RISK ANALYSIS OF ROAD TUNNELS: A QUANTITATIVE RISK ANALYSIS MODEL FOR ASSESSING THE EFFECTS OF FIRE

[1]Razieh Khaksari Haddad, [2]Zambri Harun
[1]London Bridge Associates Ltd, GB
[2]Department of Mechanical and Manufacturing Engineering
Faculty of Engineering & Built Environment, UKM, MY

DOI 10.3217/978-3-85125-996-4-30 (CC BY-NC 4.0)

ABSTRACT

The most important factor influencing fire safety in tunnels is the interaction between the fire, tunnel users, traffic, and fire safety measures. A quantitative risk analysis model has been developed to analyse the fire risk, LBA Quantitative risk analysis model (LBAQRA). This paper presents details of this quantitative risk analysis model, consisting of a quantitative consequence analysis model and a quantitative frequency analysis, which was used for this study. The quantitative consequence analysis model includes three sub-models; queue model, distribution model, and egress model to estimate the number of exposed tunnel users, their evacuation times, the extent of damage due to fires, and eventually the number of fatalities and injuries. Frequency analysis is carried out through an event tree which was built on the tunnel fire rate in UK road tunnels. This fire rate is updated considering tunnel length, time of fire incident, traffic condition, accident type, vehicles involved, and location of fire. The study of the impact of various ventilation strategies on the F/N curve showed the positive effect of the activation time of the ventilation system on societal risk. The sensitivity analysis of the model indicates that the number of fatalities increased for longer detection times and the initial fire rate and the probability of congested traffic have a direct influence on the final frequency of fire scenarios.

Keywords: fire safety, quantitative risk analysis, societal risk, road tunnels.

1. INTRODUCTION

In order to reduce congestion in developed areas and improve the connection of regions, road tunnels are one of the most critical systems for daily operation in urban areas. They also raise opportunities for the transportation of individuals and goods. Despite the benefits that road tunnels add to transportation system, their existence leads to an endogenous problem due to the severity of tunnel accidents compared to roads.

The consequence of a fire incident, especially when a heavy good vehicle (HGV) or large good vehicle (LGV) is involved, causes very high temperature, great concentration of toxic gases, and intense smoke. Therefore, disastrous consequences in terms of human losses and structural damage are expected. That is why the fire safety of road tunnels was intensely put in the center of public attention and as it is obliged by CD352 [1], the risk assessment should both inform the design and serve as a check on the adequacy of the design proposals, and identify any risks falling within the 'Tolerable' region that can need further mitigation. There are several methods of risk analysis to determine risks and evaluate the effectiveness of safety measures. One of these methods is quantitative risk analysis (QRA), which has been one of the explicit requirements under the European Union (EU) Directive (2004/54/EC) when the tunnel is opened to dangerous goods [2]. A quantitative risk analysis for road tunnels complying with EU regulations has been presented by Kirytopoulos et al. [3]. Different risk models exist in the literature, such as the Dutch TUNPRIM, a QRA model for the country's road tunnels called the QRAFT from Singapore, Austrian TuRisMo, and Italian Risk Analysis Method, IRAM. A project on the transport of dangerous goods through road tunnels was sponsored by PIARC 1995 and the PIARC/OECD/EU QRA model (QRAM) was developed. Thirteen hazardous scenarios are taken in this and was computerized by spreadsheet-based software [4]. The validation of the QRAM model was studied in Austria, France, Netherlands, Norway, Sweden, and Switzerland and various risk reduction measures were examined employing the QRAM software [5].

The societal risk is determined as a combination of event frequency and consequences. Societal risk represented graphically in the form of a frequency/number of fatalities (FN) curve, is the main output of these models. The calculated societal risk must be evaluated by comparison with the risk acceptance criteria, i.e. must be less than a specified minimum and acceptable value (threshold) as presented in the case studies, for instance, Diamantidis [6], Botschek et al. [7] and Kohl and Zibert [8].

Risk assessment of fire incidents in road tunnels includes complicated scenarios as they constitute interactions among the fire, tunnel users, and safety measures such as fire detection, tunnel alarm, or emergency ventilation. Thus, many risk indicators, which affect risks for tunnel users, describe the scenario. Factors affecting tunnel fire risk assessment are influenced by the uncertainty related to the traffic conditions or the environmental conditions, which results in making assumptions adopting a 'mean' value or a worst-case scenario.

2. METHODOLOGY

In light of the above considerations, a novel methodology to perform a quantitative fire risk assessment of road tunnels is explained in this paper. A model of quantitative risk analysis concerning safety in road tunnels called LBAQRA has been developed to perform a risk analysis as required by UK regulations. The LBAQRA performs a quantitative risk assessment and includes quantitative frequency analysis and quantitative consequence analysis. The quantitative consequence analysis section of this model was inspired by [9].

Tunnel geometry and its infrastructures, fire safety measures and the interaction between them, as well as equipment and management procedures such as emergency ventilation strategies in addition to the analysis of factors and processes related to human behavior, such as recognition and response to the incident, reluctance to leave the vehicle, interactions between occupants, interactions between occupants and smoke, and how their age and gender affect their evacuation should be considered to evaluate the tunnel fire risk. These aforementioned parameters are taken into account in this model. In this model, the risk assessment analysis is divided into quantitative consequence analysis and quantitative frequency analysis.

2.1. Quantitative frequency analysis

The frequency of defined accident scenarios was calculated via an event tree. The first column of the frequency event tree is initial fire frequency which has been obtained from the historical statics of fire incidents in England road tunnels. This statistical data has been published in [10]. Then this initial fire rate is updated by considering the length, traffic volume, and gradient of the under-studied tunnel. The second column of the frequency event tree is "The Time of the Incidents". Since drivers' eye movement and driving performance are different during day and night, the accident rate and consequently the fire rate are different in day and night. The influence of time on accidents should be considered in the frequency analysis. The third column of the frequency event tree is "Traffic Condition". As the fire rate is varied by traffic condition, the effect of traffic condition on fire rate was considered by considering the congested hours of the tunnel under study. Furthermore, two accident types were considered in this model. Incidents that include 1 vehicle are Type 1 and collisions that include more than 1 vehicle are Type 2. The probability of type 1 and 2 incidents is derived from UK road data. The fifth column is "Vehicle Type". The share of passenger cars, buses, vans, HGV, and trucks involved in fire incidents based on the tunnel fire data in PIARC 1999 is considered. The last column is Fire Source Location. The tunnel is divided into three zones and an average crash rate value was considered to evaluate the safety level of each tunnel zone [11,12].

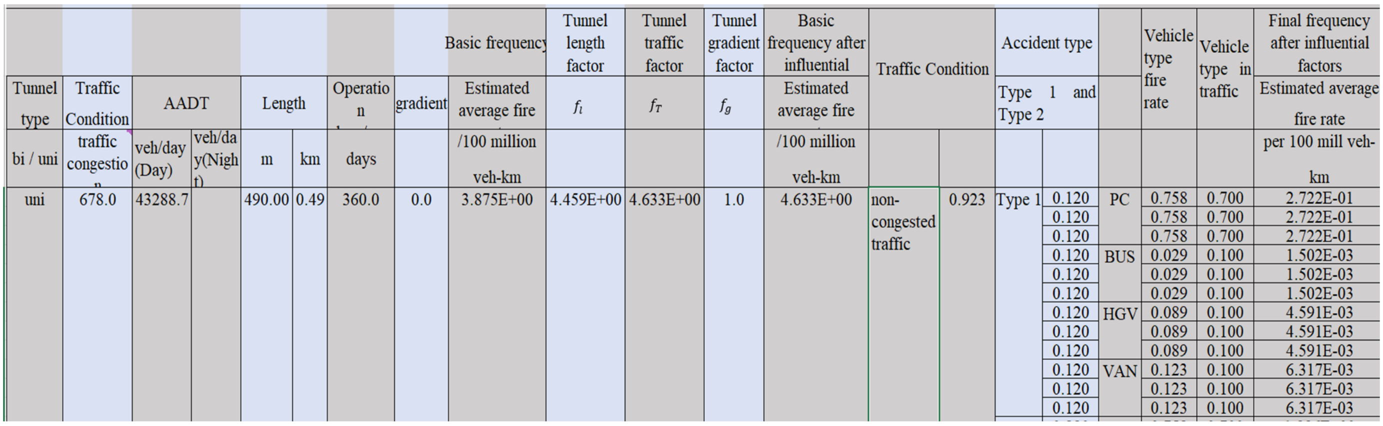
Table 1: Comparison of tunnel crash rate in different zones

Zone 1	Zone 2	Zone 3
0.23	0.2	0.15

The final fire frequency is calculated by multiplying the initial fire frequency by the below columns:

- Time of fire incident
- Traffic condition
- Accident type
- Vehicle type
- Fire source location

Figure 1 shows a section of quantitative frequency analysis event tree.



								Basic frequency	Tunnel length factor	Tunnel traffic factor	Tunnel gradient factor	Basic frequency after influential	Traffic Condition		Accident type			Vehicle type fire rate	Vehicle type in traffic	Final frequency after influential factors
Tunnel type	Traffic Condition	AADT		Length		Operation	gradient	Estimated average fire	f_l	f_T	f_g	Estimated average fire			Type 1 and Type 2					Estimated average fire rate
bi / uni	traffic congestion	veh/day (Day)	veh/day(Night)	m	km	days		/100 million veh-km				/100 million veh-km								per 100 mill veh-km
uni	678.0	43288.7		490.00	0.49	360.0	0.0	3.875E+00	4.459E+00	4.633E+00	1.0	4.633E+00	non-congested traffic	0.923	Type 1	0.120	PC	0.758	0.700	2.722E-01
																0.120		0.758	0.700	2.722E-01
																0.120		0.758	0.700	2.722E-01
																0.120	BUS	0.029	0.100	1.502E-03
																0.120		0.029	0.100	1.502E-03
																0.120		0.029	0.100	1.502E-03
																0.120	HGV	0.089	0.100	4.591E-03
																0.120		0.089	0.100	4.591E-03
																0.120		0.089	0.100	4.591E-03
																0.120	VAN	0.123	0.100	6.317E-03
																0.120		0.123	0.100	6.317E-03
																0.120		0.123	0.100	6.317E-03

Figure 1: An example of quantitative frequency analysis event tree

2.2. Quantitative consequence analysis

The number of fatalities is calculated via quantitative consequence analysis which comprises three parts: queue model, distribution model, and egress model.

The queue model calculates the number of vehicles queueing in each lane. The number of vehicles that will enter the tunnel and queue behind the fire (queue length) depends on the time duration subsequent to a fire incident and consequently the tunnel closure time, queue formation speed, stopping distance between vehicles in the queue, fire source location, and the density of stopped vehicles in each lane. The main parameters which should be considered in the queue formation model are the number of vehicles, their percentage and length, and the relative users. Since the average peak traffic density, percentage, and type of vehicles are not uniform between various lanes in a multi-lane tunnel, the traffic flow should be distributed into lanes. Saad Yousif and his colleagues [13] studied the distribution of traffic flow among the available number of lanes and modelled lane utilization. In the absence of tunnel-related information, the model developed by Yousif et al. [13] is utilized to estimate the lane utilization factor for each lane based on the total traffic flow of vehicles (veh/hr) in two-lane and three-lane tunnels.

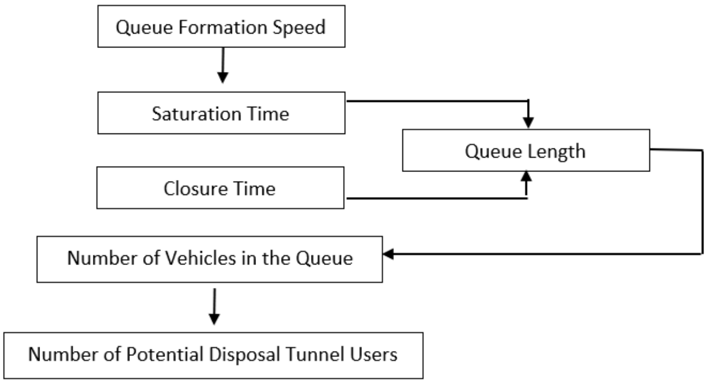


Figure 2: The process sequence of calculating the number of people in the queue

Then the number of vehicles queueing in each lane and consequently the number of exposed tunnel users is estimated by queue length and traffic density as below.

$$N_{veh} = L_q/(\%PC \times L_{PC} + \%BUS \times L_{BUS} + \%VAN \times L_{VAN} + \%TRUCK \times L_{TRUCK} + \%HGV \times L_{HGV} + d_{stop}) \tag{1}$$

$$N_i = N_{veh} \times (n_{PC} \times \%PC + n_{BUS} \times \%BUS + n_{VAN} \times \%VAN + n_{TRUCK} \times \%TRUCK + n_{HGV} \times \%HGV), \tag{2}$$

Where L_q is the queue length, N_{veh} is the number of vehicles, $L_{PC}, L_{BUS}, L_{VAN}, L_{TRUCK}$, and L_{HGV} are the average lengths of relative vehicles, $\%PC$, %BUS, %VAN, %TRUCK, and %HGV are percentage of different types of vehicles in traffic composition, and $n_{PC}, n_{BUS}, n_{VAN}, n_{TRUCK}$, and n_{HGV} are the average occupancy rate respectively of passenger cars, buses, vans, trucks, and HGVs in the i-th lane.

After calculating the number of potentially exposed people, the distribution model is used to divide the queue into cells of the same size and then distribute tunnel users homogeneously. Considering agents’ gender, it is assumed that the share of women and men is the same. The gender of cells changes alternatively. Regarding the evacuee’s walking speed, the speed calculated in the model is used for cells occupied with men and it is assumed that women’s walking speed is 20% lower than men’s. The total distance of the evacuation path is calculated by the distribution model taking into account both the longitudinal and lateral shares in the evacuation route. Exposed tunnel users distributed in each cell start the evacuation path from their initial position and they travel cell by cell towards a place of safety i.e., an emergency exit or the tunnel portal.

A timeline model is used for the egress model, which describes the sequence of events as a list of continuous phases. A four-stage evacuation process is considered. The first stage is detection which depends on the safety equipment in the tunnel. The detection times in this model based on the type of detection system are:

- Automatic detection system: 60 seconds
- Automatic detection system + confirmation by an operator: 30+60 seconds = 90 seconds
- Manual fire alarm: 180 seconds

The second stage is the alarm stage which is the time between detection and the time when the alarm system is activated. The alarm time is calculated considering the influence of provided safety systems in the tunnel such as smoke/ fire detection system and video/radar incident detection system.

The third stage is the pre-movement stage including recognition time, response time, and the time to exit the vehicle. Recognition time consists of a period between the activation of the alarm system and when occupants recognise the danger. Once evacuees recognise the fire, they do not start to travel immediately. Time takes between recognition time and leave the vehicle is response time. At this stage, people are strongly influenced by others' reactions. The tunnel length behind the fire is divided into two zones: crash zone and normal zone. Based on the fire size, ventilation velocity in a tunnel under natural ventilation and tunnel dimensions, the backlayering length, which defines the crash zone, is calculated. The people stuck behind the fire in the queue can be divided into three groups:

- Group 1: direct accident witnesses, who are in the crash zone and make the evacuation decision on their own. Their pre-movement time is before detection plus alarm time. They could see the fire and came to a rapid decision to leave their vehicles.
- Group 2: who are out of crash zone and have no knowledge of the situation and have to wait for emergency announcement. Their pre-movement time is more than sum of detection time and alarm time.
- Group 3: a small subgroup of the second group, who made their decision seeing escaping persons from the first group. Their pre-movement time is lower than Group 2 pre-movement time.

People react to extraordinary circumstances in various ways and need different amounts of time to make their decisions. Therefore, the recognition time + response time before evacuation starts is adopted with polynomial trendline with below assumptions:

- The pre-movement time range is from 30 to 300 sec based on real accidents and tunnel experiments.
- The queue length behind the fire source is divided into sections, named cell. The length of the cell influences directly the calculation precision. The smaller the length, the more accurate it is.
- The pre-movement time of the first cell of crash zone is 30 sec (Group 1).
- The pre-movement time of the last cell of crash zone is $t_{det} + t_{alarm-} - 30$ (Group 2).
- The pre-movement time of the first cell of normal zone is $t_{det} + t_{alarm-} + 30$ sec (Group 2).
- The pre-movement time of the last cell of Group 2 is 300 sec, which is also the pre-movement time of the first cell of Group 3.
- The pre-movement time of the last cell of Group 3 is $(t_{det} + t_{alarm}) + 30$ sec.
- The recognition time + response time graph can be plotted via the centre of each cell as the x-axis values.

Figure 3: An illustration of the recognition time + response time

A small share of agents in the direct vicinity of the fire, do not leave the fire site, either because of wrong behaviour or because of being unable to evacuate. A share of 3% of all evacuees is assumed to show this behaviour. It is assumed that these people stay at the place of origin and only start evacuation after 15 min.

We assume that the flow capacity of a normal vehicle door is 1 person per 4 seconds. Based on the average occupancy of each type of vehicle, the number of each type of vehicle in the queue, and the number of cells the average time of leaving the vehicle is calculated.

The last stage is traveling which depends on the movement speed and the distance to the emergency exit or portal. In this model, an approach considering a walking speed as a function of local toxic, thermal and visibility conditions is presented in [14]. The proposed approach is based on international work on the fire consequences on people regarding their evacuation capability [14].

The next step is the verification of users’ egress process to find out if evacuees can start and then continue the evacuation process based on the considered tenability thresholds. In this section, the evacuation time (RSET) is compared with the time when the tenability thresholds exceed their limits (ASET).

Two indicators are measured at humans’ face height at the centre of each cell to assess whether occupants can travel the evacuation path and reach a place of safety.

The tenability criteria used for this model are:

- $\mathrm{FED} < 1$,
- $\mathrm{FED}_{\mathrm{heat}} < 1$.

In addition to considering tenability thresholds to calculate the number of fatalities, fire spread from initial vehicle to neighbouring vehicles causes injuries as well. Radiation, convection, and conduction result in an increase of heating of the skin and consequently skin burns. The pain temperature threshold is 44.8 °C [15,16]. However, skin injury starts to develop when the skin temperature is greater than 44 °C due to the onset of protein breakdown [17,18]. In this model, 44 °C tolerable temperature is measured at the centre of each cell during evacuation to estimate the number of injuries in each quantitative risk analysis scenario as well.

The total number of casualties is defined as the sum of fatalities of each cell where the tenability thresholds are exceeded (RSET>ASET). The total number of causalities of the whole tunnel is determined by the sum of fatalities in each lane.

F/N curves of societal risk are provided with the results of quantitative consequence analysis and quantitative frequency analysis. Risk acceptance is obtained using the ALARP criterion in the UK.

The results of one of the case studies implemented by LBAQRA has been published in [19].

3. CASE STUDY

In order to achieve the purpose of this study mentioned in the introduction section, a specific tunnel was investigated. This tunnel, Southwick Tunnel, is located on the A27 between the junction of the Holmbush interchange (A27), portal A and the Hangleton interchange (A293), portal B, UK. The structure is a twin-bore curved unidirectional road tunnel. Each bore is approximately 490 meters long and carries two lanes of traffic. The bores are connected by 3 cross passages, approximately 100 m apart and 100 m from either portal. This tunnel has a positive longitudinal slope of 3% from portal A to B. The tunnel equipped with a longitudinal ventilation system consists of 14 jet fans (7 pairs) installed at the ceiling of each bore.

This tunnel has an annual average daily traffic of about 46900 vehicles/day traffic density in the Eastbound bore with an average percentage of 77% passenger car, 0.2% bus, 19% truck, and 3.8% HGV. Three different traffic conditions, free fluid, congested, and stoppage, were considered. 158 MW, 47 MW, and 30 MW fire scenarios at three locations including 0.3L, 0.5L, and 0.8L (L is tunnel length) are studied.

FN curves as the output of quantitative risk analysis and sensitivity analysis of this model taking into account detection time, fire occurrence rate, and percentage of congested traffic were studied for the scenarios understudied.

4. RESULTS

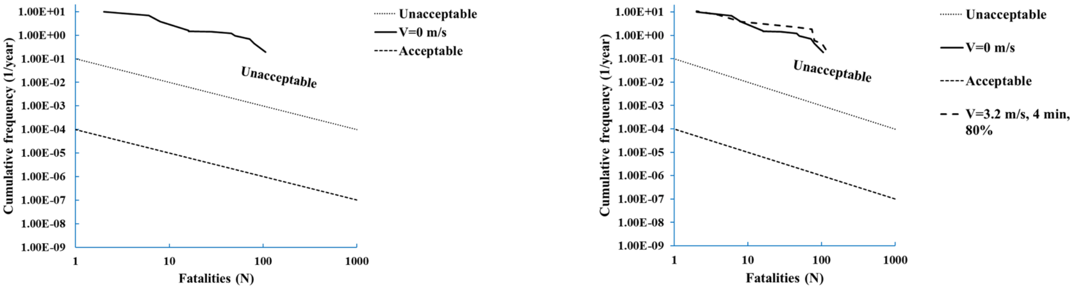
4.1. F/N Curve

Three different emergency ventilation strategies listed in Table 2 in the case of 158 MW, 47 MW, and 30 MW fire scenarios were studied to investigate the effect of ventilation system strategy on the FN curve. The ALARP limit, acceptable and unacceptable limits, was adopted by Moonis et al. (2008) [20].

FN curve of scenarios without ventilation was located at the unacceptable region which means it could not meet the safety target (Figure 4a). According to FN curves, when the ventilation system was activated at 4 min after ignition, there was no obvious difference between FN curves of V=0m/s and V=3.2 m/s with 4 min activation time (Figure 4b, 4c). It means as the ventilation system was activated very late, it could not cope with the influences of fire and smoke. On the other hand, when the ventilation system was activated 2 min after ignition (Figure 4d), the FN curve was lower than in scenarios without ventilation which showed the positive effect of the activation time of the ventilation system. Although it was still in the unacceptable region.

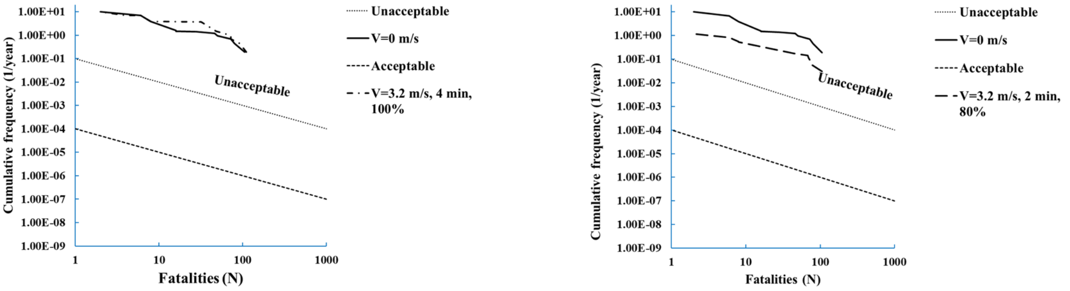
Table 2: Under study ventilation systems

Scenario No.	Ventilation velocity (m/s)	No. Fans	Ventilation activation time after ignition
1	0	-	-
2	3.2	80%	4 min
3	3.2	100%	4 min
4	3.2	80%	2 min



a) Scenario 1 (V=0)

b) Scenario 1 and 2



c) Scenario 1 and 3

d) Scenario 1 and 4

Figure 4: FN curve of different emergency ventilation systems

4.2. Sensitivity analysis

The sensitivity of the LBAQRA model has been analysed by taking into account the impact of key factors including detection time, initial fire occurrence rate, and percentage of congested traffic. These factors have been changed to evaluate their effect on the tunnel safety.

Expected Value (EV), which is the integral of the FN-curve, is used to evaluate the sensitivity of the model to chosen variables. Higher EV means higher level of risk and is defined as below:

$$EDV = \sum N_{Sc} \times F_{Sc}, \qquad 3$$

where N_{Sc} is the number of fatalities for each fire scenario and F_{Sc} is the cumulated frequency of each fire scenario.

4.2.1. Detection time

The risk assessment was carried out for ten cases with two fire sizes, three detection times, three fire source locations, and two ventilation strategies. The activation time of the ventilation system is defined as the time after ignition when the jet fans turn on. These scenarios are defined in Table 3.

Table 3: Scenarios studied to assess the sensitivity of LBAQRA to detection time

Heat Release Rate (MW)	Fire source location (%L)	Ventilation strategy	Detection time (sec)
158	0.8	No ventilation	60
158	0.8	No ventilation	180
158	0.8	Longitudinal ventilation with 3.2 m/s air velocity; 2 min activation time	60
158	0.8	Longitudinal ventilation with 3.2 m/s air velocity; 2 min activation time	180
30	0.3	Longitudinal ventilation with 3.2 m/s air velocity ; 4 min activation time	60
30	0.3	Longitudinal ventilation with 3.2 m/s air velocity; 4 min activation time	180
30	0.5	Longitudinal ventilation with 3.2 m/s air velocity; 4 min activation time	60
30	0.5	Longitudinal ventilation with 3.2 m/s air velocity; 4 min activation time	180
30	0.8	Longitudinal ventilation with 3.2 m/s air velocity; 4 min activation time	60
30	0.8	Longitudinal ventilation with 3.2 m/s air velocity; 4 min activation time	180

Detection time is the time between when the fire starts and when the tunnel safety equipment detects the fire and it is the first stage of evacuation process. The greater this parameter, the greater required safe egress time and consequently the probability that the harmful effects of the fire reach the tunnel user before they leave their vehicle.

Table 4 shows how the EDV varies when the detection time was increased from 60 sec to 180 sec. it can be seen by increasing the detection time to 180 sec, the EDV increases by about 72%. This higher value shows that greater ASET results in more tunnel users cannot start the evacuation process or they cannot finish it after being in the untenable condition for too long. In both cases they die. Consequently, the number of fatalities for scenarios with higher detection time is more than 60 sec detection time scenarios.

Table 4: EDV variation when the detection time varies

	First parameter	Second parameter
Detection time	60 sec	180 sec
EDV	2.403E-02	4.133E-02
Variation		-72.01%

The number of fatalities shown in Figure 5 provides a clear demonstration of 30 MW fire scenarios with the same frequency but different number of fatalities because of different detection times, 60 sec and 180 sec.

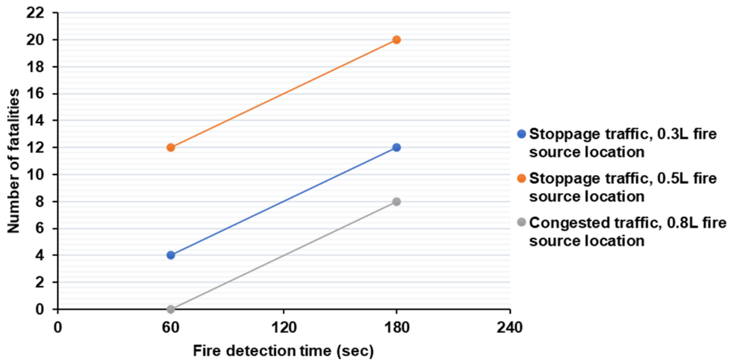


Figure 5: Dependency of number of fatalities on the fire detection time

4.2.2. Fire occurrence rate

The initial fire rate has a direct influence on the final frequency of fire scenarios in the frequency event in this model. Consequently, it has a direct effect on the EDV, which is obtained by multiplying the frequency of each scenario by the number of fatalities. The sensitivity analysis was carried out for fire scenarios with longitudinal ventilation system activated after 2 min and 158 MW and 30 MW fire loads. Three initial fire rates were studied: reference fire rate, halved fire rate, and doubled fire rate. If the initial fire rate is doubled, as it is expected the EDV is doubled and vice versa.

Table 5 illustrates the variation of the EDV for the reference fire rate, halved fire rate, and doubled fire rate.

Table 5: The variation of the EDV for various fire rate.

	Reference parameter	Halved parameter	Doubled parameter
Initial fire rate (/100 million veh-km)	1.511	0.756	3.022
EDV	1.72E+01	8.60E+00	3.44E+01
Variation	_	-50%	+100%

4.2.3. Probability of congested traffic

Probability of congested traffic is one of influential parameters which the initial fire rate is multiplied by to produce the final fire rate for each scenario considered in the frequency event tree of this model. To evaluate the sensibility of LBAQRA to this parameter, three values were considered, the actual probability of congested traffic for the tunnel under study, and the change of this variable between ±50 %.

Table 6: The variation of the EDV for various congested traffic probability

	Reference parameter	Halved parameter	Doubled parameter
Congested traffic probability	0.077	0.0386	0.154
EDV	1.72E+01	1.14E+01	2.86E+01
Variation	_	-33.32%	66.64%

5. CONCLUSION

A model of quantitative risk analysis concerning safety in road tunnels called LBAQRA has been developed to perform a risk analysis as required by UK regulations for complex fire scenarios. LBAQRA consists of two main sections: quantitative frequency analysis and quantitative consequence analysis.

The frequency of each fire scenario has been determined based on the basic fire rate of UK road tunnels per 100 million veh-km which is updated by taking into account the length, traffic, and gradient of the tunnel under study. Then the effect of time of fire incident, traffic condition, accident type, vehicle type, and the fire source location on the updated fire rate is considered through branches of the frequency event tree. The quantitative consequence model comprises three parts, the queue formation model that estimates the number of potential tunnel users for each lane, the distribution model that calculates the evacuation distance in two dimensions, and the egress model that calculates the required evacuation time.

This paper presents a brief description of the sections of this model and how it derives the societal risk. In the second part, an illustrative case study was carried out for the Southwick Tunnel to study the robustness of this model, and the risk reduction potential of different ventilation strategies was assessed.

A study of various emergency ventilation strategies shows that when the ventilation system is activated very late, it cannot cope with the influences of fire and smoke. The sensitivity analysis shows that the number of fatalities increases when the detection time rises and the initial fire rate and the probability of congested traffic have direct influence on the final frequency of fire scenarios.

6. ACKNOWLEDGMENT

We are grateful for the CPU resources possible by Universiti Kebangsaan Malaysia grant GUP-2020-015.

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