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Overview of traffic safety aspects and design in road tunnels☆

Shy Bassan

Amy Metom Engineers. Tel Aviv., Israel

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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.

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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.

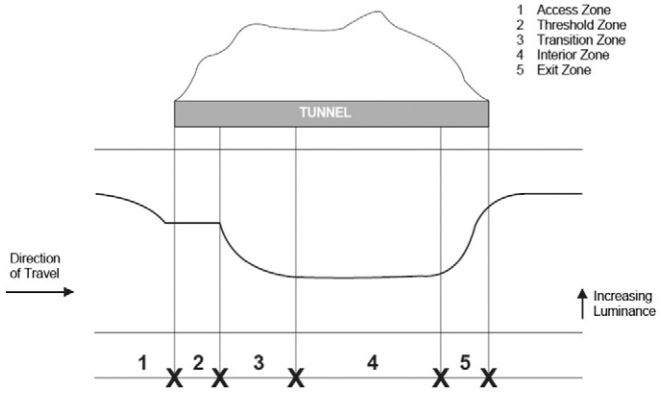

Fig. 1. Luminance change curve example (DMRB 1999).