 ÷ 15.05)
Attributable fraction in the population (%)	18.17	(11.45 ÷ 24.38)

For subset (ii), uncorrected $\chi 2$ test that OR = 1: $\chi 2$ (1) = 32.408. Pr> $\chi 2$ = <0.001. Fisher exact test that OR = 1: Pr> $\chi 2$ = <0.001. Wald confidence limits.

Accidents where trucks or special vehicles are involved (iii)	Point estimates	Confidence interval 95%
Incidence relative risk ratio	1.37	(1.04 ÷ 1.79)
Odds ratio	2.45	(1.11 ÷ 5.40)
Attributable relative risk in the exposed	20.10	(3.27 ÷ 36.93)
Attributable fraction in the exposed (%)	26.97	(4.30 ÷ 44.27)
Attributable relative risk in the population	8.61	(−6.06 ÷ 23.29)
Attributable fraction in the population (%)	13.67	(0.7 ÷ 24.94)

For subset (iii), uncorrected $\chi 2$ test that OR = 1: $\chi 2$ (1) = 5.051 Pr> $\chi 2$ = 0.025. Fisher exact test that OR = 1: Pr> $\chi 2$= 0.034. Wald confidence limits.

4 DISCUSSION

The purpose of this case-control study was to investigate the relationship between the consequences of traffic accidents and the extent of tunnels. The objective was also to analyse the same phenomenon with respect to different types of vehicles involved. The three accident subsets considered at this purpose included (i) the entirety of vehicles involved in the original dataset; (ii) the previous set, trucks and special vehicles excluded; and (iii); and the subset of accidents where at least one truck or special vehicle was involved.

Amundsen [1], Amundsen and Engebretsen [2] and Amundsen and Ranes [3] observed that the relative risk of accidents in tunnels was lower than on open roads, but that the severity of accidents was much higher. Accident severity is higher when the vehicle collides against the tunnel wall than when it collides against the guardrail, on open roads. This is compounded by the fact that there is reduced accessibility of rescue devices such as cranes in tunnels (Lemke [23]). Caliendo et al. [5] and Lemke [23] found that tunnel length negatively affects road safety because drivers tend to demonstrate less concentration in long tunnels. In addition, it has been shown through a negative binomial regression model for non-serious and serious accidents that the frequency of accidents on unidirectional tunnel increases with tunnel length, in addition to other factors (Caliendo et al. [5]). The result of our study referred overall to motorway, rural and urban roads, showed a correlation between the severity of consequences and tunnel length.

Bassan [24] included an overview of traffic safety and design aspects in road tunnels and, in addition, discussed the severity of accidents in road tunnels, including fires and their relationship to road accidents. Nævestad and Meyer [25] analysed factors associated with vehicle fires and smoke without fire (SWF) in Norwegian road tunnels. On 2008–2011, they found that an average of 21% of vehicle fires were caused by a road accident. In other words, the accident itself may be the direct cause of the fire. They also found that technical problems were the most frequent cause of fires and SWF accidents in heavy vehicles, while single-vehicle and multi-vehicle accidents were the most frequent cause of fires in vehicles weighing less than 3.5 tons (Nævestad and Meyer [25]). The largest contributor to relative risk in road tunnels is collisions and other types of road accidents (Table 1). Fires, engine or brake failures are also events that must be considered in the risk assessment of road tunnels. Similarly for rare events with potentially important consequences, such as the transport of dangerous goods (Bassan [24]).

Since the vehicle type most involved in accidents is the car, some deviation may affect the overall interpretation of the phenomenon studied. This leads to non-exhaustive conclusions about the prevalence of severe outcomes in truck or special vehicle populations. According to Xing et al. [26], vehicle type was found to be a determinant of the severity of individual tunnel accidents. Compared with cars, trucks and special vehicles had a significantly lower risk of accidents. This result can be explained by the difference in structure and speed between heavy vehicles and cars (Xing et al. [26]). Our analysis showed that the risk of serious consequences in long tunnels is higher for subset (i) (RR: 1.58; 95%; CI: 1.37 ÷ 1.82) and (ii) (RR: 1.62; 95%; CI: 1.38 ÷ 1.90). Vice versa, when considering the subset of accidents where at least one truck or the special vehicles was involved, the risk ratio (RR: 1.37) falls within a 95% confidence interval close to 1 (1.04 ÷ 1.79). Therefore, when trucks and special vehicles are involved in accidents (iii) the probability of serious accidents in long tunnels may be assumed to be the same as in short tunnels.

5 CONCLUSIONS

This case-control study was applied to real-world tunnel road accident data comprehensive in location and tunnel length involved, occurred in Italy over 2018–2020. The case-control design point out an association, to be further analysed, between the tunnel length and the consequences of road accident with injured and fatalities.

We found tunnel over 500 m, to be positively associated with serious consequences if not heavy vehicles resulted involved in the accident scenario. If heavy vehicles were involved the incremental risks achieved 38% with a CI close to 1. In this case the probability of serious accident consequences can be assumed equal than the short tunnels.

The methodology proposed in our study as well as the results obtained represent a useful tool in the risk analysis that precedes risk assessment and from which risk prevention measures are derived.

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