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Estimation of number of fatalities caused by toxic gases due to fire in road tunnels

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ABSTRACT

The quantitative risk assessment (QRA) is one of the explicit requirements under the European Union (EU) Directive (2004/54/EC). As part of this, it is essential to be able to estimate the number of fatalities in different accident scenarios. In this paper, a tangible methodology is developed to estimate the number of fatalities caused by toxic gases due to fire in road tunnels by incorporating traffic flow and the spread of fire in tunnels. First, a deterministic queuing model is proposed to calculate the number of people at risk, by taking into account tunnel geometry, traffic flow patterns, and incident response plans for road tunnels. Second, the Fire Dynamics Simulator (FDS) is used to obtain the temperature and concentrations of CO, CO_2, and O_2. By taking advantage of the additivity of the fractional effective dose (FED) method, fatality rates for different locations in given time periods can be estimated. An illustrative case study is carried out to demonstrate the applicability of the proposed methodology.

1. Introduction

Road tunnels are vital transport infrastructures, providing underground passageways for vehicles and commuters, especially useful in compact cities like Singapore. With the increasing traffic, as well as competing demands for land use in cities, more and more road tunnels are being constructed to enhance the accessibility and capacity of road transport systems. However, fires in road tunnels can lead to catastrophic consequences due to the enclosed and confined space in tunnel systems. For example, in 1999, 39 people lost their lives when fire broke out in the Mont Blanc tunnel between France and Italy, while another disaster in the Tauern tunnel in Austria resulted in 12 fatalities (PIARC, 2008). In response to these fatal accidents, the quantitative risk assessment (QRA) has been included as a requirement in the European Union directive 2004/54/EC (EU, 2004). In Singapore, QRAs are compulsory on all major urban road tunnels exceeding 240 m in length, in accordance with the Project Safety Review (PSR) procedure manual for roads in the country (LTA, 2005).

A few QRA models for road tunnels have been developed, such as the Geographic Information System (GIS)-based Transportation Risk Analysis model (Bubbico et al., 2004), the TuRisMo model for Austria, the TUNPRIM model for the Netherlands, the Italian risk analysis model, the OECD/PIARC model (PIARC, 2008), and the QRAFT model for Singapore (Meng et al., 2011a,b; Qu et al., 2011). All these models acknowledge that a fire in a road tunnel would be considered as the most disastrous initiating event (Bubbico et al., 2009; Meng and Qu, 2012). Once a fire has started, the concentration of oxygen (O_2) will decrease dramatically because tunnels are enclosed spaces; at the same time, the concentration of toxic gases such as carbon monoxide (CO) and carbon dioxide (CO_2) increase. Indeed, toxic gases have been reported as responsible for most fire fatalities (Babrauskas et al., 1998; Besserre and Delort, 1997). Further, in these QRA models, the consequences of various scenarios are evaluated based on the number of fatalities. Accordingly, it is essential to develop a method that can precisely estimate the number of fatalities resulting from fires in road tunnels.

Consequence analysis for fires in road tunnels has been studied since the 1990s (Modic, 2003). In general, the models for estimating consequences are based on empirical or semi-empirical regression models or more advanced and precise computational fluid dynamics (CFD) models (Nilsen and Log, 2009). For example, Ingason (2001) proposed a semi-empirical model. Over a number of years, Ingason and his colleagues gathered information on heat release rates from real fires, using small-scale experiments and full-scale tunnel fire tests. Several equations were proposed and calibrated on the basis of the collected data. Migoya et al. (2009) developed a CFD model to simulate accidental fires in road tunnels. A simplified tunnel model (UPMTUNNEL) for the simulation of accidental fires with longitudinal ventilation was created using two simulation tools: FLUENT and PHOENICS.

However, all the existing QRA models for road tunnels apply empirical or semi-empirical models to estimate the number of fatalities. This is because there is no method available to estimate the number of fatalities taking traffic flow patterns (tunnel users)

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into consideration. The literature review carried out for this study shows that the CFD-based approaches simply focus on estimating the concentrations and/or temperatures of smoke, without taking into account the traffic flow patterns and number of tunnel users. Although the temperature and concentration of smoke may indirectly indicate the severity of fire disasters, it would be better to use the number of fatalities or fatality rate to explicitly represent the consequences of these fires, in alignment with the requirements of the EU directive 2004/54/EC (EU, 2004) and the PSR Manual for roads in Singapore. Hence, a model is needed that estimates the number of fatalities in fires in road tunnels. This paper puts forth such a methodology that incorporates traffic flow patterns and the spread of smoke in tunnels. The methodology is then used to estimate the consequences of a particular fire occurring in a road tunnel in Singapore.

The contributions of this work can be summarized as follows. Firstly, we propose a methodology to estimate the number of fatalities, incorporating the traffic flow pattern and fire spread in tunnels. Secondly, a practical application is carried out to guide decisions-makers and policy-makers at the Land Transport Authority (LTA) of Singapore. The remainder of this study is organized as follows. In Section 2, the methodology is presented. Section 3 contains an illustrative case study. Discussion of the results is presented in Section 4. Section 5 concludes.

2. Methodology

2.1. Estimation of number of people at risk

The people upstream of cross passage doors can easily evacuate from one tunnel bore to the other. Thus, vehicles upstream of the fire site will not be affected by it while those downstream of it will be trapped. Accordingly, the area between the fire site and the nearest upstream cross passage door (see Fig. 1) should be considered as the risk area. A deterministic queuing model is adopted to estimate the number of people in the risk area as follows.

We assume that the vehicles are generally uniformly distributed across the risk area when they stop as a result of an incident in a road tunnel. Assuming continuous traffic flow, the number of vehicles per lane (N) from the time the fire starts until time t can be estimated by,

$$N\left[\sum_{i=1}^{n} P_i L_i\right] + (N-1)H = D(t) \tag{1}$$

where n is the number of vehicle types (cars or trucks), L_i is the average length of vehicle type i, P_i is the proportion of vehicles that are of type i, H is the distance between two successive vehicles when they stop as a result of the incident, and $D(t)$ is the length of the risk area, which is mathematically defined as

$$D(t) = \min\left\{D_0,\, Q \times t \times \left(H + \sum_{i=1}^{n} P_i L_i\right)\right\} \tag{2}$$

where D_0 is the distance between the fire site and the nearest downstream cross passage door, and Q is the traffic volume. According to Eq. (2), the length of the risk area will be D_0 if the area between the fire site and the cross passenger door is fully occupied with vehicles; otherwise, $D(t)$ will be the distance from the fire site to the location of the last vehicle that has entered the area.

Thus, the number of vehicles in the risk area in the various traffic lanes ($N_v(t)$) can be estimated by

$$N_v(t) = n_{lane} \times \frac{D(t) + H}{H + \left[\sum_{i=1}^{n} P_i L_i\right]} \tag{3}$$

where n_{lane} is the number of lanes in the tunnel. Accordingly, the number of people at risk ($N_{par}(t)$) is

$$N_{par}(t) = N_v(t)\left(\sum_{i=1}^{n} P_i O_i\right) \tag{4}$$

where O_i is the average number of people in a vehicle of type i.

2.2. Fire simulation model

The process of fire growth and spread can be formulated using conservation equations for mass, momentum, energy, and species, coupled with the equation of state, which is the basis and foundation of the FDS program (McGrattan, 2005). Note that all these equations are from the FDS technical reference guide by McGrattan (2005). The conservation of mass is written as:

$$\frac{\partial \rho}{\partial t} + \nabla \rho u = 0 \tag{5}$$

where $\partial\rho/\partial t$ represents the density change over time while u is the velocity vector. The following equation describes how the rate of mass storage within the control volume, due to the change in density, is balanced by the net rate of inflow. The conservation of momentum is described as:

$$\frac{\partial(\rho u)}{\partial t} + \nabla puu = -\nabla p + \rho f + \nabla \tau_{ij} \tag{6}$$

where $\partial(\rho u)/\partial t$ and ∇puu on the left-hand side of the equation define the rate of change of momentum, p represents pressure, τ_{ij} is the stress tensor acting on the fluid, and f consists of gravity plus other forces such as the drag exerted by liquid droplets (McGrattan, 2005). The conservation of energy is written as:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \rho h u = \frac{\partial p}{\partial t} + \dot{q}''' - \nabla q + \Phi \tag{7}$$

where $\partial(\rho h)/\partial t$ and $\nabla \rho h u$ are the net rate of energy accumulation within the control volume while the terms on the right-hand side represent the heat release rate per unit volume from a chemical reaction ($\dot{q}'''$), the conductive and irradiative heat flux (∇q), and the dissipation function (Φ), that is, the rate at which kinetic energy is converted to thermal energy due to the viscosity of the fluid (McGrattan, 2005). The equation of state is written as:

$$p = \rho R T \tag{8}$$

where ρ is the density, p is the pressure, R is the gas constant (287.05 J/(kg K)), and T is the temperature (K). The conservation of specifies is written as:

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \rho Y_i u = \nabla \rho D_i \nabla Y_i + \dot{m}_i''' \tag{9}$$

where the fluid consists of a mixture of species, and the transport equations for each species will need to be solved. Here, Y_i is the mass of the ith species, D_i is the diffusion coefficient of species i into the mixture and $\dot{m}_i'''$ is the production rate of species i (McGrattan, 2005).

In this study, we apply the Fire Dynamics Simulator (FDS) program to solve the above equations numerically. The program, developed by the National Institute of Standards and Technology (NIST), has been used extensively for fire simulations (e.g. Tsukahara et al., 2011). The FDS has been validated by comparing to experimental results (e.g. Cochard, 2002; Smardz, 2006; Lee and Ryou, 2006; Hu et al., 2007; Trelles and Mawhinney, 2010, etc.). It works as follows. First, the initial pressure and temperature, the tunnel geometry, the fire size and location, materials such as fuels that are present, the type of fire detection systems and ventilation systems that are in place, and the simulation period are input into the FDS program. Then, the FDS numerically solves the above