An analysis of the influence of tunnel length and road type on road accident variables

Antonella Pireddu [1], Silvia Bruzzone [2]

Abstract

In 2018, the Italian National Institute of Statistics - Istat recorded about 1,150 injuries and 700 accidents in Italian tunnels where, over the past five years, there has been an increase in the accident rate. A nationwide study, conducted in order to investigate some aspects of this phenomenon, analysed the relationship between the class of vehicle involved, the time of the accident, the trip purpose (work-related or non-work-related), the circumstances observed and the infrastructure characteristics in terms of tunnel length and road type. The study offers a methodological reference for all those who, with a reactive or proactive approach, are required to assess road safety, manage risks in a specific context and evaluate the effectiveness of prevention strategies.

Keywords: Accidents, accident circumstances, Principal Component Analysis, road tunnels, road type, tunnel length.

1 Italian National Institute for Insurance against Accidents at Work - INAIL (an.pireddu@inail.it).
2 Italian National Institute of Statistics - Istat (bruzzone@istat.it).

The views and opinions expressed are those of the authors and do not necessarily reflect the official policy or position of the Italian National Institute of Statistics - Istat.

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1. Introduction[3]

Road accidents in Italian tunnels have increased during the period 2013-2017. Data concerning tunnel collisions resulting in death or injury occurred in Italy in 2018 were analysed by tunnel type. A descriptive and multivariate analysis was applied to detect the relationship between tunnel type and road crash parameters. Absolute frequency was higher in shorter tunnels while relative frequency (per kilometre) was negatively correlated with length.

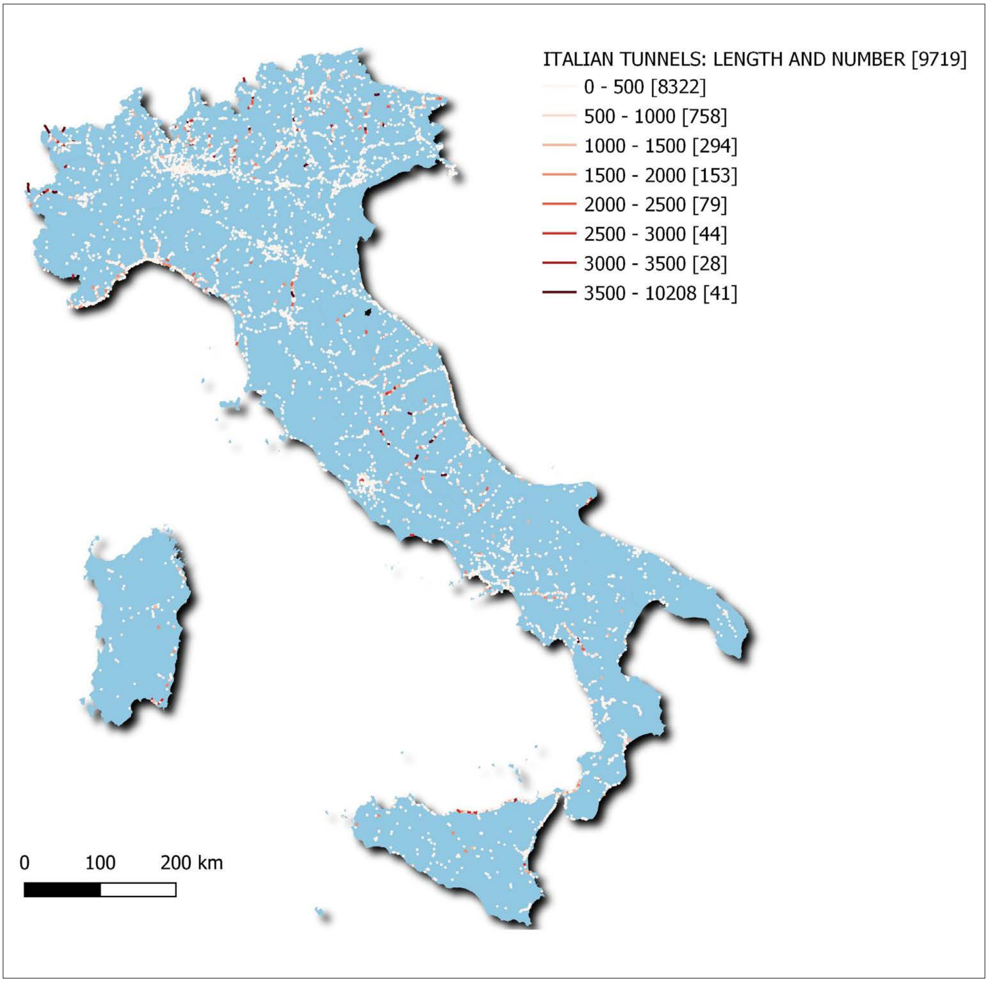
A positive association was found between short urban and motorway tunnels and 4-wheel vehicles, non-work-related trip and factors such as distances between vehicles, distraction and speeding, while urban and rural tunnels were positively associated with motorcycles, work-related trip and unspecified circumstances. The study points out essential findings for further targeted interventions in the tunnel road safety.

3 In producing this article: Antonella Pireddu dealt mainly with conceptualisation, data processing, methodology, writing the original draft, review of contents and results; Silvia Bruzzone dealt in particular with data processing, methodology, validation, review of content and results.

2. The Italian situation

In Italy, road tunnels extending for approximately 2,600 km, are distributed throughout the country: 907 km in the North West, 488 km in the North East, 410 km in the Centre, 527 km in the South and 268 km in the Islands. Underpasses, which make up 10% of the total, were also included in the analysis of the data. The authors provide an overview of the Italian road tunnel network, aggregated by classes of length (Figure 1).

Figure 1 - Italian tunnels by length and number. Year 2018



Source: Authors' processing on OpenStreetMap data

Figure 1 shows the distribution of tunnels classified by length within the national territory. The class of tunnels of up to 500 m is the largest with over 8,300 units, while there are approximately 750 tunnels of 500 to 1,000 m in length. The remaining classes are less numerous and decrease from about 300 (1,000-1,500 m) to 30 (3,000 - 3,500 m) units. The above illustration is the result of the geoprocessing of *OpenStreetMap* (OSM) data with *Quantum Gis* (QGIS) carried out by the authors. In the study, the tunnel type label represents a combination of the tunnel road (motorway, rural, urban) and length (Legislative Decree/*Decreto Legislativo* 30 April 1992, n. 285).

According to Istat data, in the five-year period 2013-2017, 3,175 accidents occurred in Italian road tunnels, 98 of which were fatal, and no less than 193 were work-related, involving at least one worker in route to/from work or driving as part of the work. In the same five-year period, 5,022 injuries were recorded. These involved at least 304 workers, 94 deaths within 24 hours and 11 deaths in the first 30 days following the accident. A 2019 study reported an increase in frequency for both collisions and injuries, with the latter increasing from 921 in 2013 to 1,161 in 2017 (Pireddu *et al.*, 2019). This increase also included work-related cases. Due to incomplete data for the five-year period, this study provides only a descriptive analysis without the accident parameters involved, the correlation between the latter and the type of tunnel affected. The trend observed between 2013 and 2017 was confirmed in 2018 when 716 road accidents were reported, with 1,159 injuries involving at least 77 work-related road injuries and 18 deaths. Throughout Italy, about 490 km out of a total of 2,600 km of tunnels were affected.

3. Data source

Statistical information on road accidents are produced by the Italian National Institute of Statistics - Istat on the basis of a survey of all road accidents occurring in Italy: the "*Survey on road accidents resulting in death or injury*". The field of observation of the survey includes all road accidents involving deaths within 30 days or injuries that occur throughout the country over a one-year period and are recorded by a police authority. Detection refers to the time the accident occurred. Istat provides data on all reported collisions (Istat data warehouse *I.Stat*. 2018, 2019) involving at least one vehicle that occur on Italian roads.

The data considered for the purposes of this paper, as defined by national standards, are those where "at least one vehicle is involved and where at least one injured person is recorded" (Vienna Convention on Road Traffic, 1968)[4].

Therefore, either accidents without injuries, or that did not occur in public roads, or without vehicles involved, or without police report were excluded (Gariazzo *et al.*, 2019).

This study data included information regarding the vehicle, the time of the accident, the trip purpose (work-related or non-work-related), the accident circumstances, the geographical coordinates and road type, and the number of deaths and injuries (Appendix F).

This work has omitted some variables such as those related to road sections, alignment and vehicular traffic on the grounds, that they should be considered in a more limited and homogeneous geographical area and over a longer period of investigation.

The availability of data and records concerning road traffic accidents is a well-established reality on the European scene. However, only recently these data have become more detailed thanks to the inclusion of information about road infrastructures, vehicles, trip purpose, time and circumstance of the crash.

4 The road accident is defined as "that event in which at least one vehicle is involved on the road network, occurring in the streets or squares open to traffic, which involves personal injuries (dead within 30 days and / or injured)" - (Convention of Vienna in 1968, UNECE, ITF and Eurostat 2019). For this reason, if the accident involves damage to objects only, it is then excluded from the statistics. This definition therefore reserves attention exclusively for reported accidents involving injury to people.

Lack of data was often due to difficulty in detecting accidents. Problems in accessing and using geolocation technologies in tunnels sometimes made empirical research impossible on account of unavailable or incomplete data.

The 2018 dataset was more detailed than in previous years since the information contained accident parameters and type of tunnel involved, thus enabling us to perform an analysis of the relationship between the most reliable variables.

This investigation was however limited to 716 records regarding 716 collisions involving 1,159 injured and 18 deaths that occurred in Italy in 2018 on 490 km of the approximately 2,600 km of Italian road tunnels.

For the purpose of this study, the Istat accident variables and label modes used for analysis were:

- Road tunnel location: motorway or road outside and inside urban areas, rural or road outside urban areas and not motorway, urban or road inside urban areas and not motorway (Legislative Decree/*Decreto Legislativo* 30 April 1992 n. 285);
- Vehicle type (Appendix A): Cars, Heavy goods vehicle (Heavy V), Motorcycles, Other vehicles (Other V);
- Time of occurrence (Appendix B): Night or Day defined according to a conventional interval;
- Trip purpose (Appendix C): work-related (trip/journey purpose in route to/from work or driving as part of the work) and non-work-related (trip/journey purpose non-work-related). Accidents work-related are underestimated due to the difficulty during the intervention by the police at the site of the accident, to record this information;
- Accident circumstances (Appendices D and E): Not keeping distances between vehicles (Distances), Distraction, Normal driving, Speeding, Unspecified and Other circumstances (Other C), corresponding to driver behaviour recorded when the accident occurred (Amundsen *et al.*, 2000; Gariazzo *et al.*, 2018). These classes, listed in Appendix D, are based on Istat and European coding (European Commission CARE 2016). The results of geoprocessing and query provided frequency of vehicle type, time of occurrence, trip purpose of driver, accident circumstances by tunnel length and road type.

4. Methods

This study used descriptive analysis combined with a multivariate approach (Bolasco, 1999; Di Franco, 2017; Johnson *et al.*, 2002; Jolliffe, 2002) based on the Principal Component Analysis (PCA). By means of geoprocessing operations (Cima *et al.*, 2014; Costabile *et al.*, 2012) the subset of Istat data was integrated with the length of the tunnel involved in the collision. The 1.3 version of the *Rstudio* and the 3.18.3 version of the *Quantum Gis* (QGIS) geographic information system were used.

For the purpose of descriptive analysis, for each variable and tunnel type, the frequency has been determined (see Appendix F). Tunnel sections were divided into 8 classes: up to 500 m (0-500); from 500 to 1,000 m (500-1000); from 1,000 to 1,500 m (1000-1500); from 1,500 to 2,000 m (1500-2000); from 2,000 to 2,500 m (2000-2500); from 2,500 to 3,000 m (2500-3000); from 3,000 to 3,500 m (3000-3500); over 3,500 m (>3500), corresponding to a range of lengths expressed in metres (Figure 1). The corresponding statistical parameters were then determined.

Based on the results of descriptive analysis, tunnels were grouped into two length classes more suitable for PCA: up to 500 metres and over 500 metres (>500) (Directive 2004/54/EC). These were then combined with tunnel location on motorway, rural and urban roads (Legislative Decree/*Decreto Legislativo* 30 April 1992 n. 285) so that indirectly different traffic conditions were also taken into consideration. Therefore, descriptive analysis was based on 24 types of tunnels, while PCA was based on 6 types (Appendix G). The two combined approaches were used to analyse the association between the accident parameters and the infrastructure in terms of length and road type.

The PCA model reproduces the information contained in the original variables, which turned out to be collinear, by concentrating all the information within the latent variables or Principal Components (PCs). The PCA enabled us to reduce redundancy (Benzécri, 1980) and provide a new representation of the coordinates of the original standardised variables that express the correlation. The combination of descriptive and multivariate analysis then revealed the association between the accident parameters and tunnel type. The frequency of vehicle type, time of accident occurrence, trip purpose and accident circumstances were then associated with the length and road type of the tunnel involved.

5. Results

5.1 Descriptive analysis

For each variable and tunnel type, defined by length and road type, frequencies (see Appendix F) and statistical parameters have been determined.

Table 1 summarises frequencies, minimum, maximum and quartiles for each variables and suggests using class aggregation more suitable for PCA.

Table 1 - Descriptive analysis of injuries by variables. Italy, 2018

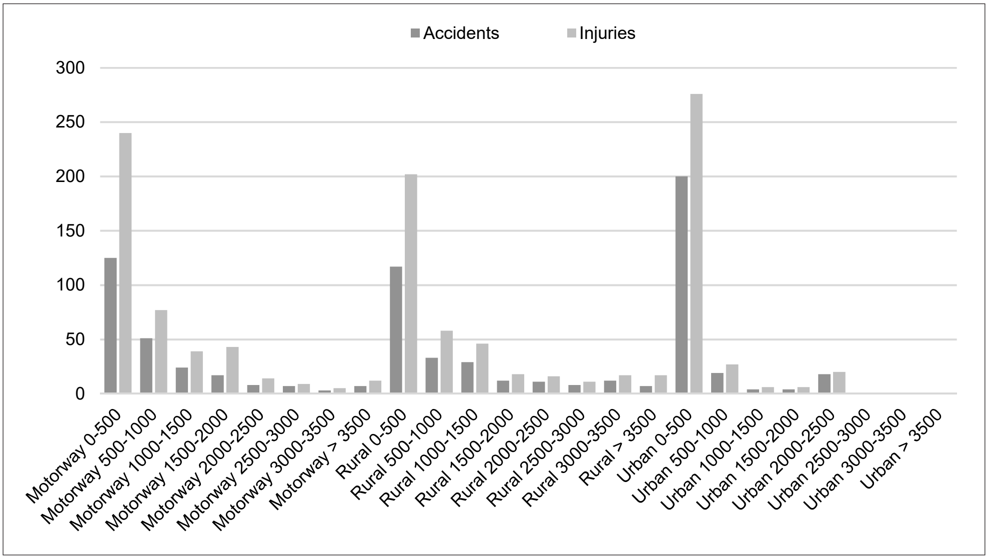
Variables	Freq.	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Cars	876	-	6.5	15.0	36.5	35.7	200
Heavy goods vehicles (Heavy V)	111	-	-	2.0	5.0	4.0	27
Motorcycles	104	-	-	1.0	4.0	3.0	49
Other vehicles (Other V)	68	-	-	-	3.0	0.5	40
Night	159	-	0.7	3.0	7.0	6.0	35
Day	1000	-	6.5	12.5	41.7	40.5	248
Work-related trip	77	-	-	-	3.0	2.0	26
Non-work-related trip	1082	-	7.5	16.0	45.1	43.0	249
Not keeping distances from other vehicles (Distances)	198	-	-	2.5	8.2	6.5	62
Distraction	153	-	-	3.0	6.0	6.0	43
Other circumstances (Other C)	213	-	1.7	4.0	8.9	10.5	56
Normal driving	309	-	0.7	3.5	12.9	12.5	79
Speeding	183	-	-	3.0	8.0	8.0	47
Unspecified circumstances (Unspecified)	103	-	-	-	4.0	2.0	32

Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury

Figure 2 illustrates absolute frequencies of accidents and injuries for the 24 tunnel types, with peaks for motorway, rural, urban tunnels of up to 500 m (the most numerous in Italy) and motorways 1,500-2,000 m. By normalising the absolute data with the total length of tunnels in each class, accidents were further characterised in relation to length and road type.

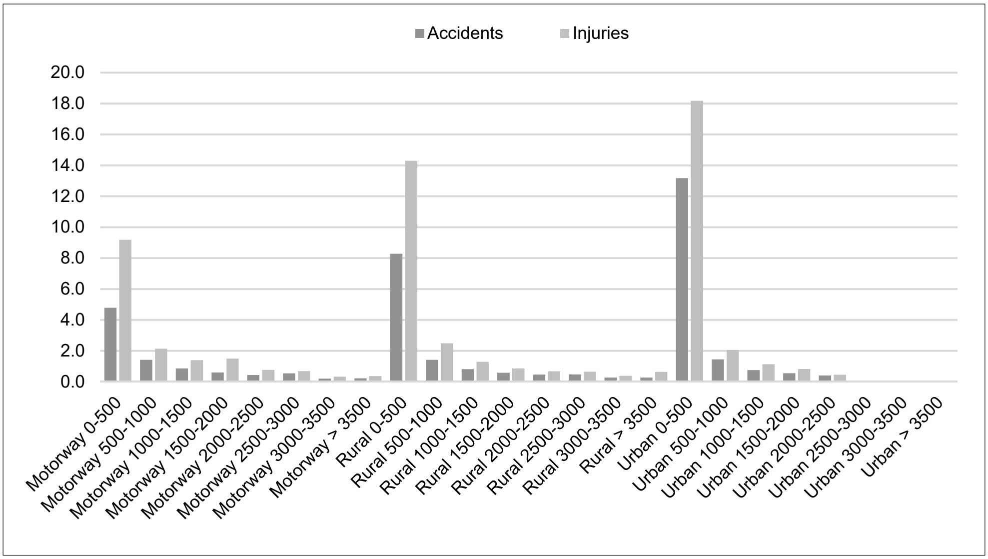
Figure 3 illustrates the ratio of the number of accidents to the total length of tunnel involved for each class, where accidents and injuries decrease with length. Further studies based on a wider range of data are needed to investigate the influence of traffic.

Figure 2 - Injuries and accidents by tunnel type. Absolute frequencies. Italy, 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

Figure 3 - Injuries and accidents per kilometre, by tunnel type. Relative frequencies. Italy, 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

5.2 Principal Component Analysis

A number of conditions were checked before conducting PCA (the verification of the linear relationship, the significance of the correlation between all quantitative variables, the absence of outliers and the number of observations). The Bartlett test results suggested proceeding with PCA. Once the conditions for applying PCA had been verified, analysis was performed on data matrix D=X1,...,Xp (see Appendix G with Matrix D). The components were extracted from the correlation matrix and analysis of variables and cases as well as the interpretation of factors were performed on the basis of variable-component or tunnel type-component association.

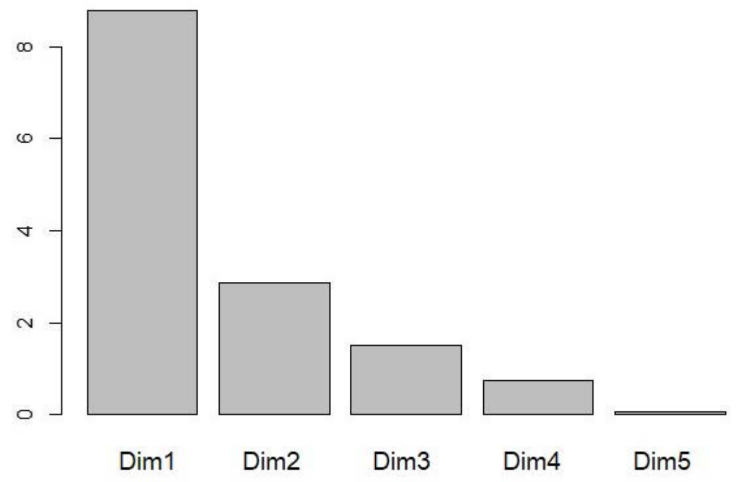
Table 2 - Eigenvalues and explained variance of the extracted components. Year 2018

Component	Eigenvalue	Percentage of variance	Cumulative percentage of variance
Dim 1	8.78	62.71	62.71
Dim 2	2.88	20.56	83.28
Dim 3	1.52	10.79	94.07
Dim 4	0.75	5.35	99.42
Dim 5	0.08	0.58	100.00

Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

The first results obtained were eigenvalues and explained variance (Table 2), which were useful for determining the number of Principal Components to use in the study. The PCs were identified by means of three criteria corresponding to eigenvalues >1, total explained variance reaching 70-90% (Table 2), and corresponding to values on the left of the inflection point on the bar plot (Figure 4).

Figure 4 - Bar plot of eigenvalues and components. Year 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury

The application of these three criteria yielded three PCs (Dim1, Dim2, Dim3) that summed up 94% (63%, 20% and 11%) of the total variance without a significant loss of information. These were explained by a general formula (1) as a combination of the eigenvalues (correlation matrix coefficients) and eigenvectors:

(1) $Dim_i = l_{i1}X_1 + l_{i2}X_2 + \ldots + l_{ip}X_p$ (i=1,2, …, p).

The next results were the factorial coordinates or correlations, cosines squared and contributions of variables (Table 3) and the coordinates or correlations, cosines squared and contributions of tunnel type (Table 4) and PCs (Dim1, Dim2, Dim3). Table 3 illustrates the coordinates and degree of correlation between variables and components. The output of *RStudio* in the case of standardised original variables implies that the coordinates coincide with the correlation and therefore the importance of each variable in relation to a factor can be deduced from the coordinates or correlation: the higher the coordinates of the variable, the more the latter affects the construction of the axis. Standardisation makes it possible to obtain a simplified representation of the phenomenon together with the correlation between variables in the system.

Table 3 - Coordinates (Correlation), contributions and cosines squared by variables and PCs. Italy, 2018

Variables	Coordinate (Correlation)			Cos^2			Contributions		
	Dim1	Dim2	Dim3	Dim1	Dim2	Dim3	Dim1	Dim2	Dim3
Cars	0.9	-0.4	0.2	0.8	0.1	0.0	9.2	5.2	3.0
Heavy goods vehicles (Heavy V)	0.8	-0.5	-0.2	0.7	0.2	0.0	8.1	7.1	1.6
Motorcycles	0.5	0.7	-0.4	0.2	0.5	0.2	2.6	18.7	12.2
Other vehicles (Other V)	0.7	0.5	-0.3	0.6	0.3	0.1	6.4	9.8	6.3
Night	0.8	-0.2	0.4	0.7	0.1	0.2	7.8	1.9	13.3
Day	1.0	0.0	-0.1	1.0	0.0	0.0	11.3	0.0	0.2
Work-related trip	0.4	0.7	0.6	0.2	0.4	0.3	2.2	15.5	20.8
Non- work-related trip	1.0	-0.2	-0.1	1.0	0.0	0.0	10.8	1.1	0.8
Not keeping distances from other vehicles (Distances)	0.7	-0.4	-0.5	0.5	0.1	0.3	6.0	4.8	17.1
Distraction	0.9	0.3	0.0	0.8	0.1	0.0	9.6	4.0	0.1
Other circumstances (OtherC)	0.9	0.2	-0.1	0.8	0.0	0.0	8.6	1.5	1.1
Normal driving	0.8	-0.1	0.6	0.6	0.0	0.3	7.3	0.2	22.5
Speeding	0.8	-0.5	-0.1	0.7	0.3	0.0	7.9	9.8	0.9
Unspecified circumstances (Unspecified)	0.4	0.8	0.0	0.2	0.6	0.0	2.2	20.4	0.0

Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury

The coordinates, cosines squared and contributions referring to the type of tunnel were also calculated. The absolute contribution expresses the extent to which each variable explains the component. The cos2 or relative contribution indicates the extent to which each component explains a variable (inertia or variance).

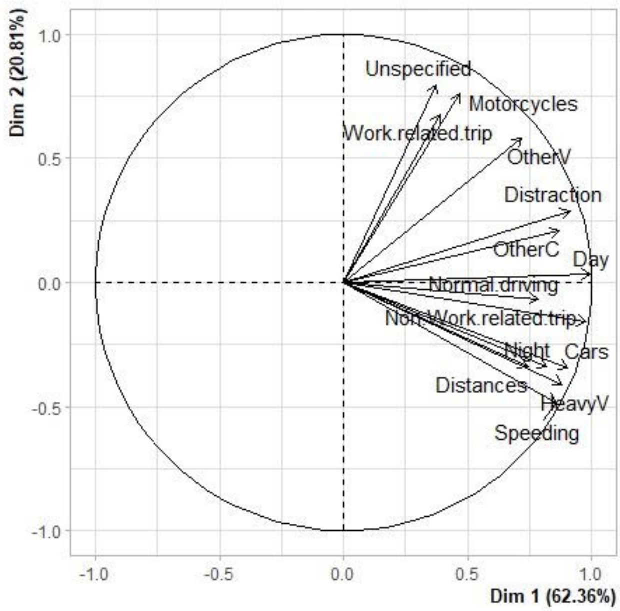
Table 4 - Coordinates (correlation), cosines squared and contributions by tunnel type and PCs. Italy, 2018

Tunnel type	Coordinate (Correlation)			Cos^2			Contributions		
	Dim1	Dim2	Dim3	Dim1	Dim2	Dim3	Dim1	Dim2	Dim3
Motorway 0-500	1.82	-2.59	-0.3	0.29	0.59	0.0	6.29	38.92	1.2
Motorway >500	-0.09	-1.68	-1.0	0.00	0.55	0.2	0.02	16.35	10.0
Rural 0-500	0.53	0.44	2.3	0.05	0.03	0.9	0.54	1.13	56.6
Rural >500	-0.27	0.34	1.0	0.03	0.04	0.3	0.14	0.68	10.1
Urban 0-500	3.85	2.56	-1.2	0.65	0.29	0.1	28.15	37.92	16.3
Urban >500	-5.85	0.93	-0.7	0.95	0.02	0.0	64.87	5.00	5.8

Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

Further results of the two combined analytical approaches are summarised in Figures 5 and 6 that show the correlation between each variable and tunnel type and the Principal Components Dim1 and Dim2.

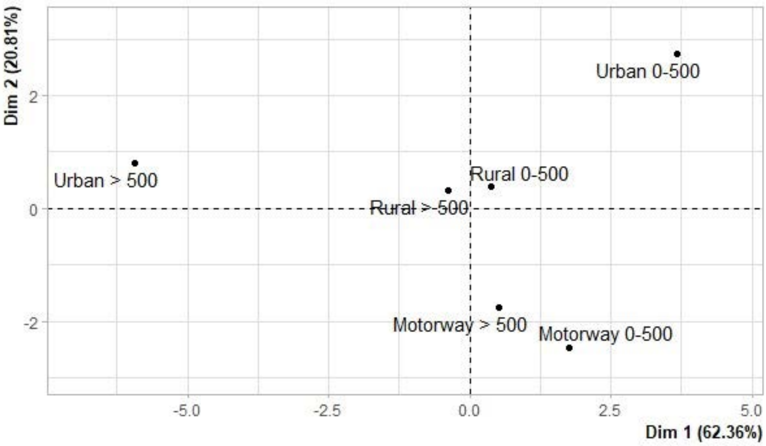
Figure 5 - Correlation between each variable analysed and the first two PCs (Dim1 and Dim2). Year 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury

On the basis of the results shown in Table 3 (contributions), the labels to be given to the three components were: "cars, heavy V, daytime driving, non-work-related trip, distances, distraction and speeding" (Dim1); "motorcycles, work-related trip, unspecified circumstances" (Dim2); "night-time driving, normal driving" (Dim3).

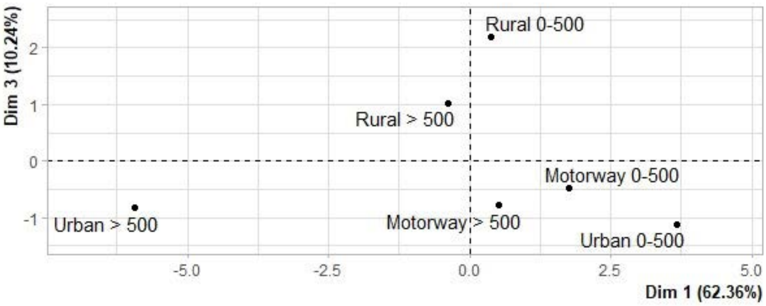
Figure 6 - Correlation between tunnel type and the first two PCs (Dim1 and Dim2). Year 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

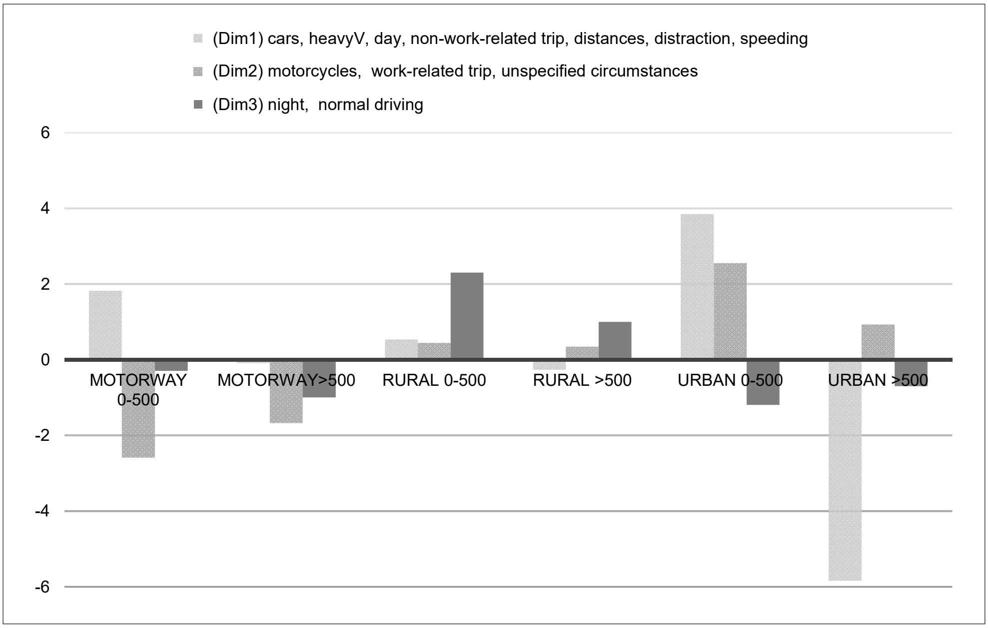
Dim1 (cars, heavy vehicles, daytime driving, non-work-related trip, distances, distraction and speeding) is seen to be positively associated with shorter urban and motorway tunnels and negatively with longer urban tunnels. Dim2 (motorcycles, work-related trip, unspecified circumstances) is negatively correlated with motorway tunnels and positively with urban ones (Figure 6). Dim 3 (night-time driving, normal driving) is seen to be positively associated with rural tunnels and shows a slight negative correlation with urban and motorway tunnels (Figure 7).

Figure 7 - Correlation between tunnel type and Dim1 and Dim3. Year 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

Figure 8 - Positive and negative correlation between the first three PCs and the tunnel type. 2018



Source: Authors' processing on Istat data - Survey on road accidents resulting in death or injury, and OSM

Figure 8 illustrates the correlation (ordinate) between the PCs (Dim1, Dim2 and Dim3) and the type of tunnel. Dim1 is seen to be positively associated with shorter motorway rural and urban tunnels and negatively with longer ones. Dim2 is negatively correlated with motorway tunnels and positively with urban ones. Dim3 is associated positively with rural tunnels and shows a slight negative correlation with urban and motorway tunnel (see Appendix H).

PCA highlighted some aspects that descriptive analysis alone failed to detect with regard to vehicles, the time of accident occurrence, the type of trip (work-related or non-work-related), the circumstance and the positive and negative correlations with the different types of tunnel.

A high frequency of injuries is found for the work-related trip variable in rural tunnels but has a poor correlation with the first two PCs and a slight correlation with the third component (Figures 7 and 8), which is, however, the least important. On the contrary, in shorter urban tunnels, the same variable has higher frequencies and correlations with both Dim1 and Dim2, thus providing a more reliable variable - tunnel type association. This type of information is the value added that PCA gives to the descriptive analysis and thanks to which it was possible to ascertain more objectively the interrelationship between the descriptive parameters of the 716 accidents recorded in the Istat database and the road infrastructure involved.

6. Discussion

Road tunnel accident rates are influenced by many factors such as tunnel length, traffic, horizontal alignment, lane width, tunnel cross section, quality of tunnel lighting, driving speed and, last but not least, national driving habits and the technical standard of the vehicles used (PIARC, 2008). As can be seen by the amount of research that has analysed the design and safety of tunnels according to differing perspectives and objectives, issues regarding these infrastructures constitute a really vast topic (Calvi *et al.*, 2013) that involves the way drivers approach, exit from and behave inside a road tunnel (Mühlberger *et al.*, 2015).

Study findings are not consistent as regards the impact of tunnel length on safety (Bassan, 2016) or on the quality of traffic. Several factors can influence in a positive or negative way the probability or the effect of a tunnel accident. All these influencing factors make it difficult to compare collision rates at a statistical level. There is still a lack of knowledge, indeed, regarding the interaction of the various factors that influence crash rates in road tunnels. Several tunnel conditions may result in misjudgement of horizontal and vertical alignment and the perception of safe distances from other vehicles and obstacles (PIARC, 2008). Records of the number of road crashes and their victims represent essential information for road safety practitioners allowing them to analyse their spatial and temporal aspects. However, they cannot provide details on the factors causing road crashes (Hollò *et al.*, 2010). The availability of national road crash data together with information on accident road type enabled us to investigate road tunnel crashes involving death or injury throughout Italy and tunnel types nationwide. Although the study refers only to 2018 datasets, our statistical analysis (descriptive and PCA) revealed that the tunnel crash rate was associated both with tunnel length and with road type (Figures 2 and 3). Recent studies highlighted that crash rate, crash type, and contributing factors are variable in different zones of the tunnel (Amjad *et al.*, 2020).

The overall negative association with absolute frequency confirms findings obtained in Norway for road tunnel crashes, where short tunnels were associated with higher crash rates than long tunnels (Amundsen, 1994; Amundsen *et al.*, 2009). Yeung and Wong (Yeung *et al.*, 2013), who investigated expressway tunnels in Singapore, also found that Road Traffic

Crashes (RTCs) were lowest in the inner zones of tunnels and highest in the entry and exit zones. In contrast, compared with previous studies, another investigation of Chinese freeway tunnels revealed a sharp decline in the crash rate at tunnel portals and in the first 100 m of tunnels (tunnel entrance), as well as an increased number of crashes inside the tunnels. This finding was explained by better lighting in the entrance zone to the tunnels (Ma *et al.*, 2009). Caliendo showed by a negative binomial regression model for non-serious and serious accidents that crash frequency on unidirectional Italian motorway tunnel sections increases with tunnel length, in addition to other factors (Caliendo *et al.*, 2019). Further studies based on a wider range of data are needed to investigate accidents in motorway tunnels.

Our study puts forward two sets of hypothetical explanations of road tunnel accidents: the first concern all lengths linked to tunnel entrance and the impact on the driver of its confined environment that leads to reactions that increase accident risk and persist in relation to the time needed to reduce the driver's discomfort. This period of adaptation appears to be lacking in shorter tunnels and could therefore explain the higher accident rate in the latter. On the other hand, the second set of causes concern longer motorway and rural tunnels where, what counts is the gradual adaptation of the driver as he proceeds and which could be associated with the increase in speed in the more inner parts of the tunnel.

The study shows that the majority of accidents occur in tunnels of up to 500 metres in length (Figure 2). The number of accidents per kilometre, in motorway, rural and urban tunnels of up to 500 metres in length was 4.8, 8.3 and 13.2 while the same index, in longer motorway, rural and urban tunnel was 0.7, 0.6 and 0.6 (Figure 3).

The average ratio of injured to crashes was 1.9 in motorway tunnels, 1.7 in rural tunnels and 1.4 in urban tunnels of up to 500 m, while the same ratio in longer tunnels was 1.7, 1.6 and 1.3). As regard road type, the average ratio of injured to crashes was 1.8 in motorway tunnels, 1.7 in rural tunnels and 1.5 in urban ones. The higher motorway ratios were confirmed by Caliendo (*et al.*) who reported a larger number of serious accidents in motorway tunnels. The same authors found that if an accident occurs in these tunnels, the severity of injuries sustained is significantly higher than on open stretches of motorways (Caliendo *et al.*, 2012; Caliendo *et al.*, 2019).

Thanks to the PCA it was possible to ascertain more objectively the interrelationship between the descriptive parameters of the 716 accidents recorded in the Istat database and the road infrastructure involved. As far as the Dim1 is concerned: cars, heavy V, daytime driving, non-work-related trips, not respecting safe distances from other vehicles (rear-end collisions), distraction and speeding had the strongest positive association with short urban and motorway tunnels, while had the strongest negative association with long urban.

Dim2 (motorcycles, work-related drivers, unspecified circumstances) was found to be positively associated with urban and rural tunnels, while a strong negative association was observed with motorway tunnels. According to recent studies conducted over the last decade, due to traffic congestion in metropolitan areas, there has been an increase in the use of motorcycles as a mode of transport. This has led to a dramatic rise in the number of crashes involving these vehicles and a concomitant increase in the number of motorcyclists who have died or been injured (Gariazzo *et al.*, 2021). This positive association, which will need to be further studied, could be attributed to the growing number of delivery riders that operate in urban areas and drive motorcycles. With regard the Dim3 (night-time driving and normal driving) was found to be positively associated with rural tunnels.

Our findings enabled us to explain by means of an integrated interpretation of the over 700 road tunnel accidents, 1,159 injuries and 18 deaths recorded in Italy in 2018 in 491 km of tunnels, the interaction of the various parameters included in the model, influencing crash rates. For reasons of data robustness and completeness, this study focusses on a single year of observation (2018) with its number of cases collected. Therefore, the results achieved represent as much detail as possible. Variables such as traffic (marginally highlighted by location on motorway, rural and urban roads), horizontal alignment, lane width, tunnel cross section, quality of tunnel lighting and different driving habits throughout Italy were also omitted, together with the safety devices and technical standard of the vehicles in use and individual driver characteristics such as fatigue and physiological conditions.

Although these limitations need to be carefully evaluated, this study offers a methodological reference for all those who, with a reactive or proactive approach, are required to assess road safety, manage risks in a specific context

(Legislative Decree/*Decreto Legislativo* 9 April 2008 n. 81) and evaluate the effectiveness of prevention strategies (Directive 2004/54/EC). In addition, this study prepares the ground for future research that can be focussed on a more homogeneous and limited subset of tunnels. This taking into account also a larger number of variables derived from the exploitation and integration of more archives than the sources used in the current analysis.

Findings from our analysis confirm some of the results obtained by other authors and suggest that strategies designed to prevent tunnel accidents should be based on improving driver behaviour and on reducing the impact on drivers entering these infrastructures. In existing tunnels, better lighting in the areas near the entrance can mitigate impact due to a reduced road section, while a reduction in the speed limit in the inner areas may be useful for improving peripheral vision and the perception of the distances from other vehicles.

7. Conclusions

Our study analysed accidents resulting in death or injury in Italian road tunnels in 2018. It investigated the relationship between tunnel type (length-road type) and other variables involved in the collisions, such as vehicle type, time of occurrence, trip purpose and driving behaviour. The study shows that the majority of accidents occurs in tunnels of up to 500 metres in length. Our analysis revealed a positive association between cars, heavy vehicles, daytime driving, non-work-related drivers, not respecting safe distances between vehicles (rear-end collisions), distraction and speeding and short urban and motorway tunnels while a strongest negative association with long urban tunnels. Motorcycles, work-related drivers and unspecified circumstances were found to be positively associated with urban and rural tunnels, while a strong negative association was observed with motorway tunnels. The analysis revealed a positive association between night-time driving, normal driving and rural tunnels.

A strong positive association was found between urban tunnels of up to 500 m and accident circumstances such as careless driving, resulting in failure to observe a safe distance between vehicles and the speed limit in motorway tunnels.

Tunnel length was found to affect the frequency of crashes, while road type was found to impact the degree of severity of accident consequences. This difference based on road type provided a possible explanation which will definitely have to be studied in more detail in further research, also in relation to the at times conflicting results obtained by other studies.

Our analysis confirms some of the results obtained by other authors and proposes prevention strategies based on engineering measures designed to reduce the impact on the driver during access to tunnels or on adapting speed limits in inner tunnel areas. Despite its limits, this study provides a useful methodological reference since it highlights the influence of tunnel length on road accident variables and the relationship between various parameters that influence accident rates in road tunnels.

However, further and more thorough research based on a longer period of time will be needed to improve the interpretative capacity of this methodology.

Appendix A - Injuries by tunnel type (road type and length) and vehicles involved. Absolute values. Italy, 2018

Tunnel type (a)	Cars	Heavy V	Motorcycles	Other V	Total
Motorway 0-500	200	27	2	11	240
Motorway 500-1,000	50	16	9	2	77
Motorway 1,000-1,500	32	4	1	2	39
Motorway 1,500-2,000	38	1	4	-	43
Motorway 2,000-2,500	14	-	-	-	14
Motorway 2,500-3,000	7	1	1	-	9
Motorway 3,000-3,500	3	2	-	-	5
Motorway > 3,500	8	2	2	-	12
Rural 0-500	167	15	10	10	202
Rural 500-1,000	42	7	9	-	58
Rural 1,000-1,500	35	5	3	3	46
Rural 1,500-2,000	16	2	-	-	18
Rural 2,000-2,500	15	-	1	-	16
Rural 2,500-3,000	9	2	-	-	11
Rural 3000-3500	13	3	1	-	17
Rural > 3,500	16	-	1	-	17
Urban 0-500	164	23	49	40	276
Urban 500-1,000	23	1	3	-	27
Urban 1,000-1,500	4	-	2	-	6
Urban 1,500-2,000	5	-	1	-	6
Urban 2,000-2,500	15	-	5	-	20
Urban 2,500-3,000	-	-	-	-	-
Urban 3,000-3,500	-	-	-	-	-
Urban >3,500	-	-	-	-	-
Total	876	111	104	68	1,159

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).

Appendix B - Injuries by tunnel type (road type and length) and time of occurrence. Absolute values. Italy, 2018

Tunnel type (a)	Night	Day	Total
Motorway 0-500	32	208	240
Motorway 500-1,000	9	68	77
Motorway 1,000-1,500	9	30	39
Motorway 1,500-2,000	4	39	43
Motorway 2,000-2,500	7	7	14
Motorway 2,500-3,000	-	9	9
Motorway 3,000-3,500	-	5	5
Motorway > 3,500	2	10	12
Rural 0-500	35	167	202
Rural 500-1,000	6	52	58
Rural 1,000-1,500	1	45	46
Rural 1,500-2,000	2	16	18
Rural 2,000-2,500	5	11	16
Rural 2,500-3,000	-	11	11
Rural 3000-3500	3	14	17
Rural > 3,500	6	11	17
Urban 0-500	28	248	276
Urban 500-1,000	2	25	27
Urban 1,000-1,500	1	5	6
Urban 1,500-2,000	3	3	6
Urban 2,000-2,500	-	-	-
Urban 2,500-3,000	4	16	20
Urban 3,000-3,500	-	-	-
Urban >3,500	-	-	-
Total	159	1,000	1,159

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).

Appendix C - Injuries by tunnel type (road type and length) and work-related or non-work-related trip. Absolute values. Italy, 2018

Tunnel type (a)	Work-related trip (b)	Non-work-related trip	Total
Motorway 0-500	-	240	240
Motorway 500-1,000	-	77	77
Motorway 1,000-1,500	-	43	43
Motorway 1,500-2,000	-	43	43
Motorway 2,000-2,500	-	14	14
Motorway 2,500-3,000	-	9	9
Motorway 3,000-3,500	-	5	5
Motorway > 3,500	-	10	10
Rural 0-500	26	176	202
Rural 500-1,000	10	48	58
Rural 1,000-1,500	7	39	46
Rural 1,500-2,000	-	18	18
Rural 2,000-2,500	3	13	16
Rural 2,500-3,000	3	8	11
Rural 3000-3500	-	17	17
Rural > 3,500	2	15	17
Urban 0-500	25	249	274
Urban 500-1,000	1	26	27
Urban 1,000-1,500	-	6	6
Urban 1,500-2,000	-	6	6
Urban 2,000-2,500	-	20	20
Urban 2,500-3,000	-	-	-
Urban 3,000-3,500	-	-	-
Urban >3,500	-	-	-
Total	77	1,082	1,159

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).
(b) The data listed are "work-related" (trip/journey purpose in route to/from work or driving as part of the work) and "non-work-related" (trip/journey purpose not professional).

Appendix D - Classification of accident circumstances

Circumstances (a) (codes by accident type and labels)	Circumstances (group labels)
22 Driving without maintaining a safe distance between vehicles 62 Driving without maintaining a safe distance between vehicles	Distances
21 Driving in a careless or indecisive manner 61 Driving in a careless or indecisive manner	Distraction
25 Straying from the right of the carriageway 26 Driving in the wrong direction 31 Overtaking incorrectly on the right, on a bend, on a hump, with poor visibility 33 Overtaking incorrectly on the right despite ‘No Overtaking’ sign 37 Driving normally to stop or park 36 Turning left 35 Merging into traffic lane 34 Reversing or U-turn manoeuvres 45 Manoeuvering 48 Driving off the carriageway and running down a pedestrian 49 Failure to stop at pedestrian crossings 51 Injuring the pedestrian with the load 66 Proceeding despite ‘NoTransit’ or ‘No Access’ signs 70 Skidding and going off-road to avoid crashing 71 Skidding and going off-road due to careless driving 72 Skidding and going off-road due to excessive speeding 73 Braking suddenly with consequences for passengers 74 Passengers falling from vehicle when opening car door 75 Passengers falling when alighting from vehicle 76 Passengers falling from vehicle for not wearing seat belts	Other C
20 Driving normally 40 Driving normally 60 Driving normally	Normal driving
23 Driving too fast 24 Speeding 41 Driving too fast 64 Driving too fast 65 Speeding	Speeding
00 Unspecified circumstance Null	Unspecified

Source: Authors’ processing on Istat data - Survey on Road Accidents resulting in death or injury
(a) The same label and different code depend on the different accident type (*e.g.* head-on collision or vehicles travelling in the same direction).

Appendix E - Injuries by tunnel type (road type and length) and group of accident circumstances. Absolute values. Italy, 2018

Tunnel type (a)	Distances	Distraction	Other C	Normal driving	Speeding	Unspecified	Total
Motorway 0-500	62	22	31	63	47	15	240
Motorway 500-1,000	15	9	14	12	25	2	77
Motorway 1,000-1,500	13	5	7	10	3	1	39
Motorway 1,500-2,000	4	7	10	14	8	-	43
Motorway 2,000-2,500	3	6	3	2	-	-	14
Motorway 2,500-3,000	-	2	2	5	-	-	9
Motorway 3,000-3,500	1	-	4	-	-	-	5
Motorway > 3,500	6	-	4	-	-	2	12
Rural 0-500	17	27	31	79	27	21	202
Rural 500-1,000	2	9	12	25	3	7	58
Rural 1,000-1,500	6	5	12	17	6	-	46
Rural 1,500-2,000	4	3	2	3	6	-	18
Rural 2,000-2,500	3	3	6	1	3	-	16
Rural 2,500-3,000	1	5	1	2	-	2	11
Rural 3000-3500	-	3	3	5	3	3	17
Rural > 3,500	-	-	6	1	8	2	17
Urban 0-500	51	43	56	59	35	32	276
Urban 500-1,000	8	4	2	4	9	-	27
Urban 1,000-1,500	-	-	6	-	-	-	6
Urban 1,500-2,000	1	-	-	5	-	-	6
Urban 2,000-2,500	1	-	1	2	-	16	20
Urban 2,500-3,000	-	-	-	-	-	-	-
Urban 3,000-3,500	-	-	-	-	-	-	-
Urban >3,500	-	-	-	-	-	-	-
Total	198	153	213	309	183	103	1,159

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).

Appendix F - Injuries by tunnel type (road type and length) and vehicles involved, time of occurrence, work-related or non-work-related trip, group of accident circumstances. Absolute values. Italy, 2018

Tunnel type (a)	Car	Heavy V	Motor-Cycles	Other V	Night	Day	Work-related trip	Non-work-related trip	Distances (b)	Distraction	Other C	Normal driving	Speeding	Unspecified
Motorway 0-500	200	27	2	11	32	208	-	240	62	22	31	63	47	15
Motorway 500-1,000	50	16	9	2	9	68	-	77	15	9	14	12	25	2
Motorway 1,000-1,500	32	4	1	2	9	30	-	43	13	5	7	10	3	1
Motorway 1,500-2,000	38	1	4	-	4	39	-	43	4	7	10	14	8	-
Motorway 2,000-2,500	14	-	-	-	7	7	-	14	3	6	3	2	-	-
Motorway 2,500-3,000	7	1	1	-	-	9	-	9	-	2	2	5	-	-
Motorway 3,000-3,500	3	2	-	-	-	5	-	5	1	-	4	-	-	-
Motorway > 3,500	8	2	2	-	2	10	-	10	6	-	4	-	-	2
Rural 0-500	167	15	10	10	35	167	26	176	17	27	31	79	27	21
Rural 500-1,000	42	7	9	-	6	52	10	48	2	9	12	25	3	7
Rural 1,000-1,500	35	5	3	3	1	45	7	39	6	5	12	17	6	-
Rural 1,500-2,000	16	2	-	-	2	16	-	18	4	3	2	3	6	-
Rural 2,000-2,500	15	-	1	-	5	11	3	13	3	3	6	1	3	-
Rural 2,500-3,000	9	2	-	-	-	11	3	8	1	5	1	2	-	2
Rural 3000-3500	13	3	1	-	3	14	-	17	-	3	3	5	3	3
Rural > 3,500	16	-	1	-	6	11	2	15	-	-	6	1	8	2
Urban 0-500	164	23	49	40	28	248	25	249	51	43	56	59	35	32
Urban 500-1,000	23	1	3	-	2	25	1	26	8	4	2	4	9	-
Urban 1,000-1,500	4	-	2	-	1	5	-	6	-	-	6	-	-	-
Urban 1,500-2,000	5	-	1	-	3	3	-	6	1	-	-	5	-	-
Urban 2,000-2,500	15	-	5	-	-	-	-	20	1	-	1	2	-	16
Urban 2,500-3,000	-	-	-	-	4	16	-	-	-	-	-	-	-	-
Urban 3,000-3,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Urban >3,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).
(b) Not keeping distances from other vehicles.

Appendix G. Matrix D - Injuries by tunnel type (road type and length) and vehicles involved, time of occurrence, work-related or non-work-related trip, group of accident circumstances. Absolute values. Italy, 2018

Tunnel type (a)	Car	Heavy V	Motor-Cycles	Other V	Night	Day	Work-related trip	Non-work-related trip	Distances (b)	Distraction	Other C	Normal driving	Speeding	Unspecified
Motorway 0-500	200	27	2	11	32	208	-	240	62	22	31	63	47	15
Motorway > 500	152	26	17	4	31	168	-	201	42	29	44	43	36	5
Rural 0-500	167	15	10	10	35	167	26	176	17	27	31	79	27	21
Rural > 500	146	19	15	3	23	160	25	158	16	28	42	54	29	14
Urban 0-500	164	23	49	40	28	248	25	249	51	43	56	59	35	32
Urban > 500	47	1	11	-	10	49	1	58	10	4	9	11	9	16

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).
(b) Not keeping distances from other vehicles.

Appendix H - Accidents and injuries by tunnel type (road type and length). Italy, 2018

Tunnel type (a)	Number of Accidents	Number of Injuries	Tunnel Extension (in m)	Accidents per km	Injuries per km
Motorway 0-500	125	240	26,145.6	4.8	9.2
Motorway >500	117	199	173,294.7	0.7	1.1
Rural 0-500	117	202	14,136.1	8.3	14.3
Rural > 500	112	183	192,714.5	0.6	0.9
Urban 0-500	200	276	15,186.5	13.2	18.2
Urban > 500	45	59	70,463.0	0.6	0.8

Source: Authors' processing on Istat data - Survey on Road Accidents resulting in death or injury, and Open Street Map
(a) Motorway (road outside and inside urban area), Rural (road outside urban area and not motorway), Urban (road inside urban area and not motorway).

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