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Accident Rates in Road Tunnels and Social Cost Evaluation

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Abstract

This work presents the results of a study carried out to estimate accident rates and associated social-cost rates in motorway tunnels. A comparison between the results obtained in the investigated tunnels and those of the corresponding motorways containing these structures was also made. A 4-year monitoring period was considered. Severe accident rates and cost rates in tunnels were often found to be higher than those on the corresponding motorways. An exemplified benefit-cost analysis was also made. The computed benefit-cost ratios may represent a preliminary support in the choice of the priority of assigning public funds in order to improve safety.

Keywords: Road safety; Tunnel; Accident rate; Accident cost rate; Benefit-cost ratio.

1. Introduction

In Europe over the last few years, the catastrophic tunnel accidents that have occurred have led public opinion, competent authorities and the international research community, to become much more involved in the safety of people who use these structures, and to encourage the introduction of common regulations. In order to achieve a uniform and high level of service, comfort and protection for tunnel users in 2004 the European Parliament and Council adopted the well-known 2004/54/EC Directive [1]. This Directive has set the minimum safety requirements for road users in tunnels by preventing critical events that may endanger human life, the environment and tunnel equipment.

Harmonizing the safety within road tunnels and the rules of managing these structures is a crucial item for allowing a road network to cross natural barriers (e.g. mountain chains) and/or dense urbanized areas where the availability of land for surface roads is constantly decreasing. However, when accidents occur in road tunnels they can have more severe human and economic consequences than those on open road sections.

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Accidents in road tunnels differ from accidents on open road sections in many respects, and more especially for the driver's behaviour. Drivers approaching the tunnel portal change their driving style both by increasing the distance from the side wall, which interferences with the traffic flow in the adjacent lane, and by reducing their speed. Another effect before entering a tunnel is that the driver's attention focuses on the tunnel entrance in such a way as to cause a loss of information provided through road signals. In addition in the first part inside the tunnel, the darkness causes poor visibility and slow adaptation of one's eyes to the reduced level of illumination. Furthermore, driving within the tunnel generates anxiety as these structures are dark, narrow, and monotonous when compared to open road sections. Besides, drivers in tunnels generally modify both their lateral position and speed in order to avoid the disturbing effects due to the tunnel wall being too close to the traffic lane. At the tunnel exit, different lighting at the threshold close/open road section and/or unexpected weather conditions (e.g. rain, snow, lateral wind, etc,) also might surprise drivers negatively.

Apart from the driver's behaviour, geometric and traffic characteristics of tunnels may also have a negative effect on road safety. When an emergency lane is not present, the aforementioned effects on lateral position and speed reduction are expected to be greater. Narrower tunnels (e.g. with fewer lanes) and/or with complicated horizontal alignments, as well as longer tunnels, are often considered to be more dangerous. Traffic volume and a high percentage of trucks also affect both total accidents and accident severity in tunnels. Finally tunnels with bi-directional traffic are considered to be less safe than those with unidirectional traffic.

Since for most drivers a tunnel is an unusual driving environment that might cause stress and the tunnel geometry with associated traffic might contribute towards generating less favourable conditions than in open road sections, it is worth making an investigation into accidents in tunnels and trying to understand whether the number of crashes per million vehicle-kilometres (accident rate) is higher than that of open sections.

As a consequence of the aforementioned considerations, a safety analysis was carried out on road tunnels in Italy. The study contained in this paper forms part of a major research project concerning both the simulation of a fire and the development of a crash-prediction model in road tunnels. This work presents more especially the results of a recent study carried out to estimate accident rates and associated social-cost rates. The analysis is based on 195 tunnels with unidirectional traffic only, with two or three lanes, and tunnel lengths between 491 and 3,254m. During a 4-year monitoring period crash data and traffic flow were collated. The data base consists of 762 severe crashes, with 775 injuries and 18 deaths.

The main objective of this research was to evaluate the accident rates of these tunnels in order to show whether these rates are lower or higher than those of the corresponding motorway sections. Since among the negative consequences of crashes there are socio-economic costs seen from the view of society, the purpose was also to determine the differences in accident cost rates. Additionally, the potential reduction in deaths and injuries estimated at 2020 when compared to those of 2010, and more especially the corresponding possible reduction in the social-costs was assumed as a criterion for evaluating the benefits to be achieved when treatments in tunnels are designed and subsequently realized. The use of the ratio between benefits and treatment-costs might support authorities in making decisions about the priority of investments concerning adjustment projects of existing tunnels in order to improve road safety in compliance with the 2004/54/EC Directive.

In the light of the above considerations, this paper is organized as follows: the next section contains a review of the literature concerning crashes in road tunnels, the subsequent section deals with data set used and the process of preparing it for analysis, then the results are presented and discussed. Finally, conclusions and addresses for further studies are made.

2. Literature review

As far the authors are aware the first studies on tunnel safety were devised by PIARC [12]. The PIARC Committee on tunnel safety reported that: i) tunnels are safer than open roads except in case of design failures (small curves, high gradients or reduced cross section width); ii) bidirectional tunnels induce more accidents than unidirectional tunnels; (iii) with reference to accidents with injuries only, the average accident rate is found to be 8 and 10 accident/10^8 veh.km for unidirectional and bidirectional tunnels, respectively.

Investigating Norwegian road tunnels, Amundsen and Ranes [3] found that accident rates are higher in the entrance zone of tunnels and that these accident rates diminish as one proceeds inside the tunnel. They also show that the accident rates decrease as the tunnel lengthens, the AADT (annual average daily traffic) makes greater, and the tunnel width increases. Lemke [4] carried out a safety analysis to estimate average accident rates and accident cost rates for different cross sections of German freeway tunnels. The main results for unidirectional tunnels showed that accident rates in these structures are fewer than those of the open roads (generally being reduced by half). The presence of hard shoulder was found to decrease accident rates in tunnels, whilst the tunnel length was positively associated with these accident rates. With reference to the accident cost rates, costs which for deceased and injured victims were estimated according to the 'human capital' approach, were found in tunnels to be between one-third and one-half of those for open sections. SAFESTAR [5] showed that the injury accident rate was in six unidirectional tunnels higher than that of the corresponding open sections and that in the remaining two tunnels investigated it was lower. This report argues that one cannot conclude in general that safety in tunnels is better than in open roads or vice versa. According to Salvisberg et al. [6], who investigated Swiss road tunnels, the risk of an accident occurring in a tunnel is lower in longer tunnels (more than one kilometre) than in shorter tunnels. This risk increases with increasing the AADT and/or the percentage of heavy vehicles. Nussbaumer [7] with reference to Austrian road tunnels supports the results of the aforementioned Swiss study, and adds that the risk of accidents is higher in tunnels with bidirectional traffic than in tunnels with unidirectional traffic. According to SWOV [8], the motorway tunnels in Netherland have more injury accidents per vehicle/kilometre than open road sections in contrast with other international studies, and higher accident rates correspond to higher traffic volumes. The above-cited literature shows that different results have been obtained with regard to accident rates in tunnels when compared to those of open roads. In addition these studies refer to foreign countries where traffic and geometric characteristics, as well as driving styles, differ from those in Italy; as a consequence it was considered worth making an investigation in this paper into crash occurrence more especially in Italian road tunnels. Since among the negative consequences of crashes there are also socio-economic costs, another purpose of this paper was to determine the corresponding accident cost rates. Estimates of road accident costs have been made in many studies, and in general they are based on two different methods, namely the so-called 'human capital' approach and the 'willingness to pay' approach. The former is based on the value of the economic production that is lost because of the accident, while the latter is based on the estimation of the amounts that road users are willing to pay for a reduced risk of accident. Discussions concerning potentiality, applicability and controversies of the economic valuations of road accidents can be found more especially in: Elvik [9]; Elvik [10]; Trawén et al. [11] and Elvik [12]. However studies based on an economic evaluation of accidents in road tunnels are most rare, while the costs per unit of person killed or injured in a road accident which are adopted in foreign countries could be different from those in Italy. Therefore, this paper makes a contribution to the state-of- the-art also by means of an economic evaluation of accidents in Italian tunnels and by comparing the results obtained to those of the corresponding roads containing these tunnels. The next section describes the data set used and the procedure of preparing it for evaluating both accident rates and accident cost rates of the road tunnels investigated.

3. Data description

3.1. Accidents in Tunnels

A 4-year monitoring period extending from 2006 to 2009 was evaluated on Italian motorway tunnels. The data base consisted of 195 unidirectional tunnels, 172 of which were two-lane tunnels while the remaining 23 were three-lane tunnels. The total length of the tunnel monitored is 217.63 km, with a total length of the two-lane tunnels of 198.99 km and 18.65 km for the three-lane tunnels, respectively. Tunnel length values ranging from 0.49 to 3.25 km were found for two-lane tunnels, while lengths between 0.52 and 0.98 km were found for three-lane tunnels. For the two-lane tunnels, the width of lane was always 3.75 m and the presence of sidewalk was recorded in 94 tunnels, while the emergency lane was present only in 2 tunnels. In the three-lane tunnels, the width lane was 3.75 m in 21 tunnels and 3.50 m in the remaining 2 tunnels, and the presence of sidewalk was recorded only in 2 tunnels, while the emergency lane was absent in the investigated cases. With reference to the emergency lane, it is to be emphasised that this lane is not generally present in the existing tunnels of Italian motorways, in contrast with the corresponding open-motorway sections. Information concerning the horizontal and vertical alignments of these tunnels was not available.

During the monitoring period, crash data and traffic flow were collated. Accident data were extracted from the official reports of the Motorway Management Agencies, which had been prepared for the Italian Ministry of Infrastructure and Transportation (MIT). For each accident a variety of details were recorded, including the name of the tunnel in which accidents occurred, date, type and accident severity, number of vehicles and persons involved. However, in this study only severe accidents (i.e. including injury and fatal accidents) are reported. Some 762 severe accidents were considered in the present paper, 668 of which occurred in two-lane tunnels and 94 in three-lane tunnels. The total number of injuries and deaths was respectively 775 and 18; 681 injuries with 17 deaths occurring in two-lane tunnels and 94 injuries with 1 death in three lane-tunnels. Table 1 gives severe accident count data observed during the 4-year monitoring period, with the numbers of injuries and deaths being given in brackets.

Traffic flow was extracted from the traffic files of the Management Agencies of the aforementioned motorway tunnels. These files contained the annual average daily traffic (AADT) for each tunnel. Since the investigated tunnels are with unidirectional traffic, the AADT refers to one travel direction only. AADT values per direction ranging from 4,500 to 40,761 vehicles per day were found for the two-lane tunnels and between 11,439 and 32,260 vehicles per day were evaluated for the three-lane tunnels. The percentage of trucks was 14÷31% and 17÷24% for two and three-lane tunnels, respectively. Summary statistics of the AADT per one travel direction in tunnels and the percentage of trucks, as well as the length of tunnels, are given in Table 2.

Table 1. Severe accident count data observed during the 4-year monitoring period, with the number of injuries and deaths given in brackets

Year	Number of severe accidents (n° of injuries and deaths)		Year's total
	Two-lane tunnels	Three-lane tunnels	
2006	246 (251* + 6**)	33 (33* + 1**)	279 (284* + 7**)
2007	180 (184* + 5**)	33 (33* + 0**)	213 (217* + 5**)
2008	122 (124* + 3**)	15 (15* + 0**)	137 (139* + 3**)
2009	120 (122* + 3**)	13 (13* + 0**)	133 (135* + 3**)
Total	668 (681*+ 17**)	94 (94* + 1**)	762 (775* + 18**)

(*) Number of injuries; (**) Number of deaths

Table 2. Summary statistics of characteristics of tunnels studied

Characteristics	Type of tunnel	Mean	Mode	Standard deviation	Minimum	Maximum
Length (km)	Two-lane tunnels	1.16	0.53	0.54	0.49	3.25
	Three-lane tunnels	0.18	0.89	0.14	0.52	0.98
AADT per one travel direction in tunnels (veh./day)	Two-lane tunnels	17,273	6,126	8,449	4,500	40,761
	Three-lane tunnels	23,416	25,533	4,857	11,439	32,260
Percentage of trucks (%)	Two-lane tunnels	21	16	4	14	31
	Three-lane tunnels	22	23	2	17	24

3.2. Accidents on corresponding Motorways

With reference to the monitoring period (2006-2009), severe accidents occurred on the motorways containing the aforementioned tunnels were also evaluated. In this respect, accident data available from the official site of the Italian Association of Motorways and Tunnels (AISCAT) [13] were used. These accident data refer to both travel directions, and also the AADT refers to both directions. The number of motorways containing the investigated tunnels was found to be 17 and the corresponding number of Motorway Agencies that manage these motorways was identified as being 10 at the time of the development of this research. The total length of motorways containing these tunnels is 3,370 km. The number of severe accidents occurring on these motorways in the 4-year period of monitoring was in total equal to 19,028 for both the travel directions; 11,654 of which occurred on two-lane motorways and 7,374 on three-lane motorways. The total number of injuries and deaths was respectively 37,614 and 1,096. Table 3 gives severe accident count data for both travel directions with an associated number of injuries and deaths observed on two- and three-lane motorways, respectively.

Table 3. Accident count recorded (both travel directions) on motorways containing the investigated tunnels.

Year	Two-lane motorways			Three-lane motorways			Two- and three-lane motorways
	Severe accidents	Injuries	Deaths	Severe accidents	Injuries	Deaths	Year's total
2006	3,344	6,252	178	2,064	3,904	118	5,408 (10,156*+296**)
2007	3,032	5,766	154	1,858	3,568	108	4,890 (9,334*+262**)
2008	2,656	5,594	234	1,694	3,498	146	4,350 (9,092*+380**)
2009	2,622	5,546	94	1,758	3,486	64	4,380 (9,032*+158**)
Total	11,654	23,158	660	7,374	14,456	436	19,028 (37,614*+1,096**)

(*) Number of injuries; (**) Number of deaths

Table 4 gives summary statistics for two- and three-lane motorways at the same time with reference to the length of motorways, AADT, and percentage of trucks.

Table 4. Summary statistics of characteristics of motorways (both travel directions) containing the studied tunnels.

Characteristics	Mean	Mode	Standard deviation	Minimum	Maximum
Length (km)	178	131	220	24	804
AADT(***) (veh./day)	33,121	32,268	14,194	8,786	59,090
Percentage of trucks (%)	22	22	4	14	31

(***) AADT for both travel directions on motorways.

3.3. Accident Costs

Information about accident costs was obtained from a study of the aforementioned MIT [14]. In this respect, the cost of a fatal accident is obtained as the sum of the costs of lost productive capacity, moral suffering, and medical care. *Lost productive cost* is the value of production lost due to a fatal accident. *Moral cost* refers to the pain, grief and suffering components that follow from a death. *Medical cost* is related to health care costs (including costs of first aid, ambulance transport, ambulatory care, and in-patient treatment) for a fatal injury in a road accident. In addition to the costs of lost production, moral suffering, and medical care, one has also to consider the general cost of an accident. *General cost* represents costs of property damage on vehicles and roads, police and court, administration for insurance companies, etc. According to the MIT study this leads to the following total costs, which refer to the year 2010, for a person killed in a road accident: 940,291 € (lost production) + 561,734 € (moral suffering) + 1,965 € (medical care) = 1,503,990 €. With regard to a person injured in a road accident, according to MIT the corresponding total cost (i.e. including lost production, moral suffering, and medical care) is 42,219 €. The general cost of an accident is, instead, assumed to be 10,986 €. Taking into account the average annual inflation rate of costs, in the present paper have been estimated the costs per unit person dead or injured, as well as the general cost per accident, in the years from 2006 to 2009 (time period in which severe accidents were observed) as reported in Table 5.

Table 5. Costs per unit of person dead or injured in a road accident, and general cost of an accident.

Year	Average total cost for unit of person dead in a road accident	Average total cost per unit of person injured in a road accident	Average general cost of a road accident
2006	€ 1,383,944.23	€ 38,851.25	€ 9,984.51
2007	€ 1,425,536.11	€ 40,018.85	€ 10,284.58
2008	€ 1,409,356.67	€ 39,564.65	€ 10,167.85
2009	€ 1,491,973.21	€ 41,883.93	€ 10,763.89

In this paper the accident cost rates both for tunnels and corresponding motorways were evaluated considering the aforementioned unit costs.

4. Analysis of results

4.1. Accidents rates

Since the investigated tunnels are unidirectional, the crash indicator used in this accidents analysis is the number of severe crashes per 100 million vehicle-kilometres per one travel direction. For this aim the number of severe accidents occurring in each tunnel in each year of monitoring (2006-2009), the corresponding annual average daily traffic per one direction (AADT/direction), and the length of the tunnel were used for computing the severe accident rates. These severe accident rates were computed for each tunnel and year, and with reference respectively to two lane-tunnels and three-lane tunnels. However, given that the number of the investigated tunnels with three lanes was much smaller than that of the two-lane tunnels, it was not assumed to be reasonable to justify also the making of a comparison between the severe accident rates of the two-lane tunnels and those of three-lane tunnels. Therefore, no distinction was made in this paper between two- and three-lane tunnels, and only a comparison between the severe accident rates in road tunnels and those of the corresponding motorways containing these tunnels is made. In this respect, the severe accident rates of motorways for one direction were evaluated by dividing by two both the number of severe accidents and the AADT observed on each of the aforementioned 17 motorways. Subsequently by using these severe accidents and AADT per direction, as well as the length of each motorway, the severe accident rates were computed being expressed as the number of severe crashes per 100 million vehicle-kilometres per one travel direction of each motorway that were compared with those of the corresponding tunnels.

Tables 6, 7 and 8 show that the severe accident rates are between 9.13 and 20.45 crashes/10^8veh.km for tunnels and between 8.62 and 10.14 crashes/10^8veh.km for motorways, respectively. These tables indicate also a systematic reduction in severe crashes over time both for tunnels and motorways (with a slight exception for the year 2009).

Table 6. Severe accident rates of unidirectional tunnels.

Tunnels	2006	2007	2008	2009
Severe accident rates (accident/10^8veh.km)	20.45	16.08	9.13	12.84

Table 7. Severe accident rates of motorways (one direction) containing the tunnels investigated.

Motorways	2006	2007	2008	2009
Severe accident rates (accident/10^8veh.km)	10.14	9.56	8.62	8.73

Table 8. Accident rates both of tunnels and corresponding motorways.

Road Management Agencies	Number of Motorways for Road Management Agencies	Number of Tunnels for Motorway	Motorway Accident Rates (per direction) [severe accidents/10^8 veh.km]					Tunnel Accident Rates [severe accidents/10^8 veh.km]				
			2006	2007	2008	2009	Average values in 4-year period	2006	2007	2008	2009	Average values in 4-year period
1	1	1$^{(1)}$	13.40	15.79	9.83	10.87	12.47	42.24	0.00	0.00	44.48	21.68
2	1	7$^{(1)}$	7.66	6.15	8.89	8.09	7.70	15.67	6.50	0.00	10.40	8.14
3	1	34$^{(1)}$	11.06	8.56	8.26	9.47	9.34	32.71	18.40	10.63	13.67	18.85
4	1	2$^{(1)}$	6.73	6.88	5.43	4.50	5.88	0.00	0.00	14.31	37.16	12.87
5	1	6$^{(2)}$	17.10	12.37	10.40	8.53	12.10	22.33	10.96	0.00	0.00	8.32
6	8	30$^{(2)}$	18.57	13.32	15.22	13.03	15.04	20.03	17.31	11.68	9.92	14.74
		16$^{(2)}$	22.73	23.13	15.84	18.09	19.95	26.68	24.70	8.97	11.33	17.92
		27$^{(1)}$	8.25	6.84	5.52	6.31	6.73	21.54	18.78	11.72	8.78	15.21
		7$^{(2)}$	12.28	10.68	10.94	12.68	11.64	20.12	19.37	4.30	2.42	11.55
		12$^{(1)}$	12.65	11.40	10.44	10.52	11.25	30.97	26.99	25.15	18.39	25.38
		1$^{(1)}$	7.12	6.78	9.75	10.20	8.46	19.74	18.99	0.00	0.00	9.68
		17$^{(1)}$	10.84	8.89	7.88	8.15	8.94	22.14	19.17	10.70	10.40	15.60
		13$^{(1)}$	8.95	9.57	8.51	7.82	8.71	19.77	13.28	9.52	6.56	12.28
7	1	4$^{(1)}$	0.95	4.83	2.85	0.00	2.16	16.45	27.43	4.89	0.00	12.19
8	1	14$^{(1)}$	5.22	5.60	6.24	6.84	5.97	15.67	3.73	14.06	10.54	11.00
9	1	1$^{(1)}$	4.34	6.24	5.98	8.04	6.15	0.00	0.00	29.36	0.00	7.34
10	1	3$^{(1)}$	4.45	5.46	4.56	5.29	4.94	21.50	47.80	0.00	34.31	25.90

$^{(1)}$ Tunnels with average severe accident rates higher than those of the corresponding motorways (136/195);
$^{(2)}$ Tunnels with average severe accidents rates lower than those of the corresponding motorways (59/195).

This reduction may be due to an increasing installation of electronic speed control systems (Tutor) carried out on Italian motorways during the aforementioned monitoring period [15], as well as to the positive effects of the introduction of the driving licence with the demerit point system in the event of Highway Code infringement.

Table 8 shows in greater detail that the average severe accident rates of the investigated tunnels are higher than those of the corresponding motorways in about two-thirds (136/195 tunnels) of the tunnels studied, and that in the remaining one-third (59/195 tunnels) are instead lower. These results prove that severe accident rates increase in tunnels in the most of the investigated cases. However, in general it cannot be concluded that safety in tunnels is always lower than that of motorways. Apart from driver behaviour and visibility, tunnel safety is affected by the geometric and traffic characteristics of the specific tunnel. Therefore different combinations of these variables can cause safety conditions that are either worse or better than those of the corresponding motorways. Figure 1 shows a visual comparison between the severe accident rates computed in the tunnels investigated and those of the corresponding 17 motorways containing these structures (the 10 motorway management agencies are also indicated in brackets).

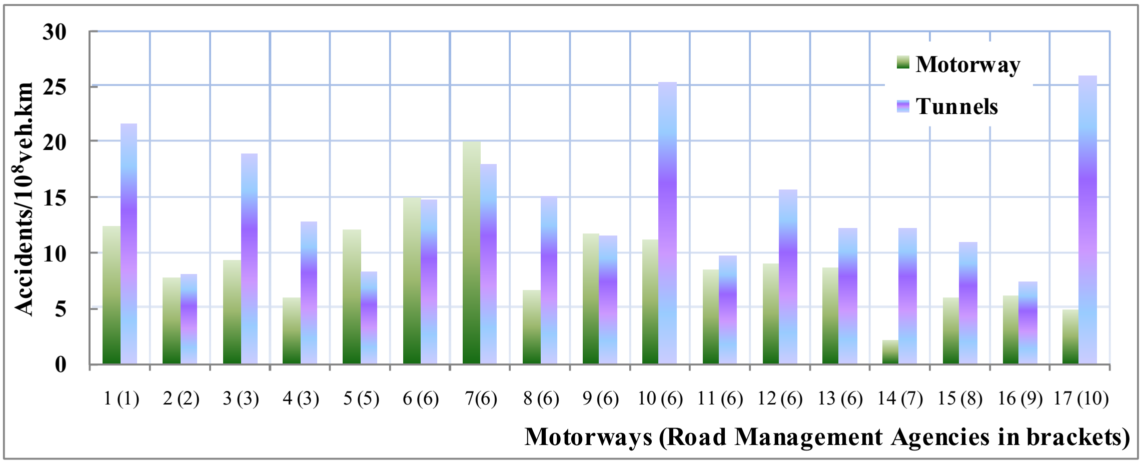

Fig. 1. Severe accident rates in tunnels and on the corresponding motorways.

4.2. Accident Cost Rates

Accident costs have been evaluated in this paper by using the aforementioned human capital approach and assuming the unit costs of the cited Table 5 as a reference.

In the evaluation of severe accident cost rates, given that the data-base concerning the numbers of injuries and deaths in each tunnel refers to the total 4-year period only (i.e. also without any distinction being made for each year), the procedure followed in this paper is as reported below. First of all, the total number both of deaths and injuries was associated to the total number of severe accidents observed in each tunnel during the 4 years. By multiplying these numbers of deaths and injuries respectively by the corresponding unit cost of Table 5, the social costs of deaths and injuries for each tunnel, as well as the general costs of accidents were evaluated. The resulting cost, which was obtained as the sum of the above-mentioned three costs (social costs of deaths, injuries, and accidents) was divided by 4 in order to compute the average costs per year. Subsequently by dividing these average yearly costs by the average AADT/direction and the length of each tunnel the average severe accident cost rates were estimated that were expressed in terms of euro per 10^3 vehicle-kilometres per one travel direction in each tunnel. A similar procedure was followed for computing the severe accident cost rates of the corresponding motorways.

Table 9 shows the results obtained both for the tunnels and the corresponding motorways.

Table 9. Severe accident cost rates both of tunnels and corresponding motorways.

Road Management Agencies	Number of Motorways for Road Management Agencies	Number of Tunnels for Motorway	Accident cost rates [€/10^3 veh.km] (average values in 4-year period)	
			Motorway (per direction)	Tunnels
1	1	1(4)	42.59	36.67
2	1	7(3)	19.86	60.77
3	1	34(3)	13.02	54.99
4	1	2(3)	4.08	60.81
5	1	6(4)	17.29	13.98
6	8	30(3)	33.57	37.04
		16(4)	332.43	44.08
		27(3)	12.41	51.48
		7(3)	71.24	54.94
		12(3)	3.46	43.24
		1(3)	17.88	284.72
		17(3)	1.10	39.79
		13(3)	3.79	137.03
7	1	4(4)	216.64	20.74
8	1	14(3)	1.81	61.20
9	1	1(4)	66.40	12.46
10	1	3(4)	104.76	44.16

Tunnels with accident cost rates higher (3) and lower (4) than those of the motorways.

This table shows that the severe accident cost rates of the road tunnels are higher than those of the corresponding motorways in about four-fifths of the investigated tunnels (164/195), and that in the remaining one-fifth (31/195 tunnels) are instead lower. These findings indicate not only that severe accidents rates are in most of the investigated tunnels higher than those of the corresponding motorways, but also that the severity of accidents in tunnels involves more injuries and deaths, and as a consequence higher social cost rates.

Figure 2 shows a visual comparison between the severe accident cost rates computed for the investigated tunnels and those of the corresponding motorways.

In the light of the results obtained, investments aimed at adjustment projects of the existing tunnels appear to be justified in order to improve the safety level of these structures in compliance with the 2004/54/EC Directive [1].

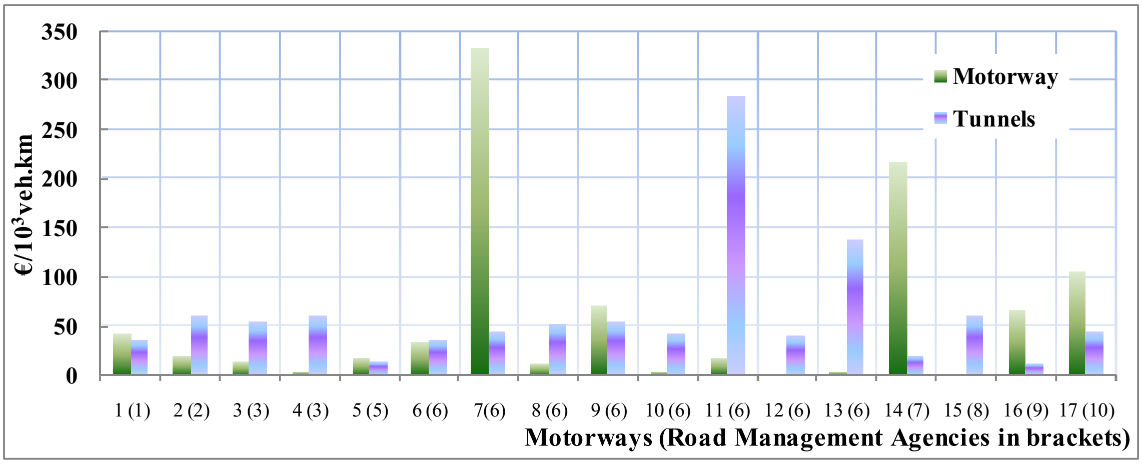

Fig. 2. Severe accident cost rates for the investigated tunnels and the corresponding motorways.

5. Benefit cost analysis

In this section an exemplified benefit-cost analysis is reported as a criterion that might be useful for setting the priorities of investments aimed at improving tunnel safety. The potential 50% reduction in the number of deaths [16] and injuries estimated at 2020 when compared to that of 2010, and more especially the corresponding reduction in social costs, is assumed in this paper as achieving a benefit when treatment in each of the examined tunnel is designed and subsequently realized. The corresponding treatment-costs of the tunnel are, in contrast, stead assumed as costs in the analysis. The ratios between these potential benefits and the associated treatment-costs might be considered as a support in making decisions about the investment policy of the MIT in order to improve tunnels safety in compliance with the 2004/54/EC Directive.

Since the aforementioned 10 Motorway Agencies made a request to the Italian Ministry of Infrastructure and Transportation (MIT) for funds for 177 of the investigated tunnels, the benefit-cost analysis was restricted exclusively to these tunnels. Table 10 gives summary statistics of investment costs required in the year 2010 for all these mentioned tunnels.

Table 10. Summary statistics of investments required for all tunnels.

Costs	Mean	Mode	Standard deviation	Minimum	Maximum
€	2,996,317.39	6,317,075.00	4,398,986.22	150,091.00	18,406,550.00

For each tunnel the benefit was evaluated in terms of the reduction in social costs due to the potential reduction by half of the number of deaths and injuries. Dividing this benefit by the fund required for the specific tunnel the corresponding benefit/cost ratio (B/C) of each tunnel was computed. Table 11 gives summary statistics of the benefit-cost ratios for all tunnels.

Table 11. Summary statistics of the benefit-cost ratios for all tunnels.

Mean	Mode	Standard deviation	Minimum	Maximum
0.61	0.0041	1.1438	0.0035	7.75

The benefit-cost ratio (B/C) was found to be included within the 7.75 and 0.0035 range with a mean of 0.61. More especially a percentage of tunnels equal to 18% (32/177) was found for having a B/C ratio higher than 1.0;

a percentage of 15% (27/177) was computed to have: 1<B/C≤0.5; a percentage of about 14% (24/177) was identified as having: 0.5 < B/C ≤ 0.25; and finally for the remaining 53% (94/177) of the considered tunnels was found with benefit-cost ratio less than 0.25. Obviously the tunnels with higher benefit-cost ratios should have priority in the assignation of funds.

However, it is to be stated that the aforementioned Motorway Management Agencies required funds not only to reduce road accidents, but also to improve tunnel safety in the event of a fire. Unfortunately, information about the benefits due to the potential reduction of the fire risk and its economic evaluation was not available at the time to develop this benefit-cost analysis. The aforementioned B/C values are referred to as a benefit to the reduction in deaths and injuries caused by road accidents in tunnels only. Therefore further studies are necessary for making a more complete benefit-cost analysis.

The authors of this paper, however, believe that the computed B/C ratios might be used as a preliminary reference point in the priority choice of assigning funds for improving tunnels safety compatibly with the budget available.

6. Summary and conclusion

This study was prevalently motivated by the need to make an analysis of accidents occurring in Italian road tunnels. Another point of interest was to determine the social costs of these accidents. The objective was also the making a comparison between the results obtained in the investigated tunnels and those of the corresponding motorways containing these structures. For this aim a 4-year monitoring period (2006-2009) was considered in the analysis. Data base consists of 195 unidirectional tunnels, in which 762 severe accidents occurred with 774 injuries and 18 deaths. On the basis of this data set the conclusions given below may be drawn.

A year effect consisting of systematic reductions in severe crashes over time both in the investigated tunnels and on the corresponding motorways containing these structures was generally found. This comparison appears to be due to an increasing installation of electronic speed control systems on Italian motorways, as well as to the positive effects of the introduction of the driving licence with the demerit point system in the cases of violations of the Highway Code.

Severe accident rates were found to be between 9.13 and 20.45 crashes /10^8veh.km in tunnels and between 8.62 and 10.14 crashes/10^8veh.km on the associated motorways.

These severe accident rates in tunnels are higher than those of the corresponding motorways in about two-thirds of the tunnels studied, and lower in the remaining one-third. These results appear to be affected, apart from driver behaviour and poor visibility in tunnels, also by the geometric and traffic characteristics of each tunnel when compared to those of the open road sections.

In the design of new motorway tunnels these results seem to encourage the need for using the same geometric characteristics and more especially the same cross-section (i.e. including the emergency lane) of the corresponding open sections in order to reduce accidents in this structures.

Also severe accident cost rates in tunnels were found to be higher than those of the corresponding motorways in about four-fifths of the investigated tunnels, and lower in the remaining one-fifth. More especially the accident cost rates are between 12.46 and 284.72 euro/10^3vehic·km in tunnels and between 1.1 and 332.43 euro/10^3veh.km on the motorways. This appears to indicate that the severity of accidents in tunnels involves more injuries and deaths, and as a consequence higher social cost rates.

An exemplified benefit-cost analysis that assumes as benefit the reduction in social-costs, which was associated to a potential 50% reduction in deaths and injuries estimated at 2020 when compared to that of 2010, and as cost the treatment-costs of tunnel was also made. The benefit-cost ratio (B/C) was found to be included within the range between 7.75 and 0.0035 with a mean of 0.61. The computed benefit-cost ratios might represent a preliminary reference point in the choice of the priority of assigning funds in order to improve tunnel safety in compliance with the 2004/54/EC Directive [1]. However, since in the benefit considered in this paper the potential reduction in the fire risk due to tunnel treatment is not contained, further studies are necessary for making these additional developments possible.

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