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Overview of traffic safety aspects and design in road tunnels☆

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ABSTRACT

This paper reviews aspects of traffic safety and behavior of drivers in road tunnels based on several case studies of traffic accidents along the traffic zones of tunnel alignment (entrance: zone 2; transition zone: zone 3; and inner zone: zone 4). This paper commences with engineering and design aspects that differentiate between road tunnel and open highways and, afterward, reviews certain issues related to tunnel safety and crashes such as driver behavior, highway alignment, tunnel length, and longitudinal friction. This paper additionally discusses the severity of crashes in road tunnels, specifically severe crashes in road tunnels, including fire incidents and their relationship with vehicle crashes. Finally, additional risk measures and classifications of tunnel safety are introduced.

The risk of a crash in a tunnel is reduced compared with crashes on the open road (approximately half); however, tunnel crash severity is higher. The catastrophe potential related to a tunnel fire is higher than in a vehicle crash, even though fire crashes are less frequent than traffic crashes.

Drivers in road tunnels generally reduce their speed and increase their lateral position from the right tunnel wall while driving. In shorter tunnels, with reduced driving speed, driver vigilance may be more robust without being hindered by dull driving, which is more common in longer tunnels. Still, in spite of driver alertness, crash rates in tunnels occur due to the tunnel's unusual driving environment. Crash rates are lower in the tunnel inner zone due to driver alertness, especially after passing the transition zone and acclimating to the tunnel environment. The number of crashes, however, is higher along zone 4 (tunnel inner zone, which is the principal zone), as it covers longer driving distance. According to most studies, short tunnels were found to exhibit higher crash rates than long tunnels because the entrance zones incorporate higher crash rates, compared with the midzones; nonetheless, longer unidirectional (freeway and multilane) tunnels with higher design speed, entail lower driver alertness and diminished concentration due to relatively monotonous driving in spite of a tunnel's closed environment.

Contents

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1. Background: tunnels versus open highways

The design of road tunnels is an essential component in maintaining highway safety and highway design. The need for roadway construction along difficult topography, including overcoming natural conditions, is the major motivation for selecting an alternative solution for a road tunnel. A road tunnel's solution minimizes the damage to environment and land, preserves land resources, and reduces traffic congestion and air pollution. Generally, the design of road tunnels should be based on the geometric design principles of open highways.

However, the chance of crash occurrence is lower in a tunnel than on an open highway section, although the likelihood of higher crash injury severities and fatalities is greater, especially in the event of fire due to the enclosed environment and expansion of heat and smoke [1,2].

The differences between tunnels and open roads are typically the result of (1) construction cost considerations; (2) lighting; (3) structural requirements; (4) cross-section implications; (5) friction coefficients and driver perception reaction time adjusted to tunnel environment; (6) the impact of ventilation design on the longitudinal gradient; and (7) the need to locate complementary elements inside the tunnel envelope in addition to the traffic envelope, transport of dangerous goods, and signs' installations (for traffic and fire safety guidance).

The main differences influencing the design of tunnels versus open roadways with respect to the user (driver) and the operator viewpoints are documented as follows.

1.1. Lighting issues

Tunnels have permanent lighting for 24 h except in the entry zone. The lighting plan depends on cross section, tunnel length, and ground and rock properties on which the tunnel alignment is located. The lighting plan during daylight is different than during night hours. Drivers entering the tunnel immediately after daylight have a short time to adapt their eyes to the relatively dark surrounding in the tunnel. The reason is that distance traveled during this adaptation process is relative to the travel speed. The slow adaptation of eyes from daylight to a tunnel's dim environment necessitates gradual reduction of tunnel lighting in the threshold and transition zones of the tunnel (Fig. 1, [3]). Similarly, a gradual amplification of tunnel lighting is made before exiting the tunnel into daylight environment. Specifically, the threshold zone (end of tunnel) has the highest tunnel lighting level, and the transition zone provides a gradual lighting reduction on the way to the interior zone. The lighting along the threshold zone enables drivers on the tunnel approach (access zone) to identify obstructions after passing the stopping sight distance. The essential illuminated elements of the tunnel cross section for safety reasons are the road surface and the lower portion of the tunnel walls [3].

1.2. Additional differences: tunnel versus open roadway

1) The design of road tunnels requires components of complementary systems (fire safety, fire detection, ventilation, communication systems), which are not critical and/or do not exist in open roadways. These components are crucial for tunnel design. The design of these components depends on the tunnel cross-section dimensions, tunnel length, etc.
2) The accessibility of rescue vehicles, ambulances, and heavy vehicles due to road crashes (accidents) has to be taken into consideration in the geometric design process of road tunnels.
3) The bounded cross section exacerbates the driver's ability to estimate how far he or she is inside the tunnel while driving along the tunnel lanes [4] and also recognizing road alignment, especially prior to horizontal curves. The reasons for this are the closed and dark environment [5,6] and the difficulty to estimate bends due to tunnel walls [7].
4) Driver perception reaction characteristics (especially for recreational drivers) are different in road tunnels. On the one hand, the driver finds it difficult to be regular with the restricted environment of the tunnel. He or she may feel confined and unable to connect the natural environment in the open area. Nonetheless, tunnels exhibit a better crash record [6,8,9,10] than open roadways because drivers (especially commuters or regular drivers) become more alert in the changed natural environment of the tunnel. Typical unique characteristics of the tunnel natural environment, as opposed to open highways, are the absence of roadside obstacles, narrow shoulders, different standards of construction, and additional safety features (traffic control and fire safety).
5) The tunnel walls and the bounded cross section are physical obstacles, which have to be considered during the design process. Heavy goods vehicle (HGV) might be restricted while passing through the tunnel section, including a potential inability to perform a U-turn maneuver.
6) Intersections and branch connections (forks) are not advisable for tunnel design. These geometric design elements significantly increase construction costs and also may confuse the drivers along the confined environment of the tunnel.
7) The construction cost of road tunnels is significantly higher than on open highways due to the use of boring machines, the amount of concrete, and the complementary systems.

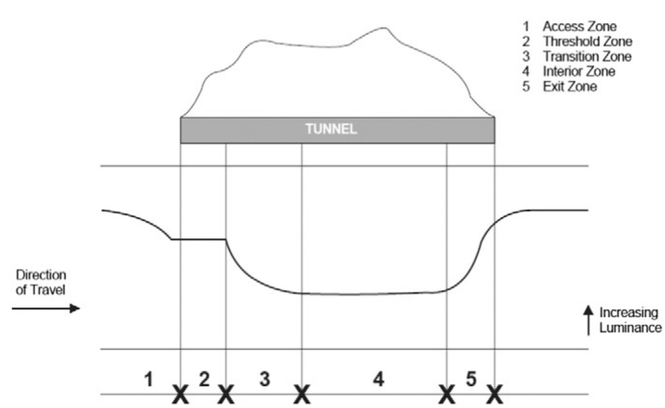


Fig. 1. Luminance change curve example (DMRB 1999).

2. Traffic safety and behavior of drivers in road tunnels

Driving along a tunnel's dark narrow environment may cause anxiety, uncertainty, and even fear of hitting another vehicle or tunnel walls and/or other dangerous circumstances such as fire or a tunnel collapse [4,7]. Drivers in tunnels generally reduce their speed and increase their lateral distance to the tunnel wall [7], which can be interpreted as increased alertness while driving along road tunnels. This change in behavior of drivers generally occurs while approaching the tunnel portals. Amundsen and Ranes [11] believe that driving in a road tunnel causes an "unease" feeling as a result of the darkness and safety concerns.

Therefore, driving in tunnels requires supplemental attention and mental workload [4], which cause drivers to increase their vigilance.

2.1. Transition zones and speed variation

Transition zones in tunnels are dangerous areas. Drivers approaching tunnels at high speed are exposed to much higher crash risk. When a vehicle approaches a tunnel, the driver normally decelerates as he approaches tunnel entrance in order to adapt to the dim light condition ("black hole"), as explained in Section 1.1. After entering a tunnel, the driver will then decelerate to a speed that is lower than that of an open road. These large speed fluctuations have a deleterious impact on traffic safety [12].

2.2. Road tunnel crash: definition and scope

A tunnel crash or a tunnel traffic accident occurs when two or more vehicles collide or when one vehicle hits an object such as tunnel wall, traffic sign, etc. (single vehicle crash). Fire or a smoke without fire (SWF) incidents, due to vehicle crash, are also included in the scope of tunnel accident (crash). Most of tunnel fires and SWF incidents are caused by vehicle crashes [13] and not by vehicle technical problems. Most studies consider a traffic crash in a tunnel when it causes fatalities, serious injuries, or slight injuries. Crash rate in this study refers to a traffic crash with injuries (slight or serious) and fatalities. Severe crash rate in this study refers to crashes that involve serious injuries and fatalities.

2.2.1. Rear–end crashes in road tunnels

The rear–end crashes category is estimated as 70% of all crashes based on Singapore CTE tunnel information during years 2006–2008 [14], 75% based on Shangyu-Sanmen-Highway in China [15], and 80% based on Lu et al. [12]. According to police investigations [12], tunnel crashes are often caused by drivers' aggressive lane changes and high speed, which leads to rear–end crashes.

2.2.2. Fire crashes in road tunnels

Fire in tunnels produces heat, smoke, and toxic fumes, which may cause the loss of life for drivers and for tunnel occupants during their evacuation process. A fire also certainly causes traffic delays as a result of a temporary closure of the tunnel.

In addition, high temperatures produced by fire also might cause damage to structures and/or installations. Therefore, economic losses due to fire crashes in tunnels are related, unlike traffic crashes, and also to traffic congestion and damaged tunnel components [16]. Fire crash in this study refers to fire incidents along the tunnel that result in injury and fatality or damage only. Therefore, fire crash rate refers to fire crashes that involve either injuries and fatalities or damage only (without injuries).

2.3. Overview of crash rates along tunnel zones

Amundsen and Ranes [11] found that the crash rates are higher in the entrance zone of tunnels and are lower as drivers continue driving inside the tunnel. The highest crash rate in crashes per million veh·km (0.30) occurred in the first 50 m beyond the tunnel opening (zone 1), 0.23 in the first 50 m inside the tunnel (zone 2), 0.16 in the next 100 m inside the tunnel (zone 3), and 0.10 in the midzone inside the tunnel (zone 4). In one-way tunnels, the crash rate in zone 1 is larger. Its distribution is 0.36, 0.16, 0.16, and 0.10 for zones 1, 2, 3, and 4, respectively. A typical sketch of the tunnel zones is presented in Fig. 2.

Similarly, according to Nussbaumer [17], the crash rate is higher before the entrance and after the exit (as well as the portal area) than in the internal zone of the tunnel. Also, Lemke [8] reported that the crash rates near the tunnel portal might be higher than those occurring inside the tunnel because of the "sudden change in visual environment" [8]. Yeung and Wong [18], who investigated expressway tunnels in Singapore, also found that road traffic crashes (RTC) are lowest in the tunnel interior zones and highest in the entry and exit zones. The authors inferred this finding by the fact that drivers, who have already passed the transition zones into the tunnel internal part, are more experienced and careful in their driving. Conflicting driver behavior and difference in driver perceptions between open roads and tunnel sections might elucidate the highest crash rates in the entry transition zones, i.e., 250 m outside the tunnel and 250 m inside the tunnel [18].

In contrast, another study of Chinese freeway tunnels [1] showed a clear decline in the crash rate along the tunnel portal and the first 100 m of the tunnel (tunnel entrance) and an increased number of tunnel crashes inside the tunnel compared with previous studies. The study explained these findings by superior illumination in the tunnel entrance zone. The major safety problem in the Chinese freeway tunnels is the high percentage of rear–end (R–E) collisions (60% of R–E collisions inside the tunnel compared with other crash types, such as collision with fixtures, sides wipe collisions, rollover, etc., as documented by Z-L Ma et al. [1]) due to the inability to maintain safe distance from the front vehicle, especially in tunnel internal zones. Potential reasons could be higher driving speeds compared with those in Norwegian tunnels [1] and apparently insufficient sight distance, which is required for higher design speeds and not necessarily driver discomfort and driver anxiety. The resulted relatively high crash rates were: zone 1 (first 100 m in front of tunnel openings): 0.56; zone 2 (first 100 m inside the tunnel): 0.53; zone 3 (the next 300 m inside the tunnel): 0.58; and zone 4 (midtunnel zone): 0.45. These considerably high crash rates are based on incident records, which consist of injury crashes and noninjury crashes as well. The majority of injury crashes in this database amount to slight injuries.

Based on Nussbaumer [17], the most frequent cause of tunnel crashes is lacking vigilance (particularly in bidirectional tunnels). Additional reasons are "wrong driving behavior," such as inability to maintain safe distance from the front vehicle (speeding especially before and in the entrance area of the tunnel) and "misinterpretation of road design and layout" [17].

Table 1 depicts a comparison of crash rate distribution along the tunnel zones (inside the tunnel: zones 2–4 and prior to the tunnel entrance: zone 1) according to several studies. The bottom line of Table 1 presents average crash rate values in order to understand quantitatively the safety level of each tunnel zone. The crash rate in units of crashes per million vehicle·km normalizes the affects of tunnel traffic volume and tunnel length (total length of travel). Therefore, average values of crash rates in these units can roughly portray the differences between the tunnel midzone and tunnel edge zones.

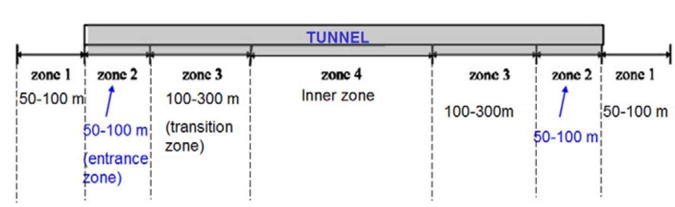


Fig. 2. Typical tunnel zones for crash distribution (not to scale).

Table 1
Comparison of tunnel crash rates (crashes per million vehicle·km) of previous studies [1,11,12,15,17–19].

Source	Tunnel type (country)	Zone 1	Zone 2	Zone 3	Zone 4	Total (inside tunnel: zones 2–4)
Z-L Ma et al. [1]	Freeway tunnel (China)	0.56	0.53	0.58	0.45	0.50
Nussbaumer [17]	Unidirectional (Austria)	0.30	0.05		0.095	0.0725 (5)
	Bidirectional (Austria)	0.30	0.10		0.075	0.0875 (5)
Amundsen [11]	All tunnels (Norway)	0.30	0.23	0.16	0.10	0.13
Amundsen [10]	All tunnels (longer than 500 m)	0.30	0.32	0.18	0.08	0.13 (5)
	Urban unidirectional	0.31	0.38	0.16	0.12	0.14
	Rural unidirectional	0.27	0.06	0.06	0.03	0.04
	Single tube: bidirectional	0.24	0.26	0.19	0.07	0.10
Brandt et al. [19]	Unidirectional (Switzerland, Norway)	0.175	0.15	0.12 (3)	0.03	0.131
Guo et al. [15] (4)	Tunnel data base (Shangyu-Sanmen-Highway (China)	1.52	1.52	1.32 (4)	1.13	~1.3
Yeung, Wong [18] [Crashes/km/year] (1)	Expressway tunnels (Singapore)	52	35		5	NA
Lu et al. [12] [Crashes/km/year] (1)	Shanghai Yangtze river crossing tunnel (China): urban expressway	700	500	370	150	340
Average (2) (Wei et al. (2013) not included)		0.33	0.23	0.20	0.15	0.19

The definitions of zones 2 and 3 boundaries by Amundsen [11,10] and Z-L Ma et al. [1] are slightly different.

(1) Different measurement units of crash rate [18,12].
(2) Excluding Yeung, Wong [18], Lu et al. [12], and Guo et al. [15] based on gray-shaded cells.
(3) The crash rate was calculated until 150 m from tunnel entrance.
(4) Considerably high rates, which consider conversion coefficients of 2.0, 1.5, 1.2 for fatal, serious, and light injury crashes type. It is assumed that zone 3 has average crash rate of zone 2 and zone 4. These results were considered outliers and, therefore, were excluded from the average computation.
(5) The average weighted value for zones 2–4 (inside the tunnel) was computed by assuming the average between zone 3 and zone 4 (in order to provide more significance to zone 4 in accordance to other results in the table).

A comparison of crash percentage inside the tunnel (zones 2–4) between Amundsen [11,10] and Z-L Ma et el. [1] is shown in Table 2. The number of crashes along zone 1 (50 m beyond the tunnel entrance) was supplemented as well. Although Table 1 indicates that crash rates (crashes per million vehicle · km) are higher in the entrance zones of the tunnel (zones 2,3), Table 2 shows that the absolute number of crashes is higher along zone 4 (inner tunnel zone), as it covers longer distance (principal tunnel zone). Overall, zone 1 portrays the highest tunnel crash rate, but zone 4 represents the highest number of crashes.

Fig. 3 presents crash rate (crashes per million vehicles·kilometers) results from the highway network in different countries for the years 2010, 2011, 2012. The resulting average crash rate is 0.345. This crash rate is similar to the analyzed average crash rate in tunnel zone 1 (50–100 m beyond the tunnel entrance) according to Table 1. It appears that crash rates results of tunnel zone 1 (before the tunnel entrance) is somehow correlated to the average roadway crash rate in developed countries. This data set includes road crashes with injuries and casualties (Israel Central Bureau of statistics [20] analyzed from IRTAD [21] database).

2.4. Driving behavior in road tunnels

According to Lemke [8] and Yeung and Wong [18], when the tunnel part in the roadway network is small, drivers in general tend to drive more carefully and at a lower speed. The risk of crash in a tunnel is reduced compared with the open road (approximately half); however, tunnel crash severity is higher, e.g., cases of vehicle crashes against tunnel wall compared with safety barrier (in open roads) and the limited availability of rescue devices in tunnels such as cranes [8].

Still the crash rates near the tunnel portal might be higher than those occurring inside the tunnel because of the “sudden change in visual environment” (Lemke [8], Table 1, DMRB [3]).

SWOV [22] documents several factors that increase the crash risk in road tunnels: proximity of the tunnel wall, limited sight distance, merging or exit lanes in or near the tunnel, and lighting characteristics. The closed construction, i.e., “the presence of tunnel wall and tunnel roof” [22] can trigger anxiety in drivers. Also, the tunnel environment may cause some drivers to reduce their speed and avoid overtaking maneuvers such that homogeneity and continuity in traffic flow are reduced, driver alertness is diminished, and therefore road safety is

Table 2
Comparison of crash percentage inside the tunnel (zonse 2–4).

Source	Tunnel type	Zone 2	Zone 3	Zone 4	Total (inside tunnel)	Zone 1*
Z-L Ma et al. [1]	Freeway tunnel (china)	17	42	57	116	18
	Percentage inside tunnel (%)	15%	36%	49%	100%	–
Yeung, Wong [18]**	Expressway tunnels (Singapore)	26		38	64	39
	Percentage inside tunnel (%)	41%		59%	100%	–
Amundsen [11]	All tunnels	94	97	181	372	127
	Percentage inside tunnel (%)	25%	26%	49%	100%	–
Amundsen [10]	All tunnels	172	187	380	739	187
	Percentage inside tunnel (%)	23%	25%	52%	100%	–
	Longer than 500 m	90	102	369	561	87
	Percentage inside tunnel (%)	16%	18%	66%	100%	–

Slightly different definitions of zones 2 and 3 boundaries between Amundsen [10,11, and Z-L Ma et al. [1].
* Zone 1 was excluded from the percentage calculation.
** Analyzed results for the average unidirectional tunnel.

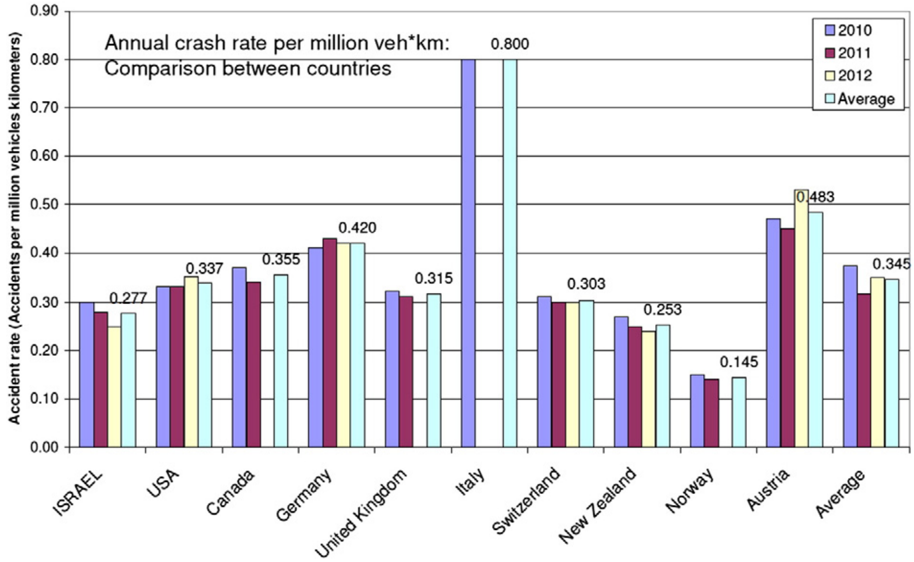


Fig. 3. Annual crash rate (crashes per million vehicle·kilometers): comparison between countries, years 2010, 2011, 2012 (analyzed from IRTAD database and annual reports © OECD/ITF [21], based on Israel Central Bureau of Statistics [20].

negatively affected. Because the risk factors are at least partially simultaneous, it might be difficult to designate on a major cause of vehicle crash [22]. Zhao et al. [23] measured changes in the pupil and heart rate while driving through the tunnel. The authors concluded that drivers feel tension, which has a negative impact on road safety and is recommended to improve illumination facilities inside the tunnel in order reduce the tension feeling and mental demand due to the different environment inside the tunnel.

Shimojo et al. [24] suggest that driving in a long tunnel causes the driver psychological stress and discomfort and propose widening the right shoulder, thus providing distance information guidance highly visible devices. Also, improvement of traffic control devices may increase driver alertness and reduce the psychological burden and crash risk.

Vashitz et al. [5] proposed in-vehicle high informative display, which has been found useful in providing the tunnel driver certainty and sense of control and, as a result, could reduce anxiety, boredom, fatigue, and impaired vigilance, which are considered common in the closed dark and monotonous tunnel driving environment. It improves tunnel safety, as long as the information provided is not excessive and does not cause distraction.

2.5. Vertical and horizontal alignment effect on tunnel traffic safety

Highway geometric design and traffic elements, which are potential factors that affect vehicle collisions and their severity (in addition to driving behavior reasons), could be average daily traffic, HGV, horizontal curvature, and gradient.

On relatively steep longitudinal grades, heavy vehicles typically reduce their speed; therefore, the increased speed difference between passenger cars and trucks increases the probability of road crash [7]. Amundsen and Ranes [11] state that sub-sea tunnels with sharp vertical curvature magnify a driver's feeling of “unease” after entering the tunnel.

Complex horizontal alignments are prone to more crashes than relatively straight alignments. The presence of bends is difficult to estimate by drivers, considering that the tunnel walls reduce the sightline of the road tunnel alignment [7]. According to SWOV [22], traffic safety improvements of road tunnels may be accomplished by increasing the distance from tunnel walls (by creating emergency lanes), thus limiting the longitudinal grade such that speed differences are reduced (e.g., separate lanes for heavy vehicles or directing heavy vehicles to other routes), flatter horizontal radii, and generating wide horizontal lateral offsets in horizontal bends, if they cannot be prevented. Also weaving lanes, along with entry and exit lanes, which cause driving overload and confusion, should be avoided inside the tunnel as well in the portal area. Calvi et al. [24] has shown that drivers significantly reduced their speed and increased their lateral position from the right tunnel wall while driving inside the road tunnel. Amundsen [10] showed that crash risk and horizontal curvature are related. Table 3 presents the crash rate (crashes per million vehicles·kilometers) results by horizontal radius group. Smaller radii increase the crash rate. A possible reason is that the small radii were partially designed for radial acceleration equilibrium but did not fulfill horizontal sight distance requirements. Reasonably, the smallest radius group (under 150 m) produces a significantly higher crash rate than other radius groups. The numbers in parentheses indicate the total length of the observed tunnels in kilometers. This data set represents zones 2–4.

2.6. Road surface condition effect on tunnel driver safety

Amundsen [10] showed that most tunnel crashes occur in dry surface conditions. Table 4 presents the correlation between tunnel surface conditions and road crashes inside the tunnel (including zones 2–4). Two thirds of the crashes occur anyway in dry surface conditions, and only 2.3% occur in slippery conditions other than wet, bare, or ice-covered pavement conditions. These other slippery conditions could be based on unclean surface due to oil, fuel, and other flammable and toxic liquids of dangerous goods' transport. This outcome might enable a reasonable implementation of dry surface friction characteristics in the design of tunnel alignment as opposed to a wet surface condition, which is conventional for open highways design.

Clearly, the results for all tunnels (including tunnels length of 500 m and below) shows a higher percentage of crashes in wet, snow, and

Table 3
Relationship between crash rate and horizontal radius [10].

Horizontal radius group (meters)	Crash rate*		
	Tunnel length: 500 m and above	Tunnel length under 500 m	All tunnels
Radius under 150 m	0.36 (8)	0.26 (7)	0.31 (15)
150–299 m	0.17 (26)	0.17 (12)	0.19 (38)
300–599 m	0.12 (73)	0.12 (14)	0.12 (87)
600 m and above	0.07 (570)	0.07 (52)	0.08 (622)

* Crash rate unit: crashes per million vehicles·kilometers.

Table 4
Relationship between crash percentage and pavement characteristics [10].

Pavement characteristics	Tunnel length: 500 m and above. Zones 2–4	All tunnels. Zones 2–4.
Dry	66.1%	63.7%
Wet	23.0%	23.8%
Snow or ice covered	1.4%	2.4%
Partly snow or ice covered	2.1%	3.4%
Otherwise slippery	2.3%	2.2%
Unknown	5.0%	4.5%
Total	561	739

partially snow- or ice-covered conditions, but the affect on percentage of crashes in dry surface conditions is minor. This implies indirectly that, in shorter tunnels, more crashes occur in winter weather conditions where vehicles arrive carrying water or snow.

2.7. Tunnel length impact on safety

Studies are not consistent in regards to the impact of tunnel length on safety. Few studies (Swiss and Austrian and Norwegian research) document that longer tunnels are safer [25]. According to other studies [8,7], the tunnel length negatively affects road safety because drivers tend to demonstrate diminished concentration in long tunnels. Lemeke [8] related this phenomenon to two-lane highway tunnels. The monotonous visual surroundings of tunnels may lead to orientation and concentration errors [26]. Caliendo et al. [7] developed a negative binomial regression model for nonsevere and severe crashes and found that the number of crashes along unidirectional tunnel sections increases with tunnel length in addition to other factors (AADT per lane, percentage of trucks, and the number of lanes). These results are based on unidirectional motorway tunnels data set in Italy. The authors' interpretation of free-flowing conditions was that the frequency of lane changing and overtaking maneuvers increase in longer tunnels, which means that more traffic crashes are expected.

Amundsen and Ranes [11] showed that crash rates declined with longer tunnels (in addition to wider roadways and higher traffic volumes). The reason is the resulting higher crash rates in the entrance zones compared with those in the midzones. Still, the absolute number of crashes in tunnels was higher in the midzone, i.e., roughly 50% (Table 2). The crash percentage in the tunnel midzone (zone 4) increases for freeway tunnels longer than 500 m, as shown in Table 2 (66% vs. 52%). Amundsen (2009) presented histograms of crash rates by tunnel length groups, as shown in Fig. 4. The weighted crash rates in urban dual-tube tunnels vary between 0.22 for short tunnels (100–500 m) and 0.08 for long tunnels (longer than 3.0 km. Fig. 4 presents a histogram of rural and urban dual-tube tunnels. In rural unidirectional tunnels, the crash rate decreases significantly for 500 m and longer; however, in urban tunnels, the reduction in crash rate is more gradual.

This pattern can be shown by a trend line graph (Fig. 5). The tendency exists in a moderate manner with a poor correlation. This means that tunnel length can be one of several factors that have an impact on tunnel crash rate.

3. Severity of crashes in road tunnels

Road tunnels have fewer crashes per vehicle/km than on comparable open roadways. The percentage of serious crashes in tunnels is only 1% of The Netherlands' motorways serious crashes (SWOV 2011). In Italian motorways, 4% of severe crashes occurred in motorway tunnels. If we consider tunnel crashes only, the risk of being killed in a traffic crash is twice as high in tunnels than on motorways [17]. In motorways, 3.3% of injury incidents in crashes are fatalities, whereas in road tunnels this percentage increases to 8.2%. This result is based on the Austrian highway database [17]. The percentage of serious injuries and fatal crashes in the Shanghai River crossing tunnels in China [12] is 2.4% compared with 1.2% in open roadways. Most injury-related crashes occur in zone 1 and zone 4 but did not result in fatalities as presented in Fig. 6.

Table 5 summarizes the percentage of crashes by severity types (fatal, seriously injured, and slightly injured) according to several studies. The table shows that the majority of crashes in road tunnels end up with slight injuries (83%), 11% are severe crashes, and 6% are fatal crashes. This outcome considers only the crashes' percentage (excluding the injury percentage results).

The average fatal crash percentage and serious crash percentage presented in Table 5 verify that the risk of being killed or seriously injured is higher in tunnels than in motorways [17,8]. Overall, the crash severity of most common road tunnel crashes is greater than the severity of crashes occurring on open air roads [27].

3.1. Severe crashes overview in road tunnels including fire

Although the vehicle crash risk is lower in road tunnels than it is on the remaining road network, the catastrophe potential related to tunnel fire is higher [4,9].

Most deaths in tunnel incidents result from common traffic crashes (about two-thirds). It is essential to address this as well as fire-related incidents, which are more likely to result in multiple fatalities.

Fatalities in road tunnel fires are strongly associated with HGVs; approximately 71% of fatalities in tunnel fires are in fires involving HGVs, 24% regular vehicles excluding trucks and HGVs, and 5% trucks or lorries [28].

Caliendo and Guglielmo [16] studied severe traffic crashes and fire crashes occurring in Italian motorway tunnels. Their database includes severe crashes (injury and fatal crashes) in unidirectional Italian motorways tunnels of two lanes or three lanes per direction.

A summary of total annual severe crash rates versus fire crash rates (crashes per million veh·km) are presented in Table 6. Also included in

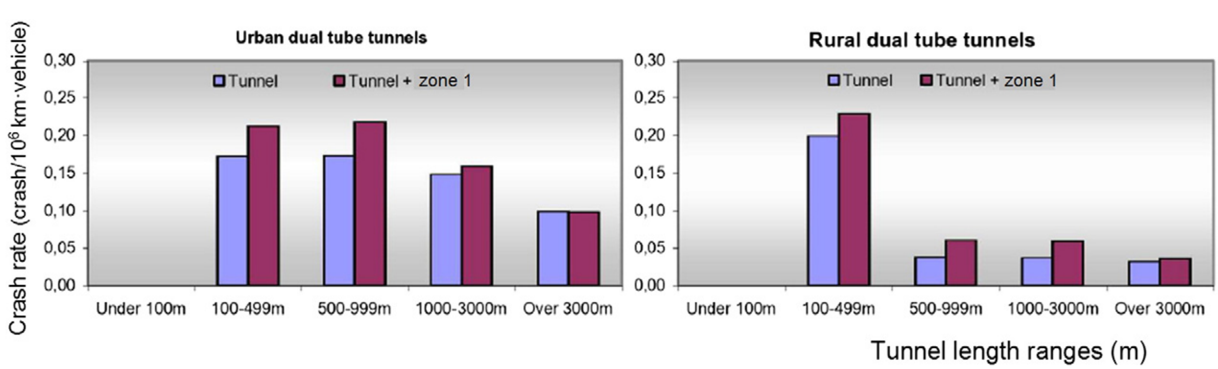


Fig. 4. Crash rates by length group in rural and urban dual-tube tunnels [10].

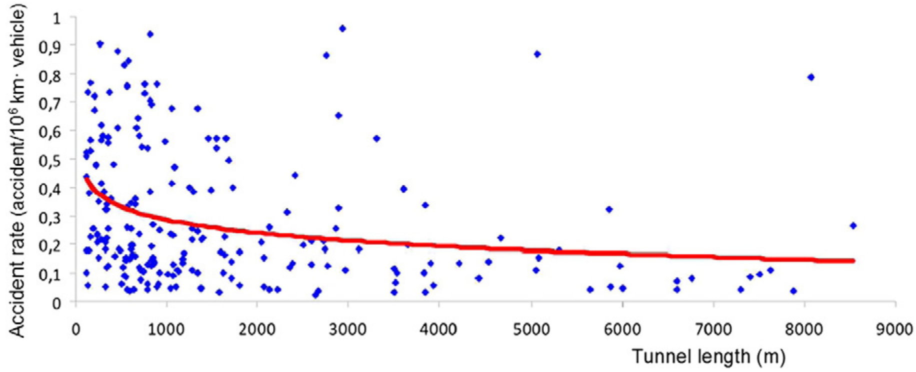


Fig. 5. Trend line of tunnel length versus crash rate excluding tunnels without crashes [10].

Table 6 are Brandt et al.'s findings of tunnels' crash rate and fire incidents' crash rates based on Norway and Switzerland databases.

Brandt et al. [19] found that the tunnel crash rate is 0.131 crashes per million vehicle kilometers, whereas the fire incident rate in the tunnel system (Norway and Switzerland) is approximately 30% of the tunnel crash rate (0.036).

Fire crashes are less frequent than traffic crashes, even if they might cause catastrophic consequences. On average, the fire crash rate was found to be 32% of the total severe crash rate.

Table 7 compares severe crash rates of the motorway tunnels (TCR) and severe crash rates of the motorways (MCR) investigated. The equivalent severe crash rate ratio between tunnels and motorways is 1.685. The average MCR is the arithmetic mean of crash rates of 17 motorways given in Table 10. The weighted average crash rate of tunnels is based on the total number of tunnels ($N = 195$). Appendix I presents the calculation of weighted average of tunnel severe crash rate and its standard deviation.

3.2. Vehicle fire and SWF incidents in road tunnels

PIARC study from 2008 documents that the most common causes of vehicle road tunnel fires are mechanical or electrical defects in vehicles [4].

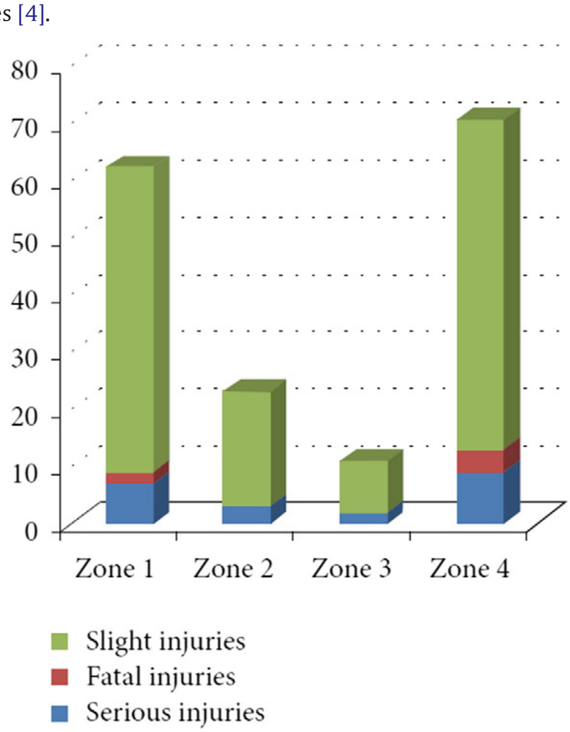


Fig. 6. Number of injuries by crash severity and tunnel zone [12].

A road tunnel fire review carried out by OECD and PIARC also indicates that technical vehicle failure is an important cause of vehicle fire in tunnels [29]. A Norwegian study from 2001 showed that only 10% of vehicle fires in road tunnels were caused by a crash [2].

Naevestad and Meyer [13] systematically examined the factors associated with vehicle fire and smoke without fire (SWF) incidents in Norwegian road tunnels based on the 2008–2011 database. These factors include vehicle type and personal injuries. According to Naevestad and Meyer [13], 21% of vehicle fires were caused by a vehicle crash on average.

3.2.1. Vehicle type associated with fire incidents [13]

The number and type of vehicles involved in tunnel fires are related to the severity of the fires; for example, 46.3% of the 135 fires involved one vehicle under 3.5 tons. In 38.1% of the fires, only one heavy vehicle was involved (above 3.5 tons); 5.2% involved one heavy vehicle and one light vehicle; 5.9% involved two light vehicles or more; and, in 4.5% of the fires, there was no information about the vehicles' involved by fire.

The causes of fires (and SWF) for vehicles under and over 3.5 tons are presented in Table 8. Technical problems are the most frequent cause of fires and incidents of SWF in heavy vehicles, while single vehicle crashes and multiple vehicle crashes (collision) are the most frequent cause of fires in vehicles weighing less than 3.5 tons.

3.2.2. Personal injuries associated with fire incidents [13]

Table 9 shows the causes of road tunnel fires, involving personal injury. The fires involving personal injury mainly are caused by single crashes and multiple vehicle crashes (collisions). The percentages related to these causes are shaded gray in Tables 8 and 9. Thus, it seems that, in the fires with reported injuries, the injuries were caused by traffic crashes and not the fires. It is likely that both fires and injuries were caused by crashes.

Single crashes caused personal injuries or deaths in 62.5% (=37.5% + 25%) of the instances, while multiple vehicle crashes (collisions) caused personal injuries or deaths in 43.8% (=12.5% + 31.3%) of the instances.

4. Additional risk measures and classifications of tunnel safety

4.1. Time to collision (TTC) risk parameter

Car following behavior (with car as the follower) in the road tunnel environment is found to be more conservative (longer headways and greater safety margins) than that in the open road environment [18]. From a microscopic behavioral perspective, traffic in tunnel expressways should be safer than on the conventional open expressways in terms of longer headway and lower rear–end collision (R–E) risks, and also longer time to collision (TTC) for the same relative speeds. This is because of the overall longer headways in the tunnel.

Table 5
Summary of crash percentage in road tunnels by crash severity.

		Fatal	Seriously injured	Slightly injured	Total	No injury crash
Amunsden [11]	Number of injuries	20	77	465	562	–
	Percentage	3.6% (2.8%)	13.7% (11.7%)	82.7% (85.5%)	100.0%	–
Amunsden [10]	Number of crashes	40	85	1005	1130	–
	Percentage	3.5%	7.5%	88.9%	100.0%	–
Z-L Ma et al. [1]	Number of crashes	5	6 (1)	24 (1)	35	81
	Percentage	14.3%	17.1%	68.6%		–
Nussbaumer [17]	Percentage	8.0% (3%)	15.0% (15%)	77.0% (2) (82%)	100.0%	–
Meng Qu [14] (3)	Number of crashes	0	45	458	503	–
	Percentage	0.0%	8.9%	91.1%	100.0%	–
Lu et al. [12]	Percentage of injuries	0.5% (4) (0.24%)	1.9% (4) (0.96%)	97.6% (98.8%)	100.0%	–
Average		5.9%	11.2%	82.9%	100.0%	

Percentages related to motorways are given in parentheses.
Assumptions:

(1) 20% of injury crashes (30 crashes) are serious and 80% are slight.
(2) Slightly injured crashes include medium injuries.
(3) Only rear–end crashes (R–E) considered.
(4) 20% of fatal and seriously injured crashes (2.4%) are fatal and 80% are seriously injured.

This conclusion, documented in Yeung and Wong [18], is consistent with the lower crash rates in road tunnels, thus suggesting that microscopic behavioral studies can serve as reliable traffic safety evaluations.

Meng and Qu [14] proposed the time-to-collision (TTC) parameter as a robust safety indicator for traffic conflict in tunnels (in addition to traffic volume and density) as proposed by Farah et al. [30], Svensson [31], Vogel [32] for open highway. This parameter measures the time that remains until a collision between two consecutive vehicles would occur if a collision is identified afterward based on speed differences [33]. Practical TTC threshold range is 2–4 s, below which there is a potential of dangerous scenario [32,34].

Mathematically, the TTC can be estimated by CCTV (closed circuit television) video cameras, as presented in Appendix II.

Meng and Qu [14] defined the exposure to traffic conflicts as the "mean sojourn time in a given time period (an hour) that the TTCs are lower than a specific threshold value (2 or 3 or 4 s)," meaning that vehicles are at risk during this period. Documenting the crash frequencies in several 1-hour periods (located in 1 km of CTE expressway tunnel section with three lanes per direction in Singapore) has resulted in the relationship between the crash frequencies and the exposure to traffic conflicts during three years for TTC threshold value, as shown in Fig. 7. Overall, TTC is a potential variable, which can describe the crash risk.

Table 6
Annual severe crash rates versus fire crash rates (crashes per million veh·km per direction) in tunnel motorways in Italy Norway and Switzerland [16,19].

Year	2006	2007	2008	2009	Average 2006–2009
Italian tunnels [16]					
Average severe (injury and fatal) crash rates	0.2045	0.1608	0.0913	0.1284	0.146
Average fire crash rates	0.0510	0.0619	0.0507	0.0433	0.057
Percentage of fire crash rates	24.9%	38.5%	55.5%	33.7%	35.4%
Norway and Switzerland [19]					
Average severe (injury and fatal) crash rates	–	–	–	–	0.131
Average fire incident rates	–	–	–	–	0.036
Percentage of fire crash rates	–	–	–	–	27.5%
Average severe crash rates					0.1385
Average fire incident rates					0.04385
Percentage of fire crash rates					31.66%

4.2. Tunnel risk and safety evaluation

Brandt et al. [19] proposed the use of Bayesian probabilistic networks (BPN) as a "hierarchical indicator based risk model." This model is widely used in the engineering sector and natural hazard management. Fig. 8 presents a basic system representation by using a BPN. This representation is valid for traffic crash risk in road tunnels. All indictors (related traffic and geometric design) cause crashes and fires. The crash itself can be the direct reason for fire. The consequences (fatalities, serious injuries, slight injuries, and damages) are caused by crashes of fire incidents.

The largest contributor to the risk in road tunnels is collisions and other types of traffic crashes. Fire incidents or engine or brake failures are also events that must be considered in road tunnel risk evaluations. Also, rare events with potential large consequences, such as events with dangerous goods transports, must be considered as well.

Xing et al. [35] set up a classification estimation for tunnel safety level (crash rate). This classification is based on a calibrated exponential model, which relates the crash rate with speed standard deviation (S.D.), and engineering judgment of the crash rate pattern according to this model. As the speed S.D. increases, the driving risk increases. Further details of the exponential model [36] and the speed and crash rate observations by which the model was calibrated is introduced in Appendix III. The tunnel safety classification is presented in Table 10.

5. Summary and conclusion

Driving in tunnels requires more attention and mental workload than open road driving. However, the closed environment, which possibly causes anxiety and psychological stress to certain drivers, might compel the typical driver to be more alert and cautious by reducing driving speed and keeping a lateral distance from tunnel walls. This can be implemented by employing lower driver perception reaction time in designing road tunnels (compared with open roads). Still, in spite of driver alertness, crashes in tunnels, which have a lower rate than crashes on open roadways, occur due to a tunnel's unusual driving environment. Furthermore, when a tunnel part in the roadway network is small, drivers in general tend to drive more carefully and reduce their speed [8,18]. The risk of crash in tunnel is reduced compared with that of the open road (approximately half); however, tunnel crash severity is higher. The risk of crash is reduced in road tunnels because the closed

Table 7
Comparison of severe crash rates between tunnels and motorways in Italy (based on data from Caliendo and Guglielmo [16]).

Motorway (i)	Number of tunnels in motorway (Wi)	Motorway annual average severe crash rate (MCR) 2006–2009*	Tunnel annual average severe crash rate (TCR) 2006–2009*	Severe crash rate ratio (tunnel/motorway)
1	1	0.1247	0.2168	1.739
2	7	0.077	0.0814	1.057
3	34	0.0934	0.1885	2.018
4	2	0.0588	0.1287	2.189
5	6	0.121	0.0832	0.688
6	30	0.1504	0.1474	0.980
7	16	0.1995	0.1792	0.898
8	27	0.0673	0.1521	2.260
9	7	0.1164	0.1155	0.992
10	12	0.1125	0.2538	2.256
11	1	0.0846	0.0968	1.144
12	17	0.0894	0.156	1.745
13	13	0.0871	0.1228	1.410
14	4	0.0216	0.1219	5.644
15	14	0.0597	0.11	1.843
16	1	0.0615	0.0734	1.193
17	3	0.0494	0.259	5.243
	Sum of tunnels	Average MCR	Weighted average: TCR	Equivalent crash rate ratio (TCR/MCR)
	N = 195	0.0926	0.1560 (arithmetic: 0.146)	1.685
		Standard deviation: MCR 0.0423	Weighted standard deviation: TCR 0.0419 (arithmetic: 0.057)	

* Crash rate units: crashes per million veh·km per direction per year.

environment of the tunnel makes typical drivers more cautious compared with driver behavior on open roadways.

Most studies consider a traffic crash in a tunnel when it causes fatalities, serious injuries, or slight injuries. A traffic crash occurs when two or more vehicles collide or when one vehicle hits an object such as tunnel wall, traffic sign, etc. (single vehicle crash). Fire or smoke without fire (SWF) incidents (due to vehicle crash) are also included in the scope of a tunnel crash. Most tunnel fires and SWF incidents are caused by vehicle crashes [13] and not by vehicle technical problems.

Safety studies indicate that crash rates are higher in tunnel entrance zones (zones 2, 3) and are lower as drivers continue inside the tunnel. The number of crashes, however, is higher along zone 4 (tunnel inner zone, which is the principal zone), as it covers longer distance.

Longer unidirectional (freeway and multilane) tunnels with higher design speed assume lower driver alertness and diminished concentration due to relatively monotonous driving [7] in spite of the tunnel's closed environment. In shorter tunnels with reduced driving speed [24], driving vigilance may be more robust without the effect of dull driving.

According to most studies [8,10,11], short tunnel lengths (which are expected to have, in general, a wet surface during rainy weather) were found to entail higher crash rates than long tunnels. In longer tunnels, drivers have already gotten used to the tunnel environment along the majority of the tunnel section.

Table 8
Causes of fires and SWF for vehicles under and over 3.5 tons, in Norway 2008–2011, N = 133 [13].

Causes	% vehicles < 3.5t	% vehicles > 3.5t	Number of fire and SWF incidents
Unclear	52%	37%	51
Technical problems	17%	49%	41
Single crashes	11%	2%	9
Multiple vehicle crashes	20%	12%	22
Total percentage	100%	100%	–
Number of fire and SWF incidents	76	57	133

Amundsen [10] observed that most tunnel crashes occur in dry surface conditions, and a negligible percentage of crashes occur in "otherwise slippery" conditions such as being due to oil and toxic liquid spillage. Overall, implementation of high-friction coefficient and low-perception reaction time in designing road tunnels [6,37,38] could have an impact on the design of horizontal and vertical alignment of road tunnels (smaller curves radii, which are derived by reduced stopping sight distance) in terms of lower construction cost without deteriorating driving safety.

The majority of crashes in road tunnels end up with slight injuries (83%): 11% are severe crashes, and 6% are fatal crashes. This outcome considers only the crashes' percentage. The risk of being killed in a traffic crash is twice as high in tunnels than on motorways [17]. About two-thirds of tunnel incidents result from common traffic crashes [28].

5.1. Fire incidents

Although vehicle crash risk is lower in road tunnels than it is on the remaining road networks, the catastrophe potential related to tunnel fire is higher [4,9]. The majority of fires do not involve personal injuries. Nonetheless, it appears that the reported injuries and deaths in the fires are caused by traffic crashes, which also typically caused fires. Hence, it

Table 9
Causes of road tunnel fires and SWF, involving personal injury in Norway, 2008–2011 (N = 131), [13].

Causes	No injury	Unclear	Minor injury	Serious injury/death	Total percentage	Number of fire and SWF incidents
Unclear	92.4%	4.5%	3%	0%	100%	66
Technical problems	95.1%	0	4.9%	0%	100%	41
Single crashes	37.5%	0%	25%	37.5%	100%	8
Multiple vehicle crashes	18.8%	37.5%	12.5%	31.3%	100%	16
Number of fire and SWF incidents	106	9	8	8	–	131

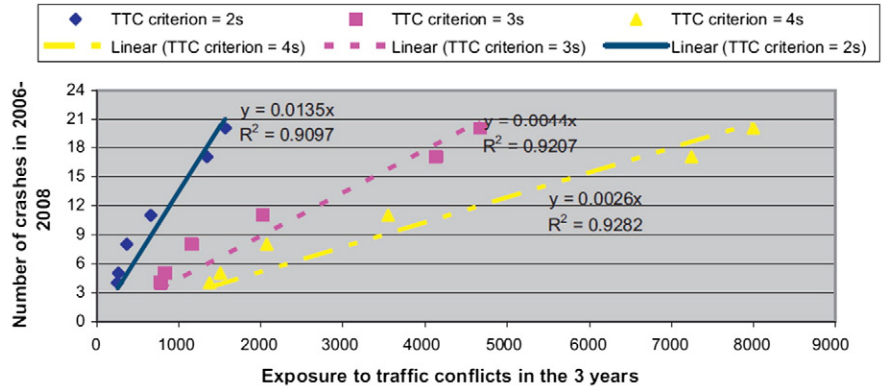


Fig. 7. Rear–end crash count traffic conflicts relationship with linear fit and 0 intercept [14].

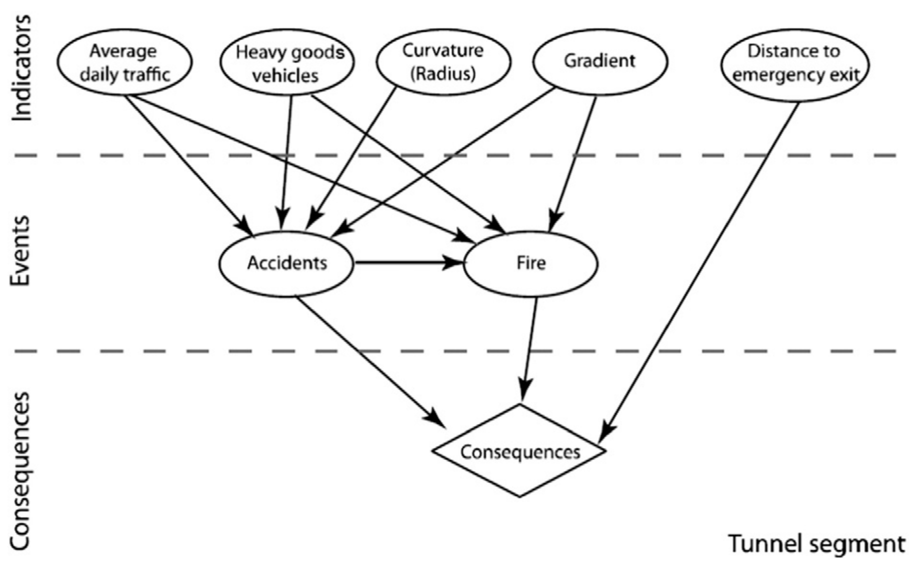


Fig. 8. Simplified illustration of a generic tunnel safety system, which includes traffic and geometric design indicators, events, and consequences by using a BPN [19].

is important to understand the causes of the fires that involved personal injuries in order to prevent these in the future.

Fire crashes are less frequent than traffic crashes. On average, the fire crash rate was found to be 32% of the total severe crash rate. According to Naevestad and Meyer [13], 21% of vehicle fires were caused by vehicle crashes on average. Approximately 71% of fatalities in tunnel fire incidents are associated with HGVs [28].

A fire also inevitably causes traffic congestion (in addition to traffic crashes and tunnel damage) as second-order cost effects. The closure of a tunnel after a fire has started may cause congestion in the highway network alternative routes and, therefore, bring about time delays. The closure time of a tunnel may take minutes, hours, or days depending on the fire size and its consequences [16]. The costs of such traffic congestion as a second-order effect due to fire incident along the road tunnel can be significant. The economic value of the lost time depends on the types of driver and passenger, the motive for going from one place to another, as well as the types of goods that are carried by HGVs (commercial vehicles).

5.2. Risk parameters and tunnel traffic safety classification

From a microscopic behavioral perspective, traffic in tunnel expressways should be safer than on conventional open expressways in terms of longer headway, lower rear–end collision risk, and also larger TTC or the same relative speeds.

Fire incidents, which are potential results of road crashes or problems with engine or brakes, also are events that must be considered in road tunnel risk evaluations.

Finally, classifications of tunnel safety levels were determined according to ranges of speed standard deviation (S.D.). As the speed S.D. increases, the driving risk increases.

5.3. Average crash rate in tunnels

Table 11 presents the average crash rate in road tunnels based on the tunnel safety research overview presented in this study. The average tunnel crash rate (0.19) corresponds with tunnel safety level II (i.e., little risk).

Table 10
Classification of tunnel safety level (based on Xing et al. [35]).

Crash rate, CR range (Crashes/million veh·km)	Speed standard deviation, S.D. (km/h)	Tunnel Safety Level	Safety level description
CR ≤ 0.15	S.D. ≤ 8.1	I	Safe: the probability of traffic crash is very small
0.15 ≤ CR ≤ 0.30	8.1 ≤ S.D. ≤ 20.635	II	Little risk: the probability of traffic crash is still small.
0.30 ≤ CR ≤ 0.50	20.635 ≤ S.D. ≤ 29.872	III	Relatively dangerous: the probability of crash is medium-large.
CR ≥ 0.50	S.D. ≥ 29.872	IV	Very dangerous: high risk of traffic crash.

Table 11
Tunnel and motorway crash rate summary based on research overview.

Average tunnel crash rate	Average tunnel severe crash rate	Average fire incident rates	Average motorway severe crash rate
0.19	0.1385	0.04385	0.0926
Percentage of average tunnel crash rate	71.87%	22.76%	–

Crash (or incident) rate unit: crashes per million veh·km per direction.

Severe crash rates in road tunnels are significant (72% percent of tunnel crashes). However, slight injury crashes make up the majority of tunnel crash percentage (83%), as presented in Table 5. The high severe crash rate in road tunnels takes tunnel length and tunnel traffic load into consideration. Most severe crashes (serious injuries and fatalities) occur in zone 4 and zone 1 (inner zone and tunnel portal), as shown graphically in the histograms of Fig. 6. There is some contradiction between the relatively low severe crash percentage results (17%, Table 5) and the relatively high severe crash rate results (Table 11 based on Tables 1, 6). Seemingly, the severe crash rate results, which are based on two sources only [16,19], are biased upward. This issue might be further investigated by additional tunnel crashes data sets.

Appendix I. Calculation clarification of weighted average of tunnel severe crash rate (Table 7)

W_i Number of tunnels in motorway i.
N total number of tunnels.

$$N = \sum_{i=1}^{17} W_i = 195$$

TCR weighted average ($\overline{X}$):

$$TCR_{W:AVG} = \overline{X} = \frac{\sum_{i=1}^{17}(W_i \cdot X_i)}{\sum_{i=1}^{17} W_i} = \frac{\sum_{i=1}^{17}(W_i \cdot X_i)}{N} = 0.15603$$

X_i: Tunnel annual average severe crash rate for motorway i.
TCR weighted standard deviation:

$$TCR_{W:SD} = \sqrt{\frac{\sum_{i=1}^{17}\left(W_i \cdot (X_i - \overline{X})^2\right)}{\sum_{i=1}^{17} W_i - 1}} = \sqrt{\frac{\sum_{i=1}^{17}\left(W_i \cdot (X_i - \overline{X})^2\right)}{N-1}} = 0.04187.$$

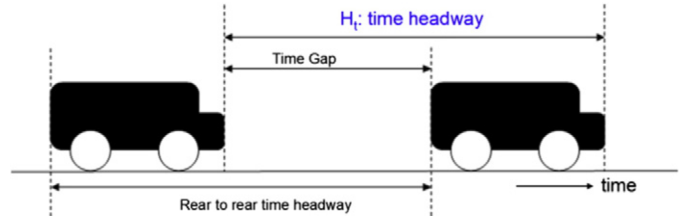
Appendix II. Time to collision (*TTC*) estimation

$TTC = \frac{H_{DG}}{V_n - V_{n-1}}$, when $V_n > V_{n-1}$.
Otherwise, there is no *TTC*.

H_{DG} distance gap between two consecutive vehicles.
V_n follower vehicle speed.
V_{n-1} leader vehicle speed.

H_{DG} $H_T \cdot V_n$- Lcar.
H_T time headway.
Lcar vehicle length (e.g. 4.5 m).

$$H_T(\text{of vehicle n}) = t_{n,L1} - t_{n\text{-}1,L1}$$



$$V_n = \frac{D}{t_{n,L2} - t_{n,L1}}$$

$t_{n,L1}$, $t_{n\text{-}1,L1}$ time stamps between two consecutive vehicles.
D distance between two reference markings.
L1 upstream reference line.
L2 downstream reference line.

The parameters D and t_n can be processed by closed circuit television (CCTV) video cameras.

Appendix III. Proposed relationship between crash rate and speed standard deviation

The data used for calibrating a model, which relates crash rate (CR) and speed standard deviation (SDD), is based on preliminary statistics of the speed and traffic crashes on seven freeways and expressways in China, as shown in the Table III.1.

Table III.1
Traffic speed, crashes, and average kilometers traveled statistics on Chinese freeways (based on Pei & Cheng [36]).

Freeway	Mean speed (km/h)	Speed standard deviation (SDD), km/h	Number of crashes per year	Annual traffic (vehicles/year)	Length (kilometers)	Crash rate (CR) crashes per million vehicles kilometer per year
Cheng-yu freeway	87.61	17.16	206	$7.7088 \cdot 10^6$	114	0.23
Shi-tai freeway	71.00	20.32	244	$3.97247 \cdot 10^6$	213.4	0.29
Guang-fu freeway	58.13	13.01	145	$42.223200 \cdot 10^6$	16	0.21
Jing-shi freeway	93.00	26.63	1065	$8.719852 \cdot 10^6$	169.6	0.45
Hu-ning freeway	79.86	14.22	194	$12.511608 \cdot 10^6$	74.08	0.21
Shen-da freeway	79.50	12.73	887	$12.334480 \cdot 10^6$	375	0.19
Jing-jin-tang freeway	88.70	22.57	140	$12.859680 \cdot 10^6$	35	0.31

The mean speed and speed standard deviation (SSD) results are based on daily average speed distribution for a specific month, augmented for 1-hour periods, 24 h per day. The mean speed is the average of the hourly speeds based on measurements of typical work-days, within 1 month. The SSD was computed accordingly by the same data set from which the mean speed was computed.

The relationship between crash rate and speed standard deviation is presented graphically in Fig. III.1. The particular model calibrated by Pei and Cheng [36] is

$$CR = 0.095839 \cdot e^{0.0553 \cdot SSD.}$$

The figure also includes the data points (CR, SDD) and the safety level classifications proposed by Xing et al. [35] for road tunnels. These safety level classifications are numerically documented in Table 10.

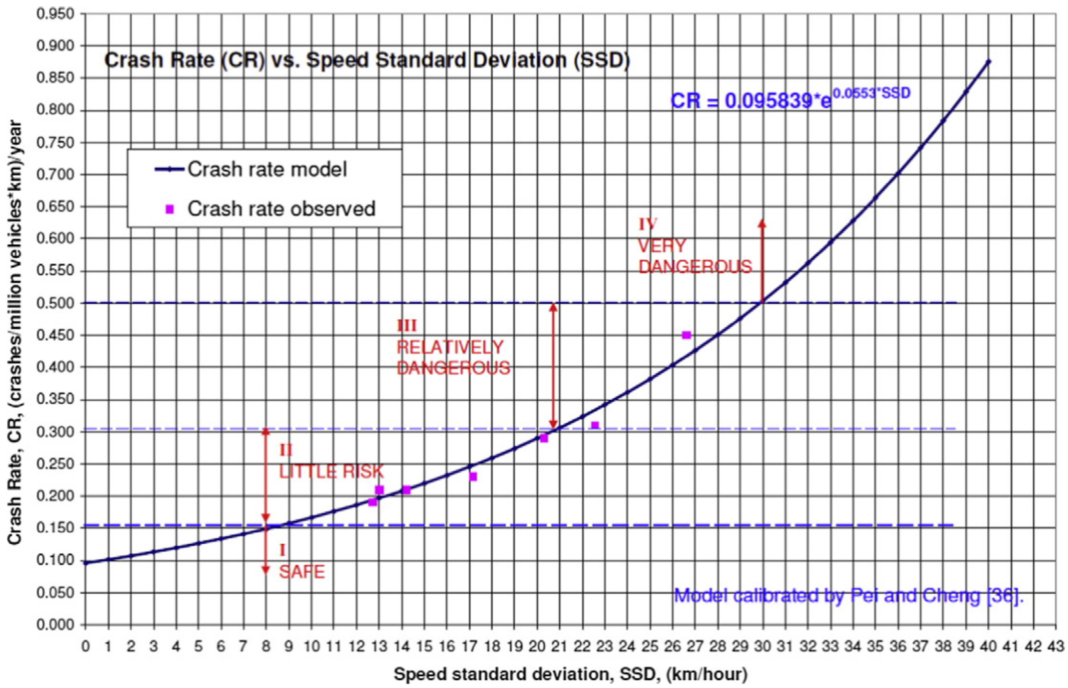


Fig. III.1 Graphical presentation of exponential model, which relates CR and SSD, data points, and safety level classifications.

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