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

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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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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:

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

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).

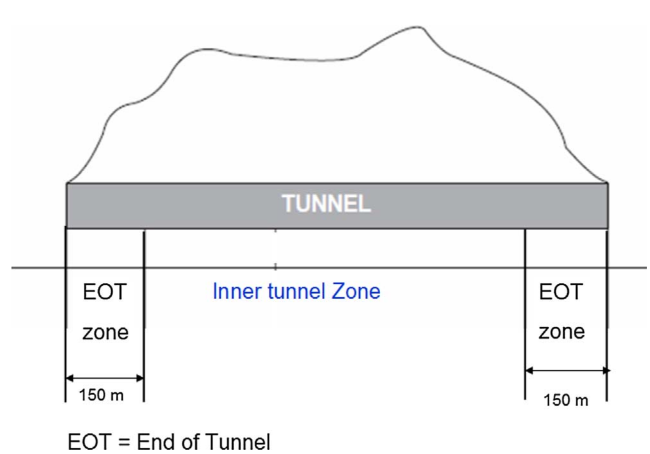

Fig. 1. Schematic presentation of tunnel inner zone and EOT zones for analyzing SSD geometric design components (not to scale).