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A modified critical velocity for road tunnel fire smoke management with dedicated smoke extraction configuration

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ABSTRACT

Life safety is one of the objectives of fire engineering design for road tunnels. Fire engineering design requires maintaining a tenable condition for a period of time to allow occupants to evacuate to safety. This will be achieved by controlling the smoke under credible design fire scenarios in a tunnel. The critical location in a tunnel fire emergency condition is the tunnel region upstream of the fire, where occupants are most likely to reside as traffic jam can usually be created by the fire incident. Tenability for the downstream region of fire is not the main focus of this research because vehicles can generally drive out of the tunnel at a higher speed than that of the smoke flow, and local damper smoke extraction can help keep a tenable condition in the downstream region beyond the local fire zone, in case there is a congestion in the downstream region of the fire.

To maintain a tenable condition in the upstream tunnel region from the fire incident, the required minimum longitudinal flow velocity to prevent smoke backlayering can be calculated based on NFPA 502 recommendations. This critical velocity takes no credit of the smoke extraction or active overhead fixed fire suppression effects.

Smoke extraction with a dedicated smoke duct along the entire length of the tunnel is gaining popularity because of its efficiency and robustness in providing a tenable environment in the tunnel with unknown upstream and downstream traffic conditions. In this paper, a modified critical velocity to control smoke back-layering while smoke extraction and fire suppression systems are operating has been analyzed. This modified critical velocity is approximately 20% lower than the critical velocity that is recommended in NFPA 502. This allows significant savings on ventilation capacity for road tunnels which have a local smoke exhaust capability using a dedicated smoke duct.

It is concluded that the smoke extraction performance is similar whether using ceiling dampers or vertical wall-mounted dampers for smoke capture to maintain tunnel tenability. However, tunnel gradients play a major role on the modified critical velocity for a nominated design fire and the required smoke extraction rate.

Introduction

Tunnel accidents involving a fire incident is a low frequency event. However, its consequence is serious if the fire emergency system is not properly designed and managed to cope with this special event.

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One of the design objectives of a tunnel fire life safety system based on smoke extraction is to maintain tenable conditions in the tunnel and to contain the smoke within a manageable segment of the tunnel, allowing the occupants to be evacuated through the exits or egress passages before developing fire hazards make the tunnel untenable.

When a fire incident happens in a longitudinally ventilated tunnel, two zones will be developed. One is the tunnel zone in the upstream traffic location relative to the fire incident, the other is the downstream traffic location relative to the fire location. In most cases, the downstream zone is of less concern because vehicles can continue to drive away at a higher speed than that of the smoke flows, if there is no traffic congestion in the downstream zone. The local smoke extraction system can also help keep a tenable condition in the downstream section of the tunnel beyond the local fire zone, which means there is less of a concern even if there is traffic congestion in the downstream. However, the upstream zone is the major concern because traffic will build up behind the fire because of the fire incident. Several publications have discussed smoke control to maintain tenable conditions upstream of the fire location [1–9]. However, the impact of smoke extraction and spray water fire suppression on the required critical velocity has not been included in their investigations.

In newly built road tunnels, local smoke exhaust systems with a dedicated smoke duct is gaining popularity because of their effectiveness in mitigating fire hazards developing in the tunnel. For example, the renovated Mont Blanc Tunnel between France and Italy, the Clem 7 tunnel and the Airport Link road tunnel in Brisbane Australia, and the Alaskan Way Viaduct replacement tunnel in Seattle have adopted the concept of a dedicated smoke exhaust duct to ensure the smoke in close proximity to fire incident can be extracted. Tunnel emergency ventilation system design to mitigate fire hazards normally utilizes air flow momentum to effect smoke control with longitudinal flows that establish critical velocity as recommended in NFPA502 for vehicular tunnels [10]. However, this flow capacity does not take into account of the local smoke extraction effects.

In some tunnels in the US, Japan and Australia, a sprinkler or deluge systems are being utilized to actively control the fire spread and protect the tunnel structure. Gas cooling of the hot upper smoke layer is achieved through heat convection, mass transport and evaporative cooling effects as a result of sprinkler spray field created by overhead fixed fire suppression system operation. Unlike tunnels with longitudinal ventilation, when the smoke exhaust and water based sprinkler fire suppression system are operating, this required critical velocity to protect the upstream zone can be reduced when the smoke extraction is enhanced with optimized local damper operation configuration to effectively limit the spread of smoke and untenable conditions within a local tunnel segment.

This paper discusses a modified critical velocity for road tunnels, where a dedicated smoke extraction system and water based fire suppression system is provided. This modified critical velocity and the extraction rate will be determined through a performance based approach considering the specific tunnel ventilation and fire safety provisions of the tunnel. Several critical fire scenarios which should be considered have been highlighted. Two different tunnel gradients have also been analyzed in this paper, and a methodology has been proposed on how to determine the modified critical velocity and the smoke exhaust capacity.

Design parameters such as fire scenarios, fire sizes, tunnel gradient, fire location, smoke extraction location and total number of open smoke extraction dampers are also analyzed to confirm the performance of this modified critical velocity with an evaluation of system robustness of operating modes and configuration.

Design methodology and parameters

The primary issue for tunnel ventilation design is to determine the required longitudinal ventilation air flow to prevent the smoke back-layering in the upstream, and to determine the required smoke exhaust capacity when a dedicated smoke extraction duct is being considered.

To mitigate fire hazards from a fire incident in a tunnel, the required smoke exhaust flowrate should be determined considering the total air supply through the available makeup airflow openings of the tunnel (i.e. entrance and exit portals). The supply air from these openings, which can be calculated based on the longitudinal flows along the tunnel, will mix with the fire generated smoke and therefore increase the overall smoke volume that is required to be extracted. According to the recommendation of PIARC fire and smoke control [11], a longitudinal ventilation velocity along the road tunnel should be controlled at around 3.0 m/s to avoid smoke backlayering under fire conditions. However, this critical velocity requirement can theoretically be reduced when considering buoyant energy generated by fire is being removed from the tunnel by extraction into a dedicated smoke duct. An initial estimate of the required extraction rate is based on establishing the 3.0 m/s velocity in the longitudinal flow generated from each side of the tunnel fire.

To analyze the modified critical velocity, an example tunnel representing a typical tunnel, as detailed in Table 1, with a dedicated smoke duct provided, has been evaluated. The evaluation incorporates an overhead fixed fire-fighting system (FFFS) [12] configuration consistent with many other system designs (12 mm/min water application rate) throughout the world for managing road tunnel fires.

A smoke exhaust duct with a fixed smoke extraction rate of 282 m^3/s was established by trial and error study of initial longitudinal airflow from each portal of the tunnel and tunnel air cooling by an overhead FFFS water spray determined with Subway Environment Simulation (SES) modeling of the example tunnel. The tunnel configuration and design parameters relevant to ventilation are listed in Table 1. The example 2-lane tunnel is assumed to have a gradient ranges from −4% to +1.6%,