Tunnelling and Underground Space Technology 70 (2017) 422–434

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Sight distance and horizontal curve aspects in the design of road tunnels vs. highways: Part II (trucks)

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ARTICLE INFO

Keywords:
Truck performance
Road tunnel
Tunnel safety
Design speed
Horizontal curve

ABSTRACT

The design of road tunnels is an essential component in highway geometric design. The study implements reasonable criteria for obtaining the sight distance and horizontal curve requirements of road tunnels vs. open roadways while considering a significant number of trucks in the traffic stream. This document continues a previous study assuming that the design vehicle is a passenger car. The engineering principles for considering trucks in the traffic stream are similar i.e. the use of perception-reaction time and longitudinal friction characteristics for obtaining the sight distance (and developing horizontal curve radii values for highway design) is applicable for trucks as well. However, truck performance characteristics affect the longitudinal friction parameters, side friction parameters, maximum superelevation, and the horizontal sightline offset (HSO) e.g. tunnel pavement status is irrelevant for deriving trucks' sight distance. It is concluded that the critical concept for safe horizontal curve radii in road tunnels (as in open roadways) is the stopping sight distance. The analysis has shown that the equilibrium requirement generated lower horizontal curve radii for the whole range of design speeds. The driver position (left hand or right hand curve) has a considerable impact on the design values of horizontal curve radii. The horizontal curve radii analyzed for trucks in road tunnels are considerably lower than the open roadways' radii for certain lower range of design speeds (50–80 km/h). However, the reduction percentage from open roads can be considered less significant in the higher range of design speeds (90–120 km/h). The results are useful to improve traffic safety if the design vehicle is a truck.

1. Background: tunnels vs. open highways and trucks' relevance

The design of road tunnels is an essential component in highway geometric design. The need for roadway's construction along difficult topography including overcoming natural conditions is the major motivation for selecting the road tunnel alternative solution. Road tunnels' solution minimizes the damage to the environment and land, preserves land resources, and reduces traffic congestion and air pollution.

As far as Heavy Good Vehicle (HGV) is concerned, the tunnel walls and the bounded cross-section are physical obstacles, which should be considered during the design process. Heavy good vehicles (HGV i.e. trucks) might be restricted while passing through the tunnel section including a potential inability to perform a U-turn maneuver. An additional issue to take into account while considering trucks in the design process is 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).

Further detail regarding the main differences influencing the geometric design of tunnels vs. open roadways in respect to the user (driver) and the operator viewpoint are documented in Bassan (2015), based on road tunnel deign guidelines and highway geometric design guidelines from several countries (Austroads, 2009, 2010; AASHTO, 2011; FHWA, 2009; RAA, 2008; PIARC, 2001, 2003, 2004, 2008; DMRB, 1999; Norway, 2004), and practical experience of recent road tunnel projects constructed in Israel.

1.1. The need for truck-based standards for horizontal curves

The standards for horizontal curve radius and horizontal sightline offset (HSO or lateral clearance) to provide horizontal stopping sight distance are strongly related. Typical truck volumes at which truck based standards for these elements are justified are presented in Table 1. The truck volumes are categorized according to the design speeds: truck volumes for 90 km/h or lower and truck volumes for 100 km/h or higher. The truck volumes are indicative and are based on Austroads (2002).

The truck volume thresholds increase for: (1) hilly and mountainous terrain, (2) as the design speed increases, (3) for multilane highways. When the terrain is more constrained the horizontal radii are

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http://dx.doi.org/10.1016/j.tust.2017.06.025
Received 18 October 2016; Received in revised form 10 June 2017; Accepted 19 June 2017

Table 1
Indicative truck volumes at which truck-based standards are justified for horizontal curve radius and horizontal stopping sight distance.

Design speed	Terrain (1)	Truck volume (trucks/day), both directions	
		Two lane highway	Multilane highway or Freeway
90 km/h or lower	Level	100	200
	Hilly/Rolling	100–150	300–400
	Mountainous	300–400	700–1200
100 km/h or higher	Level	200	400
	Hilly	300–400	600–800
	Mountainous	700–1200	1500–2500

conceptually lower and therefore more trucks in the traffic stream should be considered to apply truck based standards. Two lane highways are more sensitive to passing slow vehicles (and travel delays) and therefore, the truck volume thresholds are lower compared to multilane highways. Additionally, when the design speed increases to 100 km/h or higher the multilane highway will usually include more than two lanes per direction and therefore, will function with lower chance for delays for the passenger cars.

Terrain clarifications (based on HCM, 2000) for Table 1:

Level terrain: A combination of vertical and horizontal alignments that permits heavy vehicles to maintain approximately the same speed as a passenger car. It generally includes a short grade of 1–2%.
Rolling terrain: A combination of vertical and horizontal alignments causing heavy vehicles to reduce their speeds substantially below that of passenger cars but not to operate at crawl speeds for as significant amount of time. Typical grades are: until 4% for two lane highways (short or medium distances) and 3–5% for multilane highways.
Mountainous terrain: A combination of vertical and horizontal alignments causing heavy vehicles to operate at crawl speeds for significant distances or at frequent intervals. Typical grades are: 4% and above for two-lane highways, 5–7% for multilane highways, 4–6% for freeways.
(1) All terrain types are valid for road tunnel alignments.

1.2. Geometric design perspective and paper objectives

Horizontal and vertical curves may be necessary to align the tunnel with its approach roadway and to avoid obstacles on the ground. The same considerations and geometric design elements apply in determining the horizontal and vertical curve radii of road tunnels as in surface roadways: design speed, equivalent deceleration or friction factor, driver perception-reaction time, centrifugal force, superelevation, sight distance and line of sight.

The major objective of the current study is implementing reasonable criteria for obtaining the sight distance and horizontal curves radii of road tunnels vs. open roadways when trucks (i.e. heavy vehicles) traffic volume is significant in the traffic stream.

This paper continues a former study (Bassan, 2015) and is based on integrating unique criteria for trucks to the stopping sight distance and horizontal curve highway design concepts.

2. Stopping sight distance for road tunnels vs. open roadways: recommended concepts and evaluation for trucks

SSD is the distance that the driver must be able to see ahead along the roadway while traveling at or near the design speed and safely stop before reaching a stationary object. SSD can be limited by both vertical and horizontal curves. The fact that it impacts the design radius of both curves makes SSD so fundamental in the geometric design process.

The stopping sight distance has two components: (1) the distance traveled during the driver perception-reaction time and (2) the distance traveled during braking.

The stopping sight distance can be determined by using the following formula:

$$SSD = \frac{PRT}{3.6} \cdot V_d + \frac{V_d^2}{2 \cdot 3.6^2 \cdot d} \tag{1}$$

SSD – minimum stopping sight distance (m)
V_d – design speed (km/h)
d – deceleration of passenger car or trucks (m/s^2), equivalent to the longitudinal friction coefficient (f) multiplied by the acceleration of gravity (g), $d = f_T \cdot g$.
PRT – driver perception-reaction time (s).

The formula assumes level terrain. Ascending grade decreases the SSD and descending grade increases the SSD.

The two sensitive parameters in the SSD formula which are potential to be different in road tunnels vs. open roadways (as described in Bassan, 2015) are the perception reaction-time (PRT) and the coefficient of longitudinal friction (f_T).

The assessment of stopping sight distance (SSD) for road tunnel (either for passenger cars or for trucks) is performed by the following assumptions based on the extensive literature review presented:

The perception-reaction time (PRT) is 1.5 s for the design speed range of 50–80 km/h and 2.0 s for the design speed range of 90–120 km/h which possibly matches longer tunnels (freeway tunnels). The reason for these reduced values compared to open roadways (2.5 s) is drivers' awareness and vigilance along the bounded cross-section of road tunnels with narrow shoulders.
The friction coefficient values for passenger cars are based on two options for the tunnel surface situations: dry tunnel and moist tunnel, and the End of Tunnel zone as presented in Bassan (2015).

The desirable stopping sight distance for the End of Tunnel (EOT) zone shall be based on wet asphalt concrete surface friction coefficients as used for open roadways (Bassan, 2015).

The perception-reaction time values of this zone are the adopted tunnel PRT values since these zones are still located in a tunnel environment.

Fig. 1 depicts a schematic presentation of the tunnel inner zone and the EOT zones (entrance and exit).

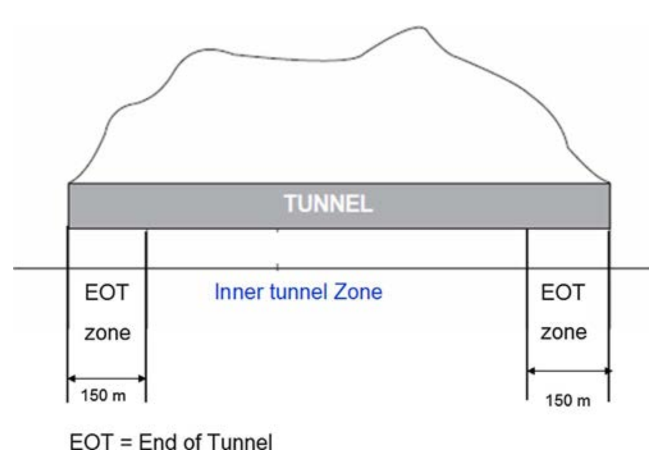


Fig. 1. Schematic presentation of tunnel inner zone and EOT zones for analyzing SSD geometric design components (not to scale).

2.1. Sight distance implementation for trucks

The sight distance design values for trucks in tunnels are similar to open roadways (Bassan, 2012) by assuming reduced perception-reaction times (PRTs) which are implemented for road tunnels and EOT zone and by considering lower equivalent friction coefficient for trucks (0.29 for 50 ≤ Vd ≤ 90 km/h, 0.28 for Vd = 100 km/h, 0.26 for Vd = 110, and 0.25 for Vd = 120). The friction coefficients for trucks are based on Austroads (2003). These values are based on minimum average deceleration achievable in braking from any speed at which the vehicle can operate: 0.29 g, and a peak deceleration achievable of 0.59 g (Austroads, 2002).

Trucks, in general, require longer stopping sight distance than passenger cars for a given design speed. The reasons for the longer truck braking distances include: (1) poor braking characteristics of empty trucks, (2) uneven load between axles which causes instability, (3) inefficient brakes of articulated trucks, and (4) assuming no antilock braking systems for the majority of truck fleet.

Hardwood et al. (FHWA, 1990) and Hardwood et al. (NCHRP 505, 2003) presented estimated deceleration rates for: (1) a truck with a conventional braking system and the worst performance driver, (2) a truck with a conventional braking system and the best performance driver, and (3) a truck with an antilock braking system. These results (assuming a wet pavement) are presented in Table 2.

Typical or experienced truck drivers would not exceed the speed limit of 100 km/h. The dry and moist tunnel friction effects are counterbalanced by the lower level functional deceleration characteristics of trucks vs. passenger cars.

The design values of friction (f_T) and deceleration (d) for trucks and passenger cars as a function of the design speed are introduced in Table 3. The truck values are identical for open roadways and for tunnels (dry, moist, and EOT zone). The recommended trucks deceleration rates (Table 3) are among the range of the trucks deceleration rates presented in Table 2 (Hardwood et al., 1990, 2003) between best performance driver and antilock braking system. This is slightly different from NCHRP 505 (Hardwood et al., 2003) principle which supports the implementation of trucks antilock braking systems for the use in highway design. This principle indicates that trucks equipped with antilock braking systems can achieve deceleration rates in controlled braking nearly identical to the rate used for passenger car drivers in AASHTO (2001) i.e. 3.4 m/s^2 or 0.346 g (NCHRP 505, 2003).

The stopping sight distance (SSD) design values for open roadways and the three tunnel surface situations are presented in Table 4and Fig. 2. Table 4 and Fig. 2 depict SSD values for trucks' drivers in tunnels and in open roadways as well. These design values are essential for horizontal curves' analysis for trucks in the following section.

In open roadways, unlike road tunnels, the higher truck driver eye height portrays an advantage to truck whereas concrete barriers generally obstruct the sightline of passenger car drivers.

The percentage differences of the trucks SSD values between open roadways and tunnels are higher at the lower range of design speeds (50–80 km/h).

Table 2
Trucks deceleration rates for use in highway design (Hardwood et al., 1990, 2003).

Vehicle speed (mph)	Vehicle speed (km/h), rounded	Deceleration rate [m/s^2]: worst performance driver	Deceleration rate [m/s^2]: best performance driver	Deceleration rate [m/s^2]: antilock brake system.
30	50	0.16 g	0.26 g	0.34 g
40	65	0.16 g	0.25 g	0.31 g
50	80	0.16 g	0.25 g	0.31 g
60	95	0.16 g	0.26 g	0.32 g
70	110	0.16 g	0.26 g	0.32 g

g = 9.81 m/s^2.

3. Horizontal curves in road tunnels based on equilibrium and stopping sight distance criteria for trucks

This section presents the required horizontal curves radii in road tunnels vs. open roadways based on equilibrium and stopping sight distance criteria for trucks. The highway design concepts which were discussed in Bassan (2015) are similar for trucks and passenger cars, however, since trucks incorporate different functional and driving characteristics such as deceleration rate, side friction coefficient, maximum superelevation, and driver position along the horizontal curve, the resulted horizontal turned out to be different and usually larger than passenger cars.

3.1. Minimum radii of horizontal curves based on equilibrium

The minimum radius or the maximum curvature has a limiting value for a given design speed as determined according to the maximum rate of superelevation (e_{max}) and the maximum side friction coefficient (f_{Rmax}):

$$R_{min} = \frac{V_d^2}{3.6^2 \cdot (g \cdot e_{max} + g \cdot f_{Rmax})} = \frac{V_d^2}{127 \cdot (e_{max} + f_{Rmax})} \quad (2)$$

R_{min} – minimum radius of horizontal curve (m)
V_d – design speed (km/h)
$g \cdot e_{max} = a_e$ = the superelevation acceleration.
$g \cdot f_{Rmax} = a_{fr}$ = the friction lateral acceleration.
$a_c = a_e + a_{fr}$ = the centripetal acceleration.
127 – conversion factor taking into acceleration of gravity $g = 9.81$ m/s^2.

3.1.1. Maximum superelevation (e_{max}) for trucks

The assumed maximum superelevation (e_{max}) for trucks (in tunnels and open roadways) is 6% which is lower than the recommended e_{max} for passenger cars. Trucks have higher center of gravity than passenger cars. The stability of high laden commercial vehicles deteriorates in a high superelevation along the circular curve with a higher rollover risk; therefore the recommended maximum superelevation for trucks is reduced for the whole span of design speeds.

3.1.2. Side friction coefficient (f_R) for trucks

The side friction coefficients for trucks are reduced values compared to the side friction coefficients adopted for passenger cars (Lamm et al., 1999; Bassan, 2013). The reduction factors range between 0.7 and 1.0, depending on the design speed. The lower range design speeds incorporate reduction factors (RFt) close to 0.7 and as the design speed increases the reduction factors become closer to 1.0. This assumption is based on the results of trucks vs. passenger cars side friction results according to Austroads (2002).

The recommended f_R values are more conservative than the AASHTO (2011) policy which permits a larger lateral acceleration on horizontal curves (NCHRP 505, 2003): 0.160 g for the design speed of 50 km/h (30 mph), 0.145 g for the design speed of 70 km/h (45 mph), and 0.130 g for the design speed of 90 km/h (55 mph). AASHTO maximum lateral acceleration requirements are based on driver comfort levels rather than the available pavement friction. The margin of safety for trucks is typically 0.18 g. This brings to a similar principle of NCHRP 505 (for longitudinal deceleration rates) that the difference between trucks and passenger cars lateral acceleration is insignificant. An NHTSA (1986) study in Chicago generated the distribution of nominal side friction demand for trucks from combined data of several horizontal curves. Fig. 3 presents a histogram of these results. The f_R value of 0.125 g received the highest frequency even though also higher lateral acceleration values such as 0.30 g were observed. MacAdam et al. (1985) found that side friction demands at various tires of a tractor-

Table 3
Tunnel and open roadways design values of equivalent deceleration (d) and longitudinal friction (f_T), and perception-reaction time (t_R) for passenger cars and trucks.

		Design speed (km/h)							
		50	60	70	80	90	100	110	120
Trucks and passenger cars									
Tunnels and End of Tunnel	PRT (s)	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
Open roadway	PRT (s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Trucks									
Tunnels and open roadway	f_T	0.29	0.29	0.29	0.29	0.29	0.28	0.26	0.25
	d (m/s^2)	2.845	2.845	2.845	2.845	2.845	2.747	2.551	2.453
Passenger cars									
Dry tunnel	f_T	0.7	0.7	0.675	0.650	0.625	0.600	0.575	0.55
	d (m/s^2)	6.867	6.867	6.622	6.377	6.131	5.886	5.641	5.396
Moist tunnel	f_T	0.569	0.569	0.552	0.534	0.516	0.499	0.481	0.464
	d (m/s^2)	5.584	5.584	5.411	5.238	5.066	4.893	4.720	4.548
End of tunnel and open roadway (wet)	f_T	0.438	0.438	0.428	0.418	0.408	0.398	0.387	0.377
	d (m/s^2)	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.7

f_T – longitudinal friction coefficient; d – equivalent deceleration.

trailer truck vary widely, as illustrated in Fig. 4. According to this study the maximum side friction factor for trucks is approximately 0.09, for travel speed 77 km/h.

Based on observed data from the U.S. it is apparent the recommended lateral acceleration in this study are somehow more conservative than NHTSA (1986) results but slightly higher than MacAdam et al. (1985) results (basically based on Germany, Lamm et al., 1999; Bassan, 2013). The differences from NHTSA (1986) are rational, taking into account that experienced truck drivers would not exceed the speed limit of 100 km/h.

The recommended side friction coefficients for trucks are not dependent on the tunnel surface (moist or dry) or the tunnel zone (inner tunnel zone or EOT zone). The truck side friction (f_R) coefficients are always inferior than passenger cars' side friction coefficients as presented in Table 5. These values are valid for tunnel as well as for open roadways. Also included in Table 5 are design values of the horizontal curve radii (R_{Hmin}) based on equilibrium (Eq. (2)), and the recommended superlevation for trucks. Table 5 also consists of the side friction coefficients and horizontal curve radii for passenger cars based on Bassan (2015).

3.2. Minimum radii of horizontal curves (R_{HSD}) based on sight distance considerations

The tunnel walls are actually a full obstruction to the sight line along the horizontal curve. An approximate calculation of the minimum horizontal sight offset (HSO) required between the centerline of the inside lane and the tunnel wall can be performed as a function of the sight distance, and the radius of horizontal curve (R_{HSD}).

Fig. 5 presents a typical sketch of the horizontal sight distance (SD) calculation.

The derived formula for the horizontal offset between the middle of sightline and the centerline of the inside lane (HSO) as a function of stopping sight distance (SSD symbolized as SD in Fig. 5) and the horizontal curve radius (R_{HSD}) is presented below:

$$HSO = (SSD)^2/(8\cdot R_{HSD}) \quad (3)$$

HSO – free horizontal offset between the middle of sightline and the centerline of the inside lane (m).
R_{HSD} – the horizontal curve radius along the centerline of inside lane (m), written as R in Fig. 5.
SSD – stopping sight distance along the sightline (m), written as SD in Fig. 5.

3.2.1. Location of the truck drivers' inside lane axis for determining the horizontal radii based on sight distance considerations

The location of the inside lane axis for determining the horizontal radii depends on the truck driver location with respect to the tunnel wall.

If the horizontal curve maneuver is left handed (left arc), the driver

Table 4
Tunnel and open roadways stopping sight distance (SSD) for trucks and passenger cars, meters.

SSD (m)	Design speed (km/h)							
	50	60	70	80	90	100	110	120
Trucks								
Tunnels, EOT	55	75	100	125	160	200	245	295
% reduction from open road (absolute reduction)*	78.6%(15)	78.9%(20)	83.3%(20)	86.2% (20)	91.4% (15)	95.2% (10)	94.2% (15)	95.2% (15)
Open roadway	70	95	120	145	175	210	260	310
Passenger cars								
Dry tunnel	35	50	60	75	105	125	145	170
% reduction from open road (absolute reduction)*	41.7% (25)	33.3% (25)	36.8% (35)	37.5% (45)	27.6% (40)	26.5% (45)	27.5% (55)	27.7% (65)
Moist tunnel	40	50	65	85	115	135	165	190
% reduction from open road (absolute reduction)*	33.3% (20)	33.3% (25)	31.6% (30)	29.2% (35)	20.7% (30)	20.6% (35)	17.5% (35)	19.1% (45)
End of tunnel (EOT)	45	60	75	95	130	155	185	220
% reduction from open road (absolute reduction)*	25.0% (15)	20.0% (15)	21.1% (20)	20.8% (25)	10.3% (15)	8.8% (15)	7.5% (15)	6.4% (15)
Open roadway	60	75	95	120	145	170	200	235

* The numbers in parentheses signify absolute reduction of SSD design values from open roadways.

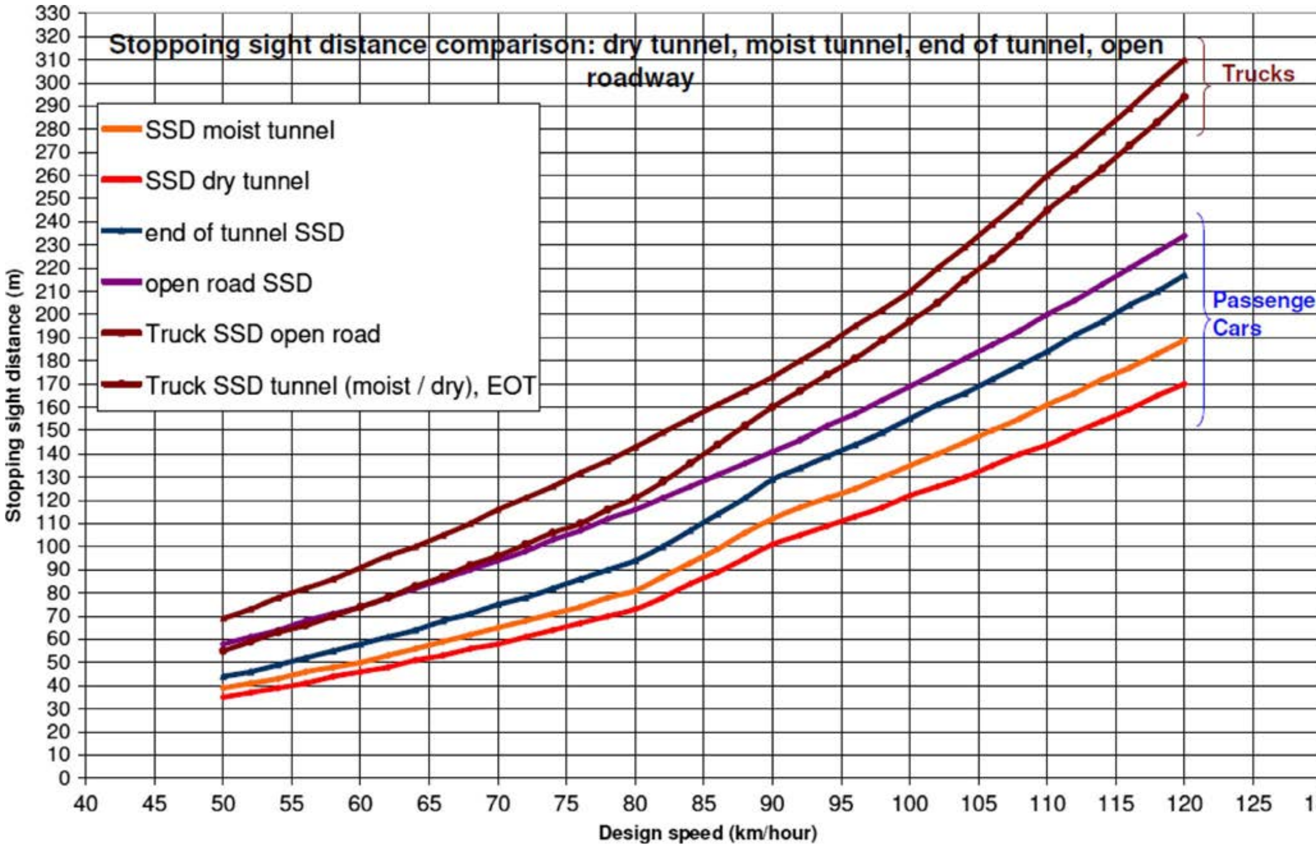


Fig. 2. Stopping sight distance for tunnels and for open roadways: trucks and passenger cars.

position is closer to the tunnel wall (left hand side of the centerline of the inside line).

If the horizontal curve maneuver is right handed (right arc), the driver position is more distant from the tunnel wall (left hand side of the centerline of the inside line).

3.2.1.1. Passenger car driver location. Referring to PIARC (2004) guidelines for designing the tunnel cross section, the assumption for passenger cars is that in the case of left hand curve the driver is located 1.5 m from the inside traffic lane edge, adjacent to the raised shoulder. Symmetrically, in the case of right hand curve the driver is located 2.1 m from the inside traffic lane edge, adjacent to the raised shoulder.

In most international geometric design guidelines the assumption is that the driver is located in the centerline of inside lane (Fig. 5) either for left hand curve maneuver or for right hand curve maneuver.

3.2.1.2. Truck car driver location. The assumption for trucks' drivers is that driver location is closer to the raised shoulder due to its lateral

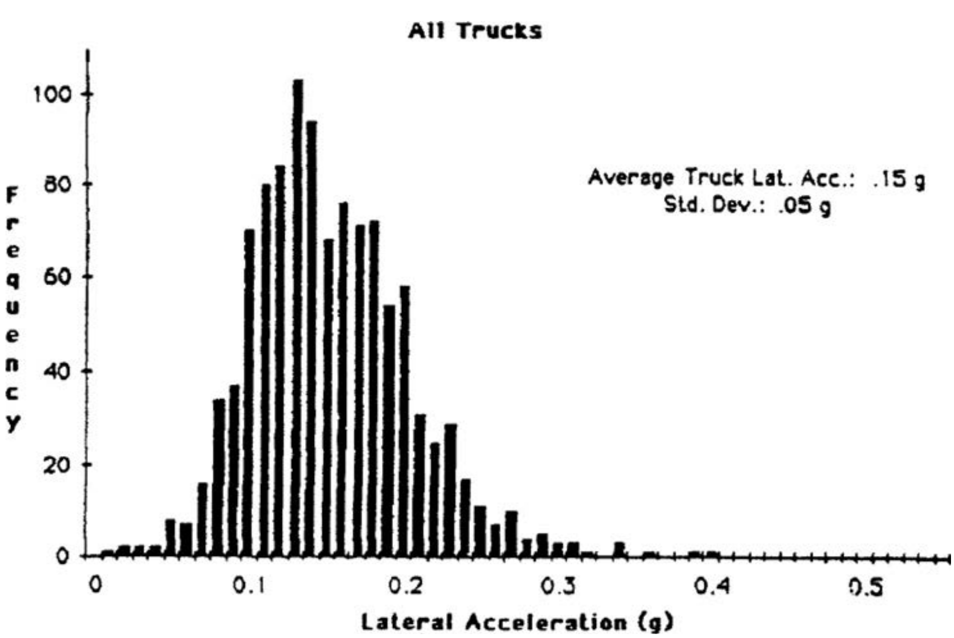


Fig. 3. Nominal lateral acceleration of trucks based on their observed speeds on selected horizontal curves in the Chicago area (NHTSA, 1986; Hardwood et al., 2003).

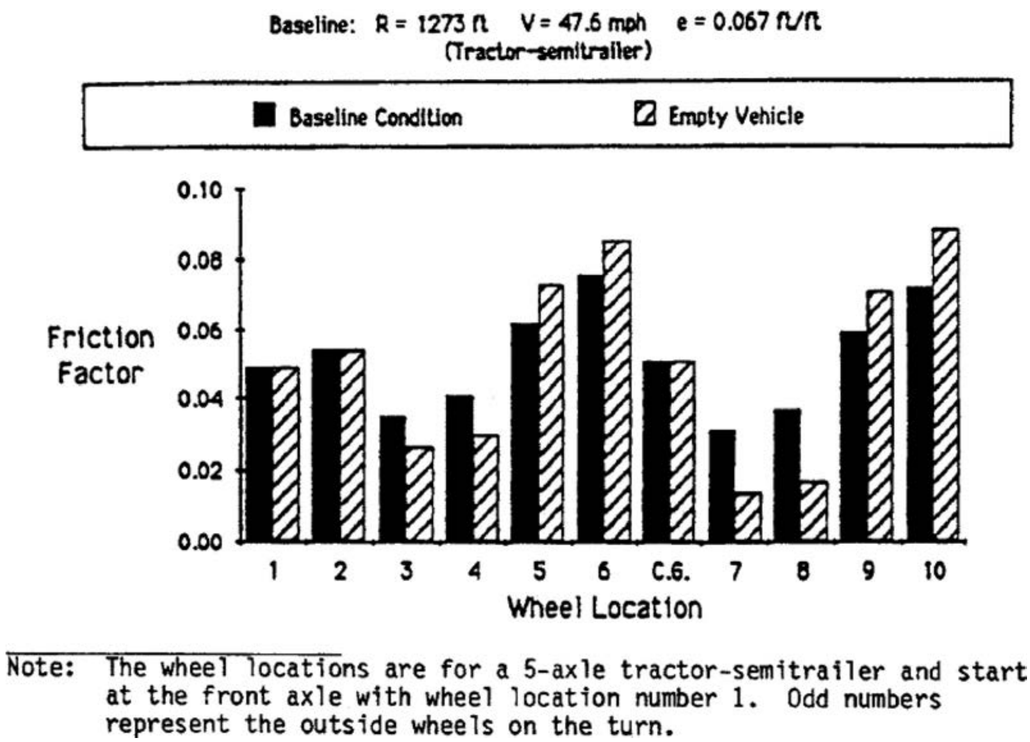


Fig. 4. Example of variation in side friction demand between wheels of a truck on a horizontal curve (MacAdam et al., 1985; Hardwood et al., 2003).

dimensions. The difference is 0.3 m. Therefore, in the case of left hand curve the truck driver is located 1.2 m from the inside traffic lane edge, adjacent to the raised shoulder. Symmetrically, in the case of right hand curve the truck driver is located 1.8 m from the inside traffic lane edge, adjacent to the raised shoulder.

Fig. 6 presents a typical traffic envelope of a directional road tunnel with 2 lanes per direction. The cross section includes a 1.10 m raised shoulder which can function as an escape footpath during emergency situation but enables additional width for vehicles usage (maintenance, etc.). The width of each traffic lane is 3.6 m. The distance between the edge of traffic lane and the tunnel wall is 1.4 m. This distance which consists of the width of the raised shoulder plus 30 cm color signing, is a vital input for the HSO analysis options in order to finalize the horizontal curve radii based on stopping sight distance considerations.

Table 6 presents three alternatives of the truck driver location and their resultant HSO: centerline of inside lane, left hand curve, and right hand curve.

Fig. 7 presents schematically the sightline of a truck driver along a left hand horizontal curve in road tunnels. The length of the sightline (LS1) which needs to coincide with the SSD length requirements, corresponds to HSO = 2.90 m.

Appendix A presents a graphical example for a right hand horizontal curve when the truck driver (or the passenger car driver) is positioned in the centerline of the inside lane (V_d = 100 km/h). The line AB is the stopping sight distance (SSD) which determines the minimum horizontal radii based on sight distance considerations for trucks or passenger car. The truck design values (AB and horizontal radii) are significantly higher.

Table 5
Design values of tunnels and open roadways horizontal curve for trucks (emax, f_R, R_{Hmin}) based on equilibrium.

		Design speed (km/h)							
		50	60	70	80	90	100	110	120
Trucks	e_{max}	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Tunnels & Open roadways	RFt	0.70	0.743	0.786	0.829	0.871	0.914	0.957	1.0
	f_{Rt}	0.112	0.109	0.106	0.103	0.100	0.097	0.095	0.094
	R_{Hmin}	115	170	235	310	400	500	615	740
*Passenger cars**									
Tunnels	e_{max}	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08
Dry tunnel	f_R	0.256	0.235	0.213	0.193	0.176	0.161	0.148	0.137
	R_{Hmin}	60	90	130	180	250	330	420	525
Moist tunnel	f_R	0.208	0.191	0.174	0.159	0.145	0.134	0.124	0.115
	R_{Hmin}	70	105	150	205	275	355	450	555
End of tunnel or open roadway (wet)	f_R	0.160	0.147	0.135	0.124	0.115	0.107	0.100	0.094
	R_{Hmin}	80	120	175	240	330	425	535	655

RFt- side friction reduction factor for trucks based on Austroads (2002).
f_{Rt} – side friction coefficient for trucks.
f_R – side friction coefficient for passenger cars.
R_{Hmin} – minimum horizontal curve radii design values based on equilibrium (m).
* Based on Bassan (2015).

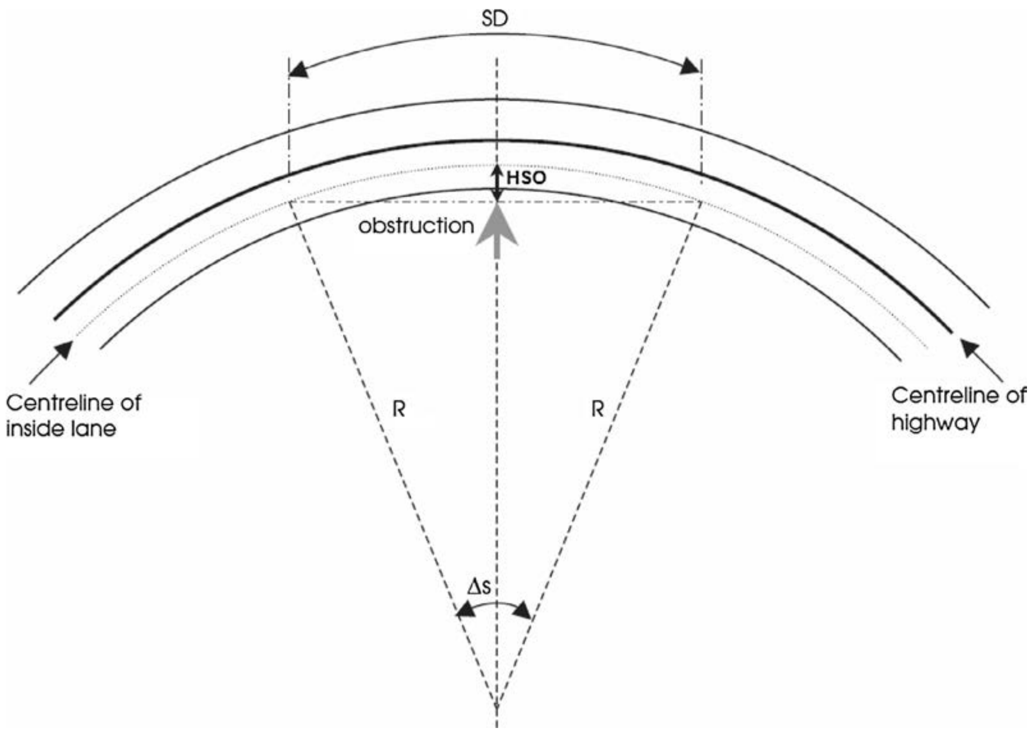


Fig. 5. Horizontal curve SD geometric configuration (Based on O'Flaherty, 1986).

3.2.2. *Design values of road tunnels horizontal curve radii for trucks based on sight distance requirements*

The minimum horizontal curve radii for road tunnels were computed for the three alternatives of the truck driver location and their resultant HSO (Table 6). Table 7 presents the minimum radii for horizontal curve in road tunnels based on sight distance considerations for trucks. Also included in Table 7 are the computed values of horizontal radii for passenger cars in tunnels (moist or dry) based on Bassan (2015). The minimum horizontal radii for trucks are not dependent on the tunnel surface (dry, moist) because the truck sight distance values are derived by the lower level functional deceleration characteristics comparing to passenger cars. The two last rows of Table 7 refer to open roadways with HSO = 3.2 m for comparison purpose. The difference between the horizontal radii of trucks vs. passenger cars is the PRT component of the stopping sight distance.

The values presented are rounded values (with 5 m accuracy). The truck horizontal radii are larger than the passenger cars horizontal radii for tunnels and for open roadways. For trucks, the critical requirement

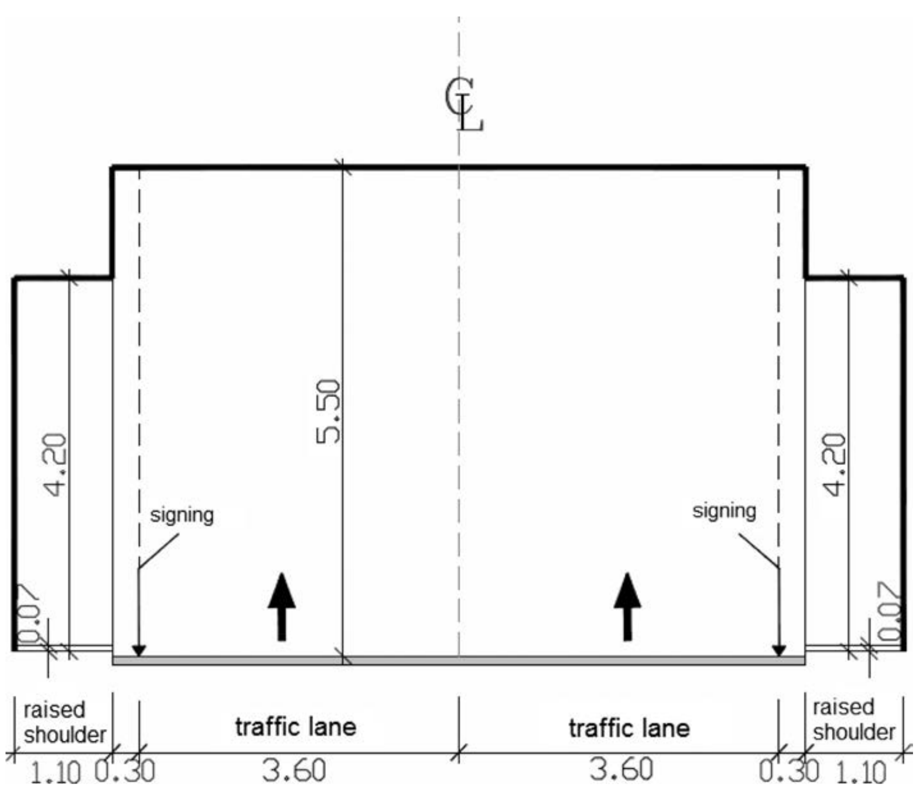


Fig. 6. Typical traffic envelope for directional rural road tunnel with two lanes per direction (Bassan, 2015).

Table 6
HSO design values according to the truck driver position with respect to the inside lane centerline.

Truck Driver position with respect to the edge of inside lane adjacent to raised shoulder (m)	Average distance between sightline and edge of raised shoulder in the middle of sightline (m)	Horizontal sight offset between the middle of sightline and the tunnel wall, HSO (m)
Left hand horizontal curve: 1.2 m	(1.2 + 1.8)/2 = 1.50 m	1.50 + 1.4 = 2.90 m
Right hand horizontal curve: 2.4 m	(2.4 + 1.8)/2 = 2.10 m	2.10 + 1.4 = 3.50 m
Left hand or right hand horizontal curve assuming the driver is positioned in the centerline of inside lane: 1.8 m	(1.8 + 1.8)/2 = 1.8 m	1.80 + 1.4 = 3.2 m

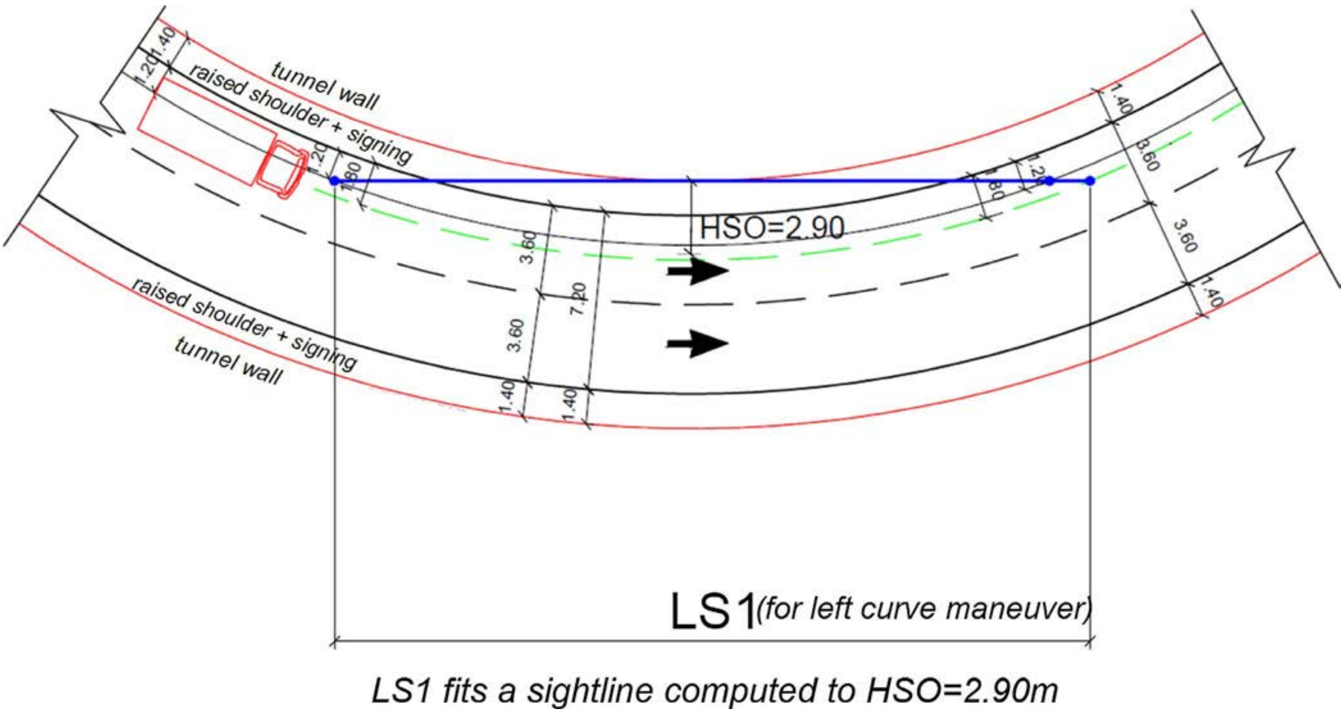


Fig. 7. Schematic truck driver sightline sketch for left-hand horizontal curve in road tunnels.

for safe horizontal curve radii is the stopping sight distance. The only case for which the equilibrium requirement governs (Eq. (2), Table 5) is when the design speed is 50 km/h and HSO suits right hand horizontal curve (R_{Hmin} = 115 m).

Similarly to passenger cars the following insights are valid for trucks as well:

(1) The driver position (left hand or right hand curve) has a considerable impact on the design values of horizontal curve radii. The difference increases as the design speed increases.
(2) The horizontal curve radii calculated for open roadways are relatively higher than the road tunnels radii.

However, the tunnel pavement status characteristics have no effect on the stopping sight distance and on the horizontal curve radii for trucks. Still the PRT component (driver behavior component), which is different for trucks in tunnels vs. open roadways, makes some difference in the horizontal radii especially in the lower range of design speeds. This outcome still provides a moderate advantage for trucks in the possibility of shorter tunnel construction length (i.e. lower construction cost) and flexibility in tunnel construction, due to ground constraints and a potential reduced damage to the ground water and aquifers.

3.2.3. "End of tunnel" (EOT) design values of horizontal curve radii based on sight distance requirements

In general a considerable horizontal curve alignment is not recommended along the tunnel portal and the "end of tunnel" (EOT) zone (until 150 m from the tunnel portals inside the tunnel). If environment and topography limitations require a considerable horizontal curve alignment along the EOT zones then the desirable minimum horizontal curve radii will be adjusted to wet pavement conditions and tunnel perception reaction time.

Horizontal curves for trucks in tunnels and in EOT zone are identical. This insight valid either for horizontal curves which are based on equilibrium requirement or for horizontal curves which are based on stopping sight distance requirement.

4. Crash relevance for trucks (HGVs)

Crash events become a major issue for safety concerns in road tunnels' design, particularly when the passage of Heavy Good Vehicles (HGVs) through the tunnel is not prohibited.

An analysis based on approximately 60 tunnels of eleven expressways in Guangdong Province in China (Zhong et al., 2016), the proportion of vehicle types of traffic crashes in tunnels was distributed as follows: passenger car under seven seats: 55%, big truck and trailer counts: 30%, medium bus and large bus over seven seats: 10%, and medium sized trucks: 5%. This information shows that the percentage tunnel crashes involving trucks is 35%.

The involvement of heavy goods vehicles (HGVs) is typically correlated with high crash severity (Lu et al., 2016). Heavy goods vehicles (HGVs) are strongly associated with fatalities in road tunnel fires. This is associated to the enclosed structure of the tunnel. Approximately 71% of fatalities in tunnel fires are in fires involving HGVs (heavy good vehicles), 24%: regular vehicles excluding trucks and HGV, and 5%:

Table 7
Minimum horizontal curve radii for road tunnels based on sight distance requirement of trucks vs. passenger cars.

Tunnel	Design speed (km/h)							
	50	60	70	80	90	100	110	120
Trucks: Left hand or right hand horizontal curve (HSO = 3.2 m)								
	120	**220**	**395**	**610**	**1000**	**1565**	**2345**	**3400**
Passenger cars: Left hand or right hand horizontal curve (HSO = 3.2 m)								
Dry tunnel	50* (60)	100	145	220	435	610	825	1130
Moist tunnel	65* (70)	100* (105)	165	285	520	715	1065	1410
Trucks: Left hand horizontal curve (HSO = 2.90 m)								
	130	**245**	**435**	**675**	**1105**	**1725**	**2590**	**3755**
Passenger cars: Left hand horizontal curve (HSO = 3.05 m)								
Dry tunnel	50* (60)	105	150	235	455	640	865	1185
Moist tunnel	70*	105*	175	300	545	750	1120	1480
Trucks: Right hand horizontal curve (HSO = 3.50 m)								
	110* (115)	**205**	**360**	**560**	**915**	**1430**	**2145**	**3110**
Passenger cars: Right hand horizontal curve (HSO = 3.35 m)								
Dry tunnel	50* (60)	95	135	210	415	585	785	1080
Moist tunnel	60* (70)	95* (105)	160	270	495	680	1020	1350
Trucks: Open roadways (HSO = 3.2)								
	195	**355**	**565**	**825**	**1200**	**1725**	**2645**	**3755**
Passenger cars: Open roadways (HSO = 3.2)								
	145	220	355	565	825	1130	1565	2160

Remarks: The values assigned by asterisk (*) are lower or identical to the minimum horizontal radii for road tunnels based on equilibrium considerations. For design needs, the radii in parentheses (which are based on equilibrium considerations) should be applied.
If the tunnel is a two-lane highway (one tube for both directions) then the critical alternative is right hand horizontal curve.
Bolded values of horizontal curve radii refer to trucks.

trucks or lorries (Beard, 2010). Typical example is the Gotthart tunnel catastrophe in Switzerland (October 2001) where HGV vehicle swerved into the opposite lane erroneously and collided another truck and therefore both trucks caught fire.

A summary of total annual severe crash rates vs. fire accident rates (crashes per million veh·km) is presented in Table 8 (Bassan, 2016). Also included in Table 8 Brandt et al.'s findings of tunnels' crash rate and fire incidents' accident rates based on Norway and Switzerland database.

Brandt et al. (2012) 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, but they have a potential to cause catastrophic consequences. In average the fire crash rate was found to be 32% of the total severe crash rate.

Brandt et al. proposed the use of Bayesian probabilistic networks (BPN) as a "hierarchical indicator based risk model". 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 interrelationship between HGVs, accidents (crashes), and fire is prominent.

The crash itself can be the direct reason for fire and the fire occurrence can be a direct reason of HGV even without a crash (i.e. a loss of control due to sight distance restriction in horizontal curves).

5. Summary and conclusion

The study implements reasonable criteria for obtaining the sight distance and horizontal curve requirements of road tunnels vs. open roadways while considering a significant number of trucks in the traffic stream. This document continues a previous study (Bassan, 2015) assuming that the design vehicle is a passenger car. The engineering principles for considering trucks in the traffic stream are similar i.e. the use of perception-reaction time and longitudinal friction characteristics for obtaining the sight distance (and developing horizontal curve radii values for highway design) is applicable for trucks as well.

However, truck performance characteristics affect the longitudinal friction parameters, side friction parameters, maximum superelevation, and the horizontal sightline offset (HSO). The tunnel pavement status **is irrelevant** for obtaining trucks' stopping sight distance.

Fig. 9 presents a graphical summary of the trucks and passenger car horizontal curve radii analysis for moist and dry tunnels according to the equilibrium and stopping sight distance criteria, and analyzing three alternatives of driver's position.

Fig. 10 presents a graphical histogram that summarizes the horizontal curve radii outcomes for trucks and passenger cars along road tunnel assuming that the driver is positioned in the centerline of inside lane (HSO = 3.2 m). Also included in Fig. 10 are the truck horizontal curves results along open roads.

It is concluded that the critical concept for safe horizontal curve radii in road tunnels (as in open roadways) for trucks (as documented previously for passenger cars) is the stopping sight distance. The analysis for trucks has shown that the equilibrium requirement generated significantly lower horizontal curve radii for the whole range of design speeds.

The difference between the horizontal radii of trucks in tunnels vs. open roads is derived by the PRT component of the stopping sight distance, especially in the lower range of design speeds.

The truck horizontal radii are larger than the passenger cars horizontal radii for tunnels and for open roadways. Similarly to passenger cars the following insights are valid for trucks as well:

Table 8
Annual severe crash rates vs. fire crash rates (crashes per million veh·km per direction) in tunnel motorways in Italy Norway and Switzerland (Caliendo and De Guglielmo, 2012; Brandt et al., 2012; Bassan, 2016).

Year	2006	2007	2008	2009	Average 2006–2009
Italian tunnels (Caliendo and De Guglielmo, 2012)					
Average severe (injury and fatal) crash rates	0.2045	0.1608	0.0913	0.1284	0.146
Average fire accident rates	0.0510	0.0619	0.0507	0.0433	0.057
Percentage of fire accident rates	24.9%	38.5%	55.5%	33.7%	35.4%
Norway and Switzerland (Brandt et al. 2012)					
Average severe (injury and fatal) crash rates	–	–	–	–	0.131
Average fire incident rates	–	–	–	–	0.036
Percentage of fire accident rates	–	–	–	–	27.5%
Average severe crash rates					0.1385
Average fire incident rates					0.04385
Percentage of fire accident rates					31.66%

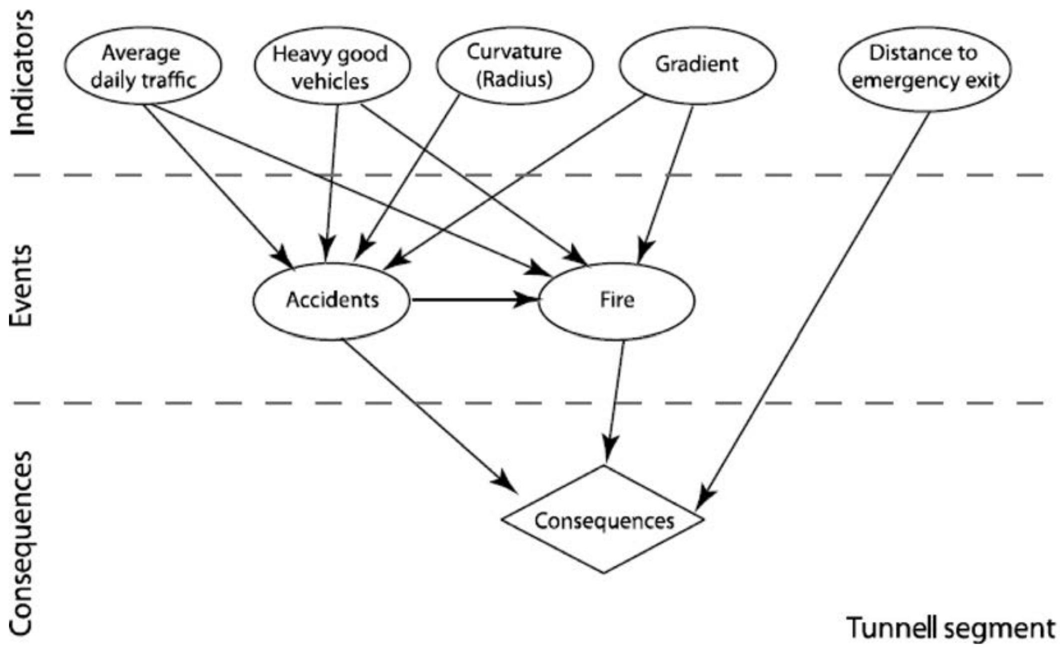


Fig. 8. Simplified illustration of a generic tunnel safety system representation which includes traffic and geometric design indicators, events, and consequences by using a BPN (Brandt et al., 2012).

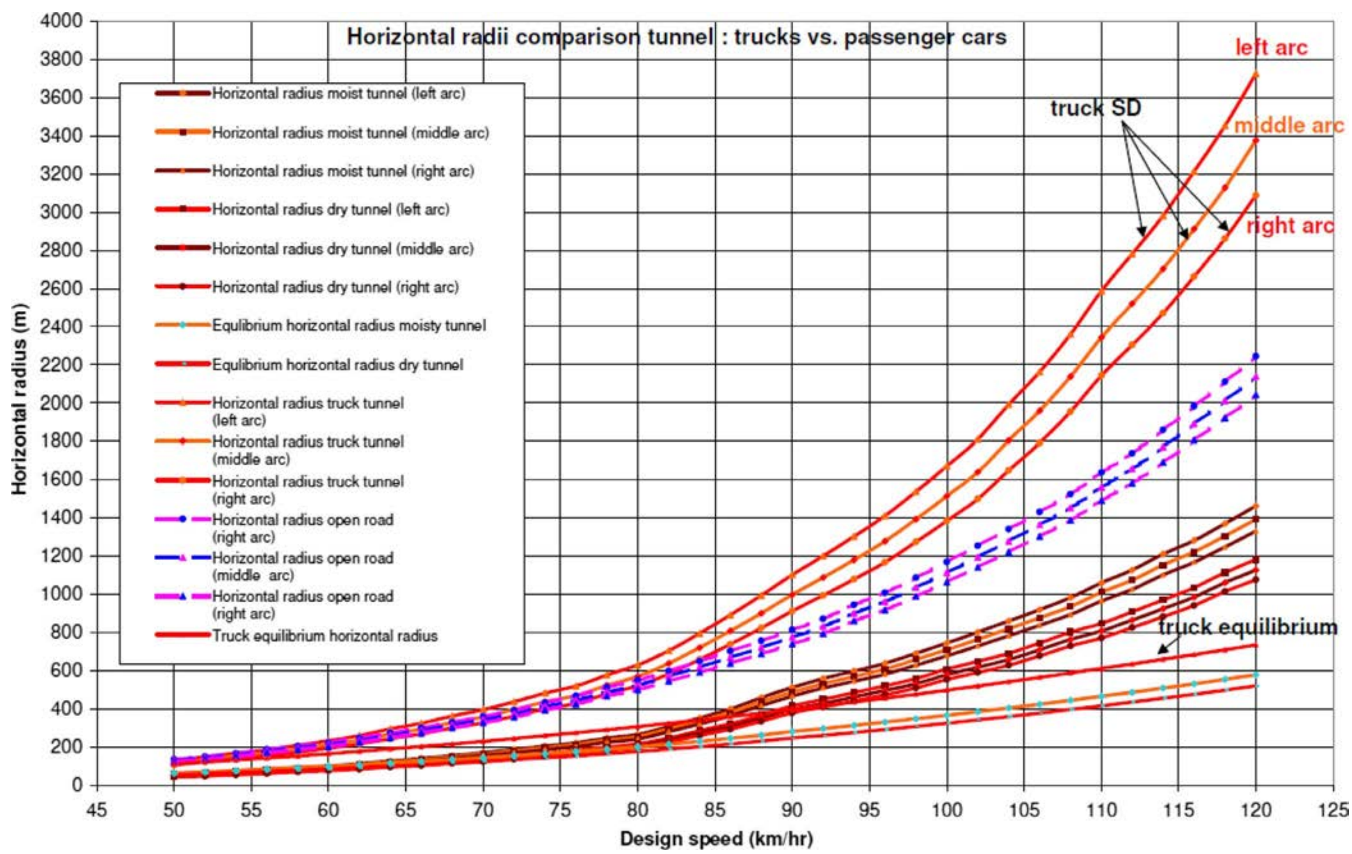


Fig. 9. Graphical presentation of horizontal curve radii analysis for trucks and passenger cars in road tunnels and open roads including left, middle, and right arcs.

(1) The driver position (left-hand or right-hand curve) has a considerable impact on the design values of horizontal curve radii.
(2) The trucks' horizontal curve radii calculated for open roadways are relatively higher than the road tunnels radii.

The results provide a reasonable advantage for trucks in the possibility of shorter tunnel construction length (i.e. lower construction cost) and flexibility in tunnel construction, due to ground constraints and a potentially reduced damage to the ground water and aquifers.

The results documented are therefore, useful to improve traffic safety and design of horizontal curves along road tunnel alignments if the design vehicle is a truck.

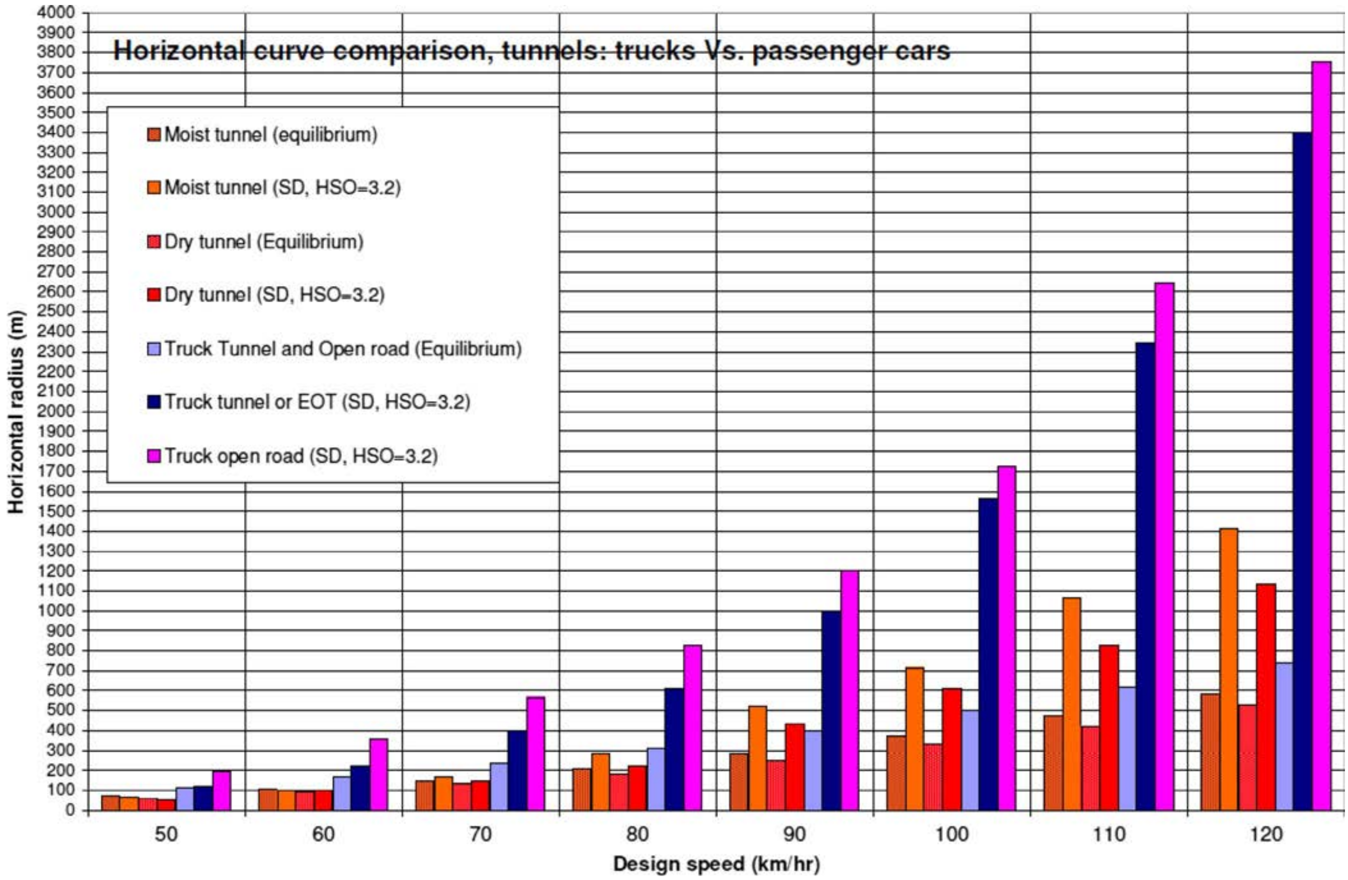
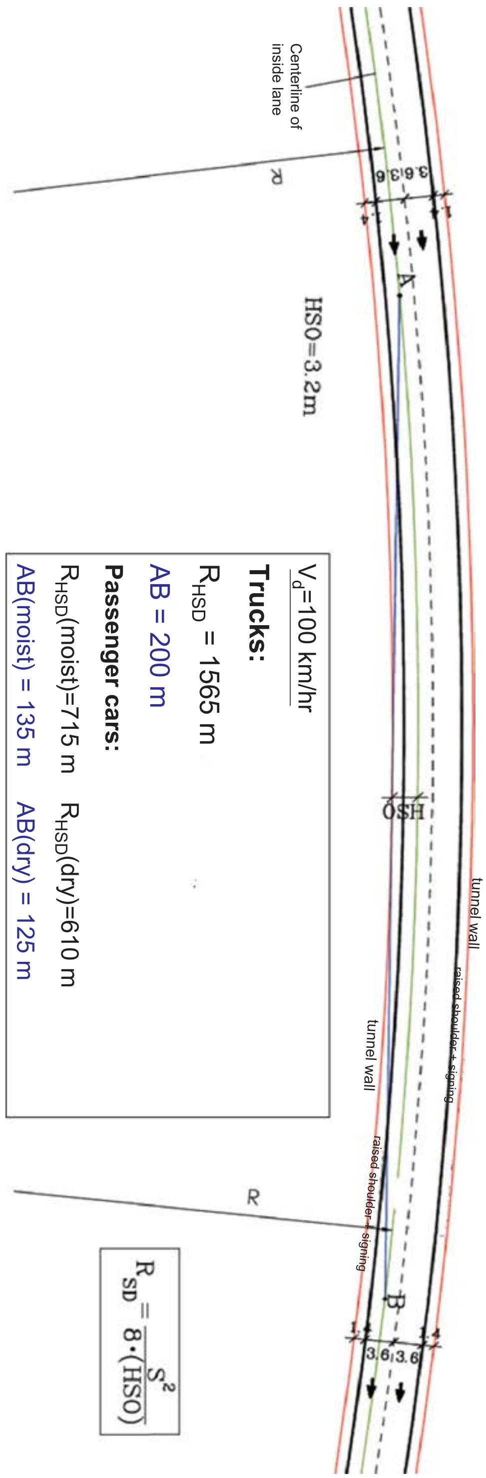


Fig. 10. Histogram summary of horizontal curves radii analysis of trucks and passenger cars in road tunnels (equilibrium concept and SD concept with HSO = 3.2 m).

Appendix A

Graphical example for a right hand horizontal curve when the truck driver or passenger car driver is positioned in the centerline of the inside lane.



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