

Quantitative Risk Assessment Modelling for Non-homogeneous Urban Road Tunnels

Qiang Meng^{a1}, Xiaobo Qu^a, Xinchang Wang^a

Vivi Yuanita^b, Siew Chee Wong^b

^a Department of Civil Engineering, National University of Singapore, Singapore

^b Systems Assurance and Integration Division, Land Transport Authority of Singapore, Singapore

ABSTRACT

Urban road tunnels provide an increasingly cost-effective engineering solution, especially in compact cities like Singapore. For some urban road tunnels, tunnel characteristics such as tunnel configurations, geometries, provisions of tunnel Electrical & Mechanical systems, traffic volumes, etc. may vary from one section to another. These urban road tunnels which have characterized non-uniform parameters are referred to as non-homogeneous urban road tunnels. In this study, a novel quantitative risk assessment (QRA) model is proposed for non-homogeneous urban road tunnels because the existing QRA models for road tunnels are inapplicable to assess the risks in these road tunnels. This model uses a tunnel segmentation principle whereby a non-homogeneous urban road tunnel is divided into various homogenous sections. Individual risk for road tunnel sections as well as the integrated risk indices for the entire road tunnel is defined. The paper then proceeds to develop a new QRA model for each of the homogeneous sections. Compared to the existing QRA models for road tunnels, this section-based model incorporates one additional top event: toxic gases due to traffic congestion and employs the Poisson regression method to estimate the vehicle accident frequencies of tunnel sections. This

¹ Address correspondence to Associate Professor Qiang Meng, Department of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 117576; Tel.: +65-65165494; Fax: +65-67791635 cvemq@nus.edu.sg

paper further illustrates an aggregated QRA model for non-homogeneous urban tunnels by integrating the section-based QRA models. Finally, a case study in Singapore is carried out.

Keywords: non-homogeneous urban road tunnel, QRA, individual risk, traffic congestion

1. INTRODUCTION

Road tunnels have been deemed to be increasingly cost-effective infrastructures which provide underground vehicular passageways for motorists and commuters, especially in densely populated countries like Singapore.⁽¹⁾ With the increasing traffic volume and urban development as well as growing needs for land use, especially in urban areas, constructing road tunnels are becoming more popular and challenging. For some urban road tunnels, due to the complexity of traffic conditions, tunnel characteristics such as tunnel configurations, geometries, provisions of tunnel Electrical & Mechanical systems (e.g. tunnel ventilation system), traffic volumes, accident frequencies, etc. may vary from one section to another. These urban road tunnels which have characterized non-uniform tunnel parameters are referred to as non-homogeneous urban road tunnels in this paper.

The safe operation in road tunnels is of utmost concern due to the heavy traffic volume that urban road tunnels carry. Accidents occurring in a road tunnel may lead to severe consequences in terms of deaths due to the enclosed nature of tunnel structure. For example, in 1999, 39 people lost their lives in a fire disaster that happened in the Mont Blanc Tunnel from France to Italy and another disaster in Tauern Tunnel of Austria resulted in 12 fatalities.⁽²⁾ These accidents have raised the awareness among the public as well as the government on both the safety aspect of the tunnels and that of the road tunnel users. Thus, quantitative risk assessment (QRA) has been one of the explicit requirements under the European Union (EU) Directive (2004/54/EC).⁽³⁾ In Singapore, a safety target or risk criteria is necessary for all major road tunnels of length > 240

meters, in accordance to the Project Safety Review (PSR) procedure manual for roads in the country.⁽⁴⁾ Accordingly, it is important to build a QRA model for the non-homogeneous urban road tunnels.

1.1 Relevant Studies

A QRA model, which consists of fault trees, event trees, and consequence estimation models, evolved from the application concepts of reliability and statistics to engineering design and it has been proven to be an efficient and effective methodology to quantitatively assess the safety level of hazardous installations. In 1950s, a report issued by the US Atomic Energy Commission proposed a model to estimate risks (in terms of deaths, injuries and land contamination) of catastrophic accidents at nuclear power plants with major radioactive releases. However, it was only in 1975 that a full scale study,⁽⁵⁾ using numerical techniques to evaluate probabilities and consequences of large accidents with nuclear power reactors, was published in USA. This landmark study introduced quantitative risk assessment essentially in the form that we use today, as a numerical tool for evaluating safety level of hazardous installations. Since then, we have seen a number of methodological applications in various industries. These studies include electrical accident countermeasure systems for mines,⁽⁶⁾ fusion fission hybrid reactor failures,⁽⁷⁾ water resource planning,⁽⁸⁾ steam generator tube ruptures,⁽⁹⁾ and emergency response in the context of chemical hazards or spills.^(10, 11) In 1990s, researchers began to apply the methodology to assess the risks for the homogeneous road tunnels.⁽¹²⁻¹⁴⁾ All these case studies show the usefulness and suitability of QRA methodology.

The safety targets have evolved in parallel with the development of QRA as an integral analytical technique. In 1967, Farmer's pioneer paper defined the concept of risk in terms of a "probability consequence diagram".⁽¹⁵⁾ Individual risk (IR) and societal risk (SR) were defined

and gradually recognized by researchers and industries as two risk indices to evaluate the safety level of a hazardous installation.^(1, 13) The IR is defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity.⁽¹⁶⁾ The SR reflects the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards.^(1, 13) In reality, the IR represents the risk to individual users and the SR expresses the overall safety level of hazardous installations. It should be pointed out that this conventional IR is inapplicable for the road tunnels as tunnel users are not permanently present at a certain location of the road tunnels.

As mentioned above, QRA is now explicitly required by the EU Directive 2004/54/EC, on minimum safety requirements for road tunnels in the Trans-European Road Network.⁽³⁾ In addition to the above-mentioned academic studies on the QRA of road runnels, some countries have developed their own QRA models for risk assessment of road tunnels in their countries. Some examples include OECD/PIARC model, Dutch TUNprim model, Austria TuRisMo model, Italian risk analysis model, French model.⁽¹³⁾ Among these models, OECD/PIARC model^(17, 18) and Dutch TUNprim model⁽¹⁹⁾ are well recognized by researchers and the authorities for land transport in various countries. Table I lists the model structures, top events, consequence estimation models, and safety targets of the two models.

(Table I is inserted here)

Table I shows that OECD/PIARC model focuses on the risk analysis of hazardous materials transportation in road tunnels and Dutch TUNprim model was built for the homogeneous road tunnels. The Center for Chemical Process Safety (CCPS) had earlier proposed the idea of dividing the route into a number of homogeneous portions for risk assessment of hazardous

materials transport in 1995.⁽²⁰⁾ In the model, all the parameters involved in risk calculations (accident frequency, scenario probability, population at risk, etc.) for each homogeneous portion is assumed to be constant numbers.

1.2 Contributions and Objectives

From the literature review, it can be concluded that there is no generic QRA model that is applicable for evaluating safety level of non-homogeneous urban road tunnels. This is because non-homogeneous urban road tunnel cannot be examined homogeneously without taking the multifarious geometric layouts of its tunnel sections into account. Different from other road tunnels, toxic gases due to congestion should be considered as a unique characteristic for urban road tunnels in view of their high traffic volume as well as enclosed environments. Frequently traffic congestions might result in high concentration of toxic gases in the enclosed area if the tunnel ventilation system fails to work. Furthermore, frequency of vehicle collisions in road tunnel section is difficult to estimate due to lack of historical records. Thus, we need a robust method that can estimate accident frequency by using limited historical records. In addition, the conventional definition of IR is not suited for the risk assessment of road tunnel⁽²¹⁾ as tunnel users are not permanently present at a specific location in the tunnel. Necessary revisions to the definition of IR need to be taken into consideration so that it is able to assess the risks for road tunnel users. Individual risk is considered as a risk to individual tunnel users with distinct travel profiles in this article, which is indicated in detail in Section 2.

This paper aims to propose a QRA model for non-homogeneous urban road tunnels by taking into account the unique characteristics of the non-homogeneous urban road tunnels. Firstly, a tunnel segmentation principle dividing a non-homogeneous urban road tunnel into a number of homogeneous road tunnel sections is developed. Then the individual risk for a road tunnel

section as well as the integrated risk indices for the entire road tunnel is defined. This paper proceeds to develop a new QRA model for each homogeneous urban road tunnel. Compared to the existing QRA models for road tunnels, this section-based QRA model includes one additional top event: toxic gases due to traffic congestion and employs the Poisson regression method to estimate the accident frequency. This paper will thus build an aggregated QRA model for the non-homogeneous urban tunnels by integrating the section-based QRA models. Finally, a case study in Singapore will be used to elaborate on the QRA model proposed in this study.

The remainder of the paper is organized as follows. The road tunnel segmentation principle and risk indices are introduced in Section 2. The QRA model for particular urban road tunnel section is illustrated in Section 3. Section 4 aggregated the risks of the homogeneous road tunnel sections and a case study in Singapore is carried out in Section 5. The conclusions and recommendations are given in Section 6.

2. ROAD TUNNEL SEGMENTATION AND RISK INDICES

2.1 Tunnel Segmentation Principle

A non-homogenous urban road tunnel comprises of multiple entry and exit slip roads as well as main tunnel bores hence possesses the non-homogeneous characteristics. The urban road tunnel segmentation principle aims to divide the whole road tunnel into several individual homogeneous sections. These homogeneous sections can be classified into 3 types according to their geographical layouts and characteristics. Type I represents slip road sections, which is an enclosed roadway section entering or leaving the main road tunnel. Type II refers to road tunnel intersections. This section is where the traffic from slip road tunnels merges with main tunnels or leaves main tunnels to slip road tunnels. Type III represents main road tunnel sections. Figure 1 gives an example of how a road tunnel can be segmented according to the principle. Note that the

geometric layouts, traffic conditions, E&M system installations, and traffic accident rates for each road tunnel section may have distinct values.

(Figure 1 is inserted here)

2.2 Risk Indices

The conventional definition of individual risk is to evaluate the risk exposed to residents close to nuclear power plants under an assumption that the residents are permanently present at a location, which is unrealistic for road tunnels. Therefore, the definition of individual risk for road tunnels is not suited for road tunnel risk assessment. Assume that a non-homogenous urban road tunnel has K homogenous tunnel sections where K is a positive integer. IR for a particular homogeneous road section is defined as follows: “Individual risk of a road tunnel section is the probability that a particular unprotected individual is killed due to an incident resulting from a hazardous activity in the road tunnel section”. Different from the conventional definition of individual risk, the IR for road tunnel does not assume that a tunnel user is permanently present at a location. Instead, it reflects the risks exposed to individual tunnel users with distinct travel profiles. Let IR_k denote the IR of road tunnel section k and it can be expressed by

$$IR_k = \frac{n_k \times L_k}{\sum_{i=1}^I Q_{ki} \lambda_i} \times \sum_{j=1}^{J_k} F_{jk} N_{jk}, k = 1, 2, \dots, K \quad (1)$$

where n_k is the number of times that a given individual tunnel user passes through tunnel section k per year; L_k is the length of tunnel section k (km); I is number of vehicle types; Q_{ki} is yearly travel rate of all type i vehicles passing through tunnel section k (veh·km/ year); λ_i is average number of travelers using vehicle type i vehicle; F_{jk} is the yearly frequency of accident scenario j occurred at tunnel section k ; N_{jk} is number of fatalities when scenario j occurred at

tunnel section k ; J_k is the total number of accident scenarios that could be occurred at tunnel section k .

SR is defined as the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards^(22, 23). It can be represented graphically in the form of an F/N curve. The concept of F/N curve to represent societal risk has been applied in the existing QRA models for road tunnels^(1, 13). The curve reflects the relationship between the frequencies and the number of fatalities of all the possible scenarios on a double logarithmic scale. Let $F_k(N)$ denote the cumulative frequencies of all the accident scenarios occurred at tunnel section k with N or more fatalities. We thus have:

$$F_k(N) = \sum_{j=1}^{J_k} [F_{jk} \times \delta(x_{jk} - N)], k = 1, 2, \dots, K \quad (2)$$

where x_{jk} is the number of fatalities caused by accident scenario j occurred at tunnel section k and indicator function $\delta(x_{jk} - N)$ has the expression:

$$\delta(x_{jk} - N) = \begin{cases} 1, & \text{if } x_{jk} \geq N \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

The frequencies and fatalities of all possible accident scenarios are the basis used for the calculation of IR and SR. The method used to estimate the frequencies and number of fatalities will be illustrated in the following sections. The upper bound curve of societal risk has been adopted by various countries as the safety target,⁽²²⁾ namely,

$$F(N) \leq \frac{C}{N^k} \quad (4)$$

where parameters k and C specify the steepness and intercept of the safety target. Alternatively, eqn. (4) can also be represented by:

$$k \log(N) + \log(F(N)) \leq \log(C) \quad (5)$$

It should be noted that k represents a slope, i.e. gradient of the safety target, and C denotes an intercept, i.e. constant value that determines the position of the target. Different combinations of k and C express various strictness degrees of the safety target. As a result, different countries may propose their own safety targets. For example, the k and C values adopted by Netherlands are $C=10^{-3}$ and $k=2$, while Switzerland adopts $C=10^{-4}$ and $k=1$.^(1, 16, 21)

In order to measure severity of societal risk, slack clearance index is defined as the minimum gap from safety target to the F/N curve, namely,

$$SL = \min_{i \in A} \{ \log(C) - k \log(N_i) - \log(F(N_i)) \} \quad (6)$$

where A is the set of the selected values of number of fatalities, $F(N_i)$ is the cumulative frequency of all the accident scenarios occurred at the road tunnel with N_i or more fatalities. The index indicates the slack clearance between safety target and F/N curve. SL takes non-negative values if the tunnel is considered safe according to the predetermined safety target. The less SL is, the riskier the tunnel is in terms of societal risk.

The authorities for road tunnel may require an integrated index to evaluate the individual risk and societal risk for the road tunnel as a whole. Therefore, we define two types of integrated risk indices for the entire non-homogenous road tunnel after obtaining the IR and SR values expressed in the eqns. (1) and (2) for each homogeneous tunnel section. Eqns. (7) and (9) illustrates the risk in the worst section of the tunnel while eqns. (8) and (10) defines the risk for overall road tunnel by weighing the risk indices for each tunnel section. Therefore, two integrated IR risk indices can be mathematically expressed as follows:

$$\hat{IR} = \max_{k=1,2,\dots,K} \{ IR_k \} \quad (7)$$

$$\overline{IR} = \sum_{k=1}^K [\omega_k \times IR_k] \quad (8)$$

where parameter ω_k is the weight of tunnel section k . Note that these weights are determined by tunnel risk evaluators. For example, the section travel rate (veh·km/year) is considered as the weight in Singapore road tunnel risk assessment. In reality, the tunnel section length, traffic volume of tunnel section, accident rate of tunnel section, etc. can also be considered as the weight.

Similarly, two integrated societal risk indices can be equally defined below.

$$\hat{F}(N) = \max_{k=1,2,\dots,K} \{F_k(N)\} \quad (9)$$

$$\overline{F}(N) = \sum_{k=1}^K [\omega_k F_k(N)] \quad (10)$$

Eqns. (7) and (9) represent a pessimistic principle from the viewpoint of tunnel designers, who adopted the risk of the worst section in the road tunnel. This principle is attractive to those who wish to guard against the “worst case” at least for contingency planning. Evidently, tunnel designers are more concerned about the high consequence events (worst case). Eqns. (8) and (10) express a mean value principle from the standpoint of tunnel managers, which defines the risk for overall road tunnel by weighing the risk indices for each tunnel section. Tunnel managers focus on minimizing the total fatalities of the road tunnel. These two principles are widely used in game theory and statistics. ^(24, 25)

3. QRA MODEL FOR A PARTICULAR ROAD TUNNEL SECTION

Given a particular homogeneous tunnel section k of a non-homogeneous urban road tunnel, its QRA model is built according to the following procedures. Firstly, all possible hazards such as fire, flooding in this tunnel section are identified as the top events. Subsequently, fault trees

and event trees for each of the top events are built. An event tree consists of a number of particular accident scenarios triggered by a top event. Fault tree is used to estimate the frequency of a top event that could occur. The frequency of each particular accident scenario can be calculated by multiplying the frequencies of top event and the fractions / probabilities of sequential events (e.g. peak hour, fire detection failure, etc.) associated with this scenario. Furthermore, consequence estimation models are required to calculate the number of fatalities for various accident scenarios involved in an event tree. After obtaining the frequency and fatality of each accident scenario, the IR and SR expressed by eqns. (1) and (2) can be calculated.

3.1 Seven Top Events and Their Event Trees

A top event is a possible hazard which can lead to fatalities in the homogeneous tunnel section. Fire, flooding, chain collision, tunnel collapse, explosion and spillages due to hazmat materials are selected as the 6 top events. These 6 top events cover all the top events used by the existing QRA models developed for the homogeneous road tunnels. ^(1, 13, and 19) Traffic congestion is unavoidable in urban road tunnels due to increasingly heavy traffic. Although traffic congestion itself is not possible to result in fatalities, heavy traffic congestion in combination with failure of ventilation may lead to highly dense toxic gases in the enclosed space and thus causes fatalities, especially in urban cities. The air quality in a tunnel can deteriorate easily if air pollutants emitted from vehicles are not promptly diluted. The situation may even worsen during traffic jams as more pollutants are emitted at low vehicle speeds. The toxic gases may accumulate in road tunnels at a high concentration, which poses serious health problems. ^(26, 27) In addition, in some densely populated cities, traffic congestion problems are frequently taken place due to limited roads and heavy traffic. Thus, toxic gases due to traffic congestion should be identified as the 7th top event.

Top events may trigger a series of simple events with different results (frequencies and consequences). These simple events can be represented logically by an event tree. An event tree is simply a tree diagram referring to complex events that can be discretized in terms of their possible outcomes and possibly in terms of their distinction by sequential events into a series of simple events. Figure 2 depicts the event tree starting from “Fire in tunnel” and terminating at Fire Fighting Column. Because A4 page cannot accommodate the event tree, the tree is decomposed into two sub-event trees, namely, sub ET 1 and sub ET 1.1. Sub ET 1.1 continues from all the leaf nodes of sub ET 1. There are 240 scenarios (leaf nodes of the tree) in the event tree. The top two sequential events (period of day and vehicle composition) are the same for all the seven event trees. The differences between event trees of various top events are dependent on the tunnel mitigation facilities. Figure 3 depicts the tunnel mitigation facilities with respect to the other four top events: flood, chain collision, spillages due to hazardous materials, and toxic gases due to traffic congestion. Note that the consequences caused by the top events of tunnel collapse and explosion are catastrophic and instantaneous, thus no mitigation facility can immediately evacuate tunnel users so as to reduce the fatality rate. The event trees initiated by these two top events only involve the top four sequential events.

(Figure 2 is inserted here)

(Figure 3 is inserted here)

The frequency of each scenario can be regarded as the product of frequency of top event and conditional probabilities / fractions of sequential events. The frequencies of top events can be estimated by using fault tree technique (Section 3.2). The conditional probabilities / fractions of sequential events can be calculated by historical statistics or instruction manuals of tunnel mitigation facilities. As for the number of fatalities for each scenario, it can be computed by the

consequence estimation models (Section 3.3).

3.2 Fault Trees and Parameters Estimation

Fault tree is a good tool used to estimate frequency of a top event. Fault tree of the top event “Fire in tunnel” is built as shown in Figure 4. Fault trees of the other top events are collectively depicted in Figure 5. The circles attached to the leaf nodes of fault trees are the notations of input parameters to the fault tree. For example, PI and VD shown in Figure 4 denote probability of ignition when vehicle defect takes place and frequency of vehicle defects respectively. The meanings of notations in fault tree for fire in tunnel top event are explained in Figure 4. Note that the frequency of chain collision can be derived from historical statistics. Thus, it is unnecessary to develop a fault tree for chain collision.

(Figure 4 is inserted here)

(Figure 5 is inserted here)

3.2.1 Accident frequency estimation model

Most input parameters of the fault trees can be obtained from the historical statistics. However, accident frequency (frequency of vehicle collisions) is difficult to estimate due to little collision records in one particular road tunnel section. In this section, a Poisson regression model is adopted to compute an upper bound of the frequency of vehicle collisions in a road tunnel section.

In 1994, Miaou illustrated that the frequency of collision in one particular road section is determined by road characteristics such as road section length, horizontal curvature, vertical grade, lane width, and traffic volume.⁽²⁸⁾ The relationship between frequency of vehicle collision accidents and highway characteristics have been studied using multiple linear regression models, Poisson / Negative Binomial (NB) regression models, and zero inflated models in numerous

previous studies. ⁽²⁹⁾

However, it is not possible to calibrate the relationships by using the limited accident records in road tunnel sections. Literature shows that the frequency of collisions inside tunnels is a little lower than inside open roads ^(30, 31). The highway accident records are used to calibrate the accident frequency regression model in road tunnels in view of the higher safety requirement in road tunnels and better availability of accident records. In this study, the highway data collected from LTA of Singapore are applied to calibrate the Poisson regression model in order to build the relationships between frequency of collisions and road characteristics. The calibrated regression model is used to estimate the frequency of vehicle collisions in a road tunnel section. It should be pointed out that the accident frequencies estimated from the model based on highway data are higher than actual frequency of road tunnel sections and could be considered as an upper bound of frequency of vehicle collisions of a road tunnel section. In view of the higher safety requirements in road tunnels, the upper bound is adopted in this study to represent the vehicle accident frequencies in road tunnel sections. The Poisson regression model is described as follows.

$$P(Y_k = y_k) = P(y_k) = \frac{\mu_k^{y_k} e^{-\mu_k}}{y_k!}, k = 1, 2, \dots, n \quad (11)$$

where parameter

$$\mu_k = E(Y_k) = v_k \exp(x_k' \beta) \quad (12)$$

where β is a $n \times 1$ vector of unknown regression parameters and x_k' is the road characteristics vector (road section length, traffic volume, lane width, number of lane, and etc.). The model assumes that the number of vehicle collision (frequency of collisions) $Y_k, k=1, 2, 3, \dots, n$ are

independently Poisson distributed random variable with mean μ_k . $P(Y_k = y_k)$ denotes that the probability that y_k collisions take place in tunnel section k in a year. The expected number of vehicles in accidents μ_k or $E(Y_k)$ in the model is proportional to traffic volume v_k . According to Miaou,⁽²⁸⁾ the model assumes an exponential rate function: $\lambda_k = E(Y_k) / v_k = e^{x_k \beta}$, which ensures that accident-involvement rate is always nonnegative. This type of rate function has been widely employed in statistical literature and found to be very flexible in fitting different types of count data^(32, 33). The regression parameters β of the model can be estimated using the Maximum Likelihood (ML) method, the quasi-likelihood method⁽³⁴⁾, or the generalized least squares method⁽³⁵⁾. The estimated parameters from the last two methods would converge to those from the ML method as more iteration is used.

After obtaining the $e^{x_i \beta}$, the average frequency of collision (μ_k) can be estimated by substituting the value of the tunnel characteristics such as tunnel section length, lane width, tunnel lane curvature and etc., which can be obtained from tunnel designers.

3.3 Consequence Estimation Models

3.3.1 Branch-based generic consequence estimation method

In this section, the branch-based consequence estimation method is illustrated. There are a number of particular branches for each event tree. The model for estimating the number of fatalities for each branch is called branch-based consequence estimation models. The models for all the branches are the same. However, the input parameters may differ according to the choice of sequential events (failure or success).

(Figure 6 is inserted here)

Without loss of generality, we use a simple “Fire in tunnel” event tree example to illustrate

the branch-based consequence estimation approach. Assume that the number of fatalities for various branches in the event tree for fire in tunnel shown in Figure 6 can be calculated by using the formula

$$F = f(u_1, u_2, u_3, u_4, u_5) \quad (13)$$

where u_1 is frequency of fire in tunnel, u_2 is heat release rate, u_3 is the traffic volume, u_4 is the air velocity, u_5 is the delay time with respect to different working conditions of fire detection system. For example, if we want to calculate a scenario that two cars collides during peak hour in combination of all tunnel E & M systems failing to work, u_2 should take values with respect to two car colliding, u_3 should take value of traffic volume in peak hour, u_4 and u_5 should use the corresponding values of “Fire detection failure” and “Tunnel ventilation failure”, respectively.

Consequence estimation models have been studied in order to estimate the consequence for each top event. Numerous scholars contribute their efforts on this problem. An overview is given in Table II. Those models can be applied to road tunnel consequence estimation. For traffic congestion, its consequence estimation model will be proposed in Section 3.3.2. The details of other models can be found from the Appendix. It should be pointed out that several top events may be involved in a particular accidental scenario. Consider a combinational event that vehicle collision causes fire as well as traffic jams. Not only fire but also toxic gases due to traffic congestion are involved in this scenario. The fatalities caused by different top events will be estimated separately and their summation is considered as the number of fatalities that the combinational event occurs.

(Table II is inserted here)

3.3.2 Consequence estimation model for toxic gases due to traffic congestion

Traffic congestions take place frequently in urban road tunnels in highly populated cities. For example, the average travelling speed in Singapore CTE road tunnel in morning peak hour is around 10 km/hour and the tunnel is called “the largest car park in Singapore”. Heavy traffic congestion in combination with failure of ventilation may lead to highly dense toxic gases in the enclosed space and thus cause fatalities. Traffic congestion is a low consequence – high probability event, which should also be addressed carefully in risk assessment procedure. Therefore, it is considered as a top event in our study.

There has been an increasing interest in air pollution as people want to better comprehend the dangerous effects of air pollutants on human health.^(26, 42) As a result, a considerable number of studies have been done on this study.^(43, 44) In our model, a basic assumption is that the congestion cannot lead to fatalities if the tunnel ventilation system works normally. Our model considers the scenario whereby the tunnel ventilation fails to work in order to estimate the fatality rate. Firstly, traffic emission rates are estimated according to the model developed by Chung and Chung.⁽⁴⁴⁾ The model illustrated that the traffic emission rates rely on the traffic volume, speed, vehicle composition, and cross-sectional area of the tunnel. After that, the Bellasio approach⁽⁴³⁾ is adopted to calculate the concentrations of various emission gases. The approach provides an equation to calculate the concentration of various emission gases using tunnel configuration parameters, vehicle emission rate, sink rate, and advection speed. Finally, the fatality rate due to toxic gases generated by traffic congestion can be calculated using the Persson approach.⁽³⁸⁾

According to Chuang and Chuang⁽⁴⁴⁾, the traffic emission rate q_{ik} of type i in the k -th lane is determined by,

$$S_{ik} = \frac{E_{ik}(t) \times N(t)}{A \times 1000} \quad (14)$$

where E_{ik} is the emission factor of type i in the k -th lane; A is the cross-sectional area of the tunnel; and N is the average traffic flow rate (or number of vehicles per unit time). Because both N and A are determined from measurements, q_{ik} can be evaluated once E_{ik} , which depends on the vehicle speed, is known. In this paper, E_{ik} is adopted as given by TANEEB⁽⁴⁵⁾ and listed in the Table III for the two types of vehicles.

$$C = C_B + \frac{S}{A\varpi + \frac{2AK_x}{L} + R^*} \quad (15)$$

where C is the concentration of toxic gases, C_B is the external concentration, L is the tunnel length, S is the emission rate which can be calculated by equation (14), K_x is the dispersion coefficient, ϖ is the air velocity, R^* is the sink rate which can be determined by tunnel ventilation system, A is the cross sectional area of the tunnel.

(Table III is inserted here)

According to the research done by Persson,⁽³⁸⁾ the fatality rate due to CO can be estimated by,

$$F_{CO} = 2K \left(X_{CO}^{1.036} \right) t \quad (16)$$

where parameter D is %COHb at incapacitation (30%) or a death 50%; X_{CO} is CO concentration; and $K = 8.2925 \times 10^{-4}$.

Similarly, the fatality rate due to NO_x could be calculated by,

$$F_{NO_x} = -18.6 + \ln(X_{NO_x}^{3.7} t) \quad (17)$$

where X_{NO_x} is the concentration of NO_x , t is the exposure time⁽³⁸⁾.

3.3.3 Validation of the consequence estimation model due to tunnel fire

Based on the historical record of Mont Blanc, Burnley, and Tauren road tunnel fire incidents, the input parameters such as vehicle composition, distance between two consecutive exits, traffic

volume, delay time for response, and tunnel configurations can be calibrated. Some other input parameters of our model, such as the ratio of different age group of Italy and French in the case study for Mont Blanc tunnel fire, can be obtained from internet search. The key input parameters are as follows shown in Table IV.

(Table IV is inserted here)

The comparison between historical record of death and number of fatalities generated by the model is shown in Table V. The results have proven the effectiveness and reliability of the proposed model.

(Table V is inserted here)

4 AGGREGATED QRA MODEL FOR THE NON-HOMOGENEOUS URBAN ROAD TUNNELS

Having established the QRA model for homogenous road tunnel section, an aggregated QRA model for the non-homogeneous urban road tunnels can be developed. Figure 7 shows the customized framework for building the aggregated QRA model. Firstly, according to the proposed tunnel segmentation principle, a non-homogeneous road tunnel is segmented into a number of homogeneous sections, where all the parameters involved in risk calculations can be assumed to be constant. The QRA models for the various road tunnel sections are built separately and the IR and SR for each tunnel section are calculated independently. Subsequently, the integrated risk indices shown in eqns. (7) - (10) can be evaluated for the entire road tunnel. Table VI shows the merits and explanations of the aggregated QRA model. The model incorporates more accidental scenarios and considers more specific input parameters than the existing models for road tunnels. More importantly, the section-based risk assessment is employed to better support tunnel managers' decisions. This model is thus considered as an appropriate approach to

estimate the risks for non-homogeneous urban road tunnels.

(Figure 7 is inserted here)

(Table VI is inserted here)

5. A CASE STUDY

Marina Coastal Expressway (MCE) is built to serve the projected increase in traffic volume due to the large number of developments in the Marina Bay area, Singapore. It also serves as a vital transport link from Marina Bay to other parts of the island. MCE will be the tenth expressway, which is the key element of the strategic island-wide road network to support the long-term growth of Singapore. It is a dual five-lane, 5km long expressway with 3.8km of it built underground. It will run through segments of reclaimed land as well as a 420m section that runs below the seabed of Marina Bay. The functionality and working profiles of the E & M systems can be obtained from their instruction manuals. The values of the vehicle profiles can be obtained from the planning department of LTA of Singapore. The distance between two emergency exits is 100 meters. The tunnel air velocities when tunnel ventilation works normally and fails to work are 4 m/s and 1 m/s, respectively. The safety target of $(10^{-3}/N^2)$ is applied in this case study.

(Figure 8 is inserted here)

By adopting the tunnel segmentation principle, MCE can be divided into 16 sections, 7 sections on the eastbound and 9 sections on the westbound tunnel. On the eastbound tunnel, there are 2 tunnel slip road sections, 2 tunnel intersection sections and 3 main tunnel sections are considered. As for the westbound tunnel, there are 3 tunnel slip road sections, 3 tunnel intersection sections and 3 main tunnel sections. Table VII shows samples of the type, length and traffic volume of each section.

(Table VII is inserted here)

The geometry figure of the segmented MCE tunnel is as follows:

(Figure 9 is inserted here)

5.1 Accident Frequency Estimation and the Other Parameters

In this case study, the highway accident record and road characteristics were used to calibrate the Poisson Regression model in view of the higher safety requirement and better availability of the data. Actual data, including accident records and highway/tunnel characteristics, which were provided by Land Transport Authority of Singapore, were used to establish the relationships among accident frequency and road characteristics. For the study, accident records for 15 different expressway sections from 2006 to 2007 were used. During these two years, 412 vehicles were reported to be involved in accidents on the selected sections, regardless of vehicle types and accident severities. Number of lanes, lane width, shoulder width, curvature, and section length were considered as the most critical geometric design factors. Note that the vertical gradient was not considered as a covariant because the gradients of Singapore road tunnels were not steep⁽⁴⁾.

The Poisson model performs the best in estimating the frequency of road sections with four or more accident involvements⁽²⁸⁾. From the data, only 1 section out of 13 sections had less than 4 accidents per year. Meanwhile, the hypothesis test showed that the accident record data follow Poisson distribution. Therefore, Poisson regression model was adopted to predict the accident frequencies for tunnel sections.

The Poisson regression model can be solved by the statistical analysis software - Matlab. The induced Poisson regression model is as follows:

$$P(Y_k = y_k) = \frac{\mu_k^{y_k} e^{-\mu_k}}{y_k!} \quad (18)$$

where parameter:

$$\mu_k = v_k \times \exp(8.7407x_{1k} + 2.5173x_{2k} - 0.0185x_{3k} - 3.1132x_{4k} - 1.7361x_{5k} - 1.1161) \quad (19)$$

$$k = 1, 2, \dots, n$$

where y_k is yearly frequency of vehicle collisions happened in the tunnel section k , $P(Y_k = y_k)$ stands for the probability that y_k vehicle collisions happen in the tunnel section k which can be estimated from accident historical records, μ_k denotes average number of vehicle collisions in a year, x_{1k} stands for length of the section k (km), x_{2k} denotes horizontal curvature of the section k (degrees per 100 meters arc), x_{3k} is lane width (m), x_{4k} stands for shoulder width of section k (m), x_{5k} stands for number of lanes, and v_k is the traffic volume of section k (veh/hour). Thus, the relationship among tunnel characteristics and yearly vehicle collision frequency is established in eqn. (18).

T-statistics test concluded that the relationships between accident frequencies and the examined traffic and geometric design variables are consistent. Actual accident record data from Singapore Central Expressway road tunnel (CTE) was adopted to further validate the model. Accident records from 2007 to 2008 were used in validation model. The results are shown in Table VIII, which show the practicality and accuracy of the proposed method. By using this model, accident frequency can be estimated based on the traffic volume and tunnel geometries.

(Table VIII is inserted here)

As for other fault tree parameters, such as ignition probability when there is vehicle defect or collision, can be obtained from the academic papers, historical statistics, or expert assumptions.

5.2 Results and Discussions

The aggregated QRA model is coded by C# on a desktop personal computer. After considering all the above-mentioned input parameters for the MCE tunnels, the aggregated QRA

software can generate the expected value of number of fatalities per year, IR and SR for each road tunnel section and the integrated risk indices.

Figure 10 shows the expected value of number of fatalities per year, the individual risk, and societal risk represented by F/N curve. Figure 10(a) is the calculation results by QRA model for non-homogeneous road tunnels proposed in this paper. Figure 10(b) depicts the results if the MCE road is regarded as one tunnel section. Figure 10(c) presents the results if the traffic congestion top event is not taken into account in the QRA model for non-homogeneous road tunnel. Figure 10(d) shows the result of the section with the highest risk in terms of societal risk.

(Figure 10 is inserted here)

As shown in Figure 10(a) and Figure 10(b), both the individual risk and societal risk generated by the two models are of significant difference, which is reflected by the frequency intercept of the F/N curve and the value of individual risk. It draws the conclusion that QRA model for non-homogeneous road tunnels such as MCE road tunnel is necessary. A and B display the first point of the F/N curves shown in Figure 10(a) and Figure 10(b), respectively. The corresponding frequencies for the two points are 1.48×10^{-4} /yr and 1.07×10^{-4} /yr respectively. This means the frequencies of lower consequence events may significantly vary with respect to different tunnel segmentations. By comparing Figure 10(a) and Figure 10(c), traffic congestion contribute 11% of the number of fatalities for MCE road tunnel. It illustrates that the traffic congestion is a considerable top event which should be paid attention to. QRA model for non-homogeneous road tunnel can further generate the risks of individual section. Hence, the section with the highest risk can be identified. This is very important for tunnel manager to decide risk reduction strategy.

From the results, we found that tunnel sections 1, 6, 7, 8, 10, 11, 14, and 16 have higher

tunnel risks in terms of individual risk (individual risks are greater than 6×10^{-9}). All the tunnel sections are considered safe according to the test safety target. Tunnel sections 6, 8, 10, 11, 14, and 16 have smaller slack clearances (less than 0.2) which indicate that they are riskier in terms of societal risk. Compared to other tunnel sections, the above-mentioned sections have higher traffic volume and frequencies of collisions. In reality, the traffic volumes of eastbound are indeed less than that of westbound from the planning data. This is because more traffic transits from the East Coast Expressway, one of the busiest expressways in Singapore, to MCE road tunnel. In addition, there are limited tunnel mitigation facilities in slip roads. These may also result in higher risks in slip road tunnel section. However, the total travel rates (weights for risk integration) of tunnel section 7, 8 (slip roads), 6, 11, 14 (tunnel intersection), and section 1 (short main tunnel) are much smaller than those of tunnel section 10 and 16 (long main road tunnel). Therefore, tunnel section 10 (41,686,921 veh·km/year) and section 16 (12, 161, 137 veh·km/year) contribute most to the overall road tunnel risk.

6. CONCLUSIONS

This paper proposed a novel QRA model to effectively and efficiently evaluate the risks for non-homogeneous urban road tunnels. In this proposed QRA model, urban road tunnels are segmented into a number of homogeneous sections and the section-based QRA models are built for each individual section. Risk indices for the entire road tunnel are integrated by pessimistic principle and average principle. In contrast to the existing QRA studies for road tunnels, the proposed section-based model incorporates one additional top event: traffic congestion and employs the Poisson regression method to estimate the accident frequency. An aggregated QRA model for the non-homogeneous urban tunnels is finally built by integrating the section-based QRA models and a case study in Singapore is carried out.

Based on the proposed QRA model, the risk assessment of a road tunnel is determined by a variety of input parameters. However, the values of input parameters are difficult to obtain due to their variability and/or lack of information. In the present study, an input parameter is represented by a crisp number (worst case / most probable value from expert judgment or mean value from the historical record) without considering the inherent random uncertainty and/or imprecision of the parameter, which is unrealistic and could result in unreliable assessment. Further research is needed for better representing input parameters as well as propagating parameter uncertainty. Probability theory, possibility theory, and evidence theory may be useful to address the parameter uncertainty problem. Another future work proposed by the authors is that a simulation model for road tunnel traffic may be helpful to obtain historical data for those low frequency events.

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Table I Model structures, top events, etc. of existing QRA models

Models	Procedure	Top events	Consequence estimation	Risk index
PIARC/OECD/EU GRAM	<p>(1) Option of a restricted number of dangerous goods;</p> <p>(2) Option of representative accidental scenarios implying those dangerous goods;</p> <p>(3) Identification of physical effects of those scenarios on an open air or a road tunnel section;</p> <p>(4) Evaluations of their physiological effects on road or rail users and on the local population taking into account of the possibilities of escape/sheltering;</p> <p>(5) Determination of yearly frequency of occurrence for each scenario.</p>	13 hazardous scenarios	<p>The consequences of a restricted number of scenarios is examined including:</p> <p>(1) Physical modelling of the effects: explosions, fire or toxic releases.</p> <p>(2) Effects on road/ rail users and local population.</p>	<p>Individual risk</p> <p>Societal risk</p> <p>Expected value of fatalities</p>
Dutch TUNprim model	<p>(1) Identification of initial events;</p> <p>(2) Identification of accident scenarios in an event tree, each branch of the event tree is a scenario;</p> <p>(3) Frequency calculation for each scenario;</p> <p>(4) Consequence estimation for each scenario;</p> <p>(5) Calculation of the overall risk.</p>	<p>(1) Traffic disturbance without damage;</p> <p>(2) Collisions;</p> <p>(3) Fire;</p> <p>(4) Explosion;</p> <p>(5) Leakage of aggressive and toxic materials.</p>	<p>Consequence for each scenario is calculated as the number of fatalities.</p> <p>Evacuation possibilities:</p> <p>(1) Free fleeing distance</p> <p>(2) Traffic jam</p>	<p>Individual risk</p> <p>Societal risk</p>

Table II Various models to estimate consequences of the five top events

Top event	Model description	Source(s)
Flood	Overview of methods for loss of life estimation for river, coastal and dam break floods	Jonkman et al., 2008 ⁽³⁶⁾ Jonkman, 2007 ⁽³⁷⁾
Fire	Assessment of consequence for fires in road tunnels	Persson, 2002 ⁽³⁸⁾ Nilsen and Log, 2009 ⁽³⁹⁾ Beard, 2009 ⁽⁴⁰⁾
Explosion	Assessment of consequence for explosion in road tunnels	Persson, 2002 ⁽³⁸⁾
Toxic gases	Propose the probit equation for various toxic gases	Weger et al., 1991 ⁽⁴¹⁾

Table III Emission factors of light-good vehicles and heavy-good vehicles

Speed (km/h)	NO_x (g/km)	CO (g/km)
LGV		
30	2.25	19.20
40	2.31	14.10
50	2.39	10.02
60	2.64	7.31
70	3.03	5.61
HGV		
30	14.0	7.5
40	13.7	5.5
50	13.5	4.0
60	14.2	3.2
70	15.5	3.0

Table IV Input parameters for simulating Mont Blanc, Burnley, and Tauern road tunnel fire incidents

Input Parameters	Mont Blanc	Burnley	Tauern
Car Proportion	0.385	0.79	0.76
Bus Proportion	0	0.02	0.02
Motorcycle Proportion	0.038	0	0
HGV Proportion	0.577	0.19	0.22
Distance Between Consecutive Exits	Two 1200m	800m	400m
Traffic Volume	306	2000	882
	veh/hour lane	veh/hour lane	veh/hour lane
Average Length-Bus	20m	20m	20m
Average Length-Car	3.5m	3.5m	3.5m
Average Length-Motorcycle	2m	2m	2m
Average Length-HGV	20m	20m	20m
Average Length-Hazmat	20m	20m	20m
Average Persons Per Bus	35	20	20
Average Persons Per Car	2.5	3	3
Average Persons Per Motorcycle	1.2	1.2	1.2
Average Persons Per HGV	1.8	1	1
Average Persons Per Hazmat	2	1	1
Delay Time for Response to Accidents	10 min	1min	1min
Wind Velocity in Tunnel	6 m/s	4m/s	4m/s
Number of Lanes	1	3	2
Ratio for elderly people	0.17	0.15	0.13
Ratio for elderly people	0.83	0.85	0.87

Table V Comparison between number of fatalities generated by the proposed model and number of death of actual record

	Number of fatalities generated by the proposed model	Number of death of actual record
Mont Blanc road tunnel disaster	33.43	37
Burnley road tunnel disaster	3.51	3
Tauern road tunnel disaster	0.87	1

Table VI The merits and explanations of the new QRA model

Model	Merits and Explanations
Risk assessment method	QRA model incorporating all possible scenarios is more realistic
Input parameters	Consider more specific input parameters than previous developed models: Tunnel configurations; Traffic volume and vehicle composition; Human and vehicle factors; Tunnel E&M system, etc.
Top events	Seven top events such as fire, chain collision, explosion, traffic congestion, spillages of hazardous materials, flooding, and tunnel collapse cover almost all possible scenarios for urban road tunnels
Model building structure	Segment-based risk assessment is employed. The tunnel is divided into several segments, and the overall risk can be the combination of segment-based risks
Frequency estimation and consequences estimation	Event tree and fault tree particularly designed for Singapore is used; complex multi-dimensional consequence estimation model which can get the more reasonable results in the probabilistic context is developed to evaluate the number of fatalities per event

Table VII MCE Tunnel Segmentation

MCE – Eastbound				
Section number	Type of section		Length of section (m)	Traffic volume (veh/hour lane)
1	Main Tunnel	Type III	850	771.0
3	Tunnel Intersection	Type II	100	690.3
4	Slip road	Type I	250	271.3

Table VIII Comparison between regression results and real accident records

	Regression results	Real accident record
Section 1	1.49	5
Section 2	3.75	7
Section 3	6.97	6
Section 4	9.27	8

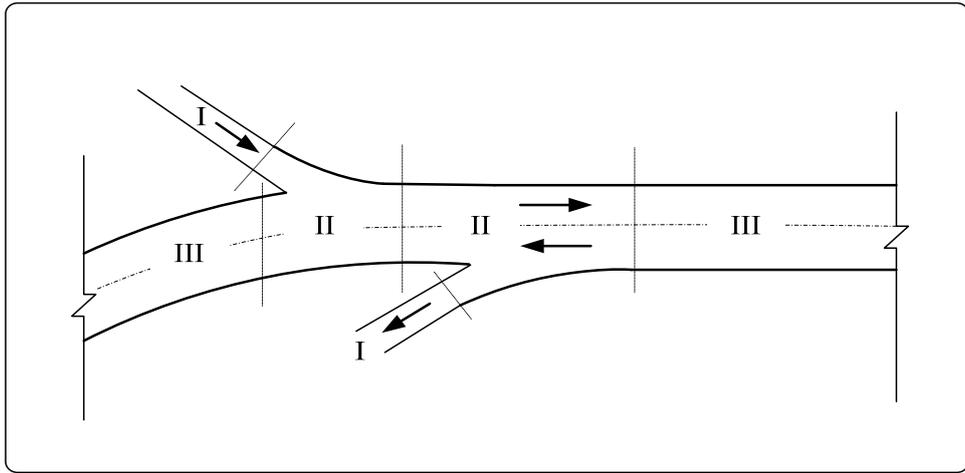
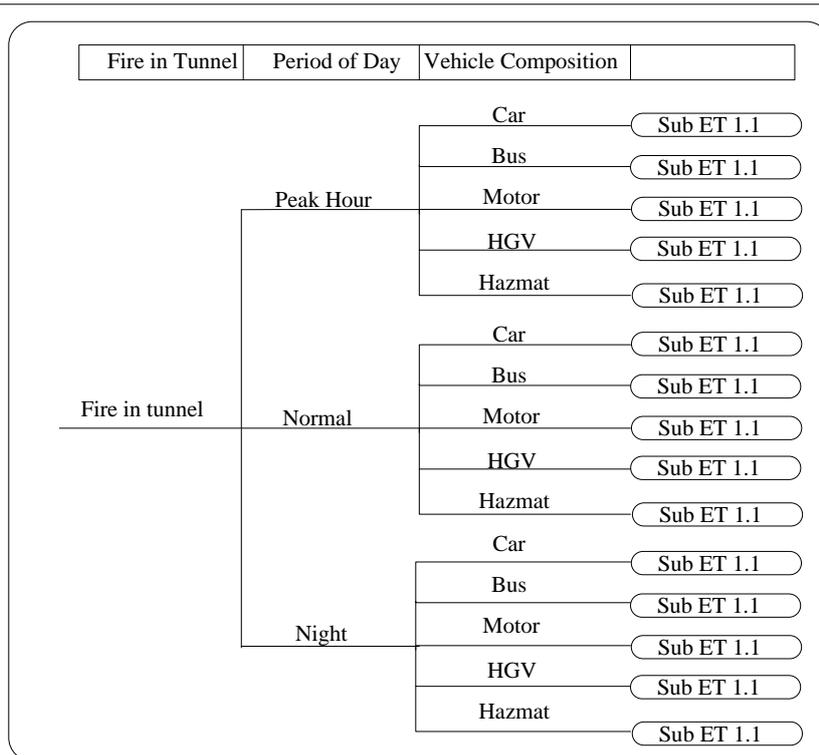
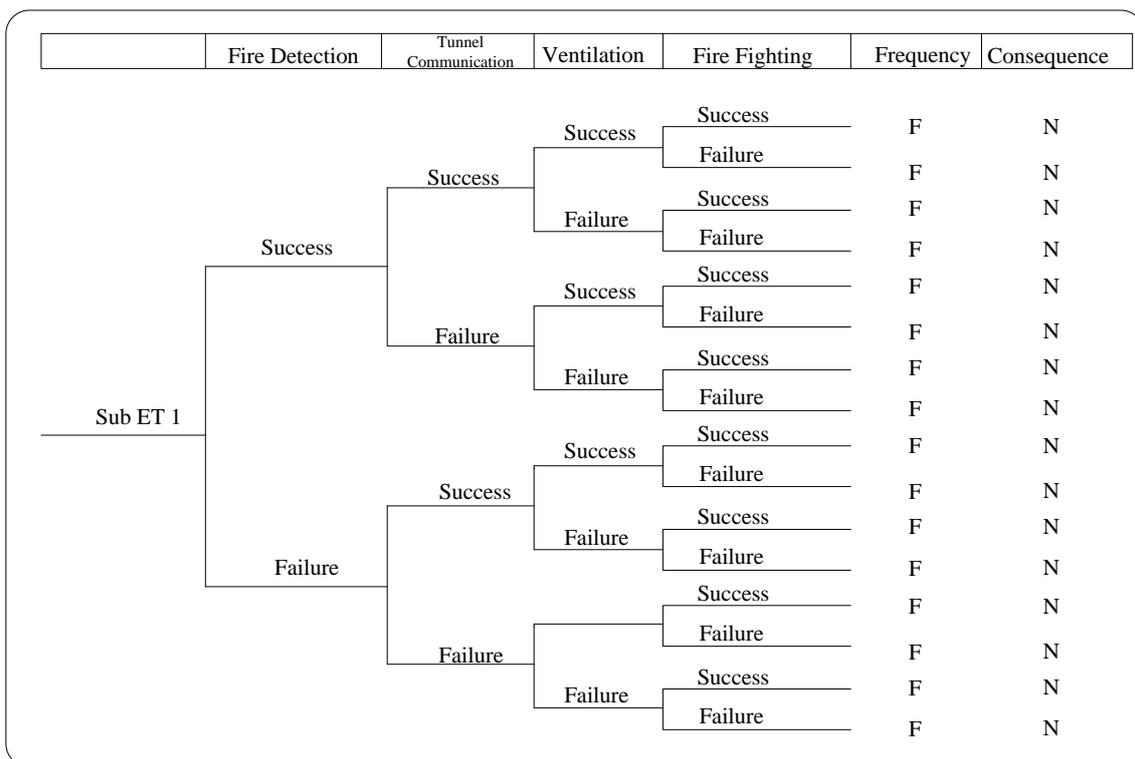


Figure 1 An example for tunnel segmentation



(a) Sub ET 1



(b) Sub ET 1.1

Figure 2 Event Tree for fire in tunnel top event

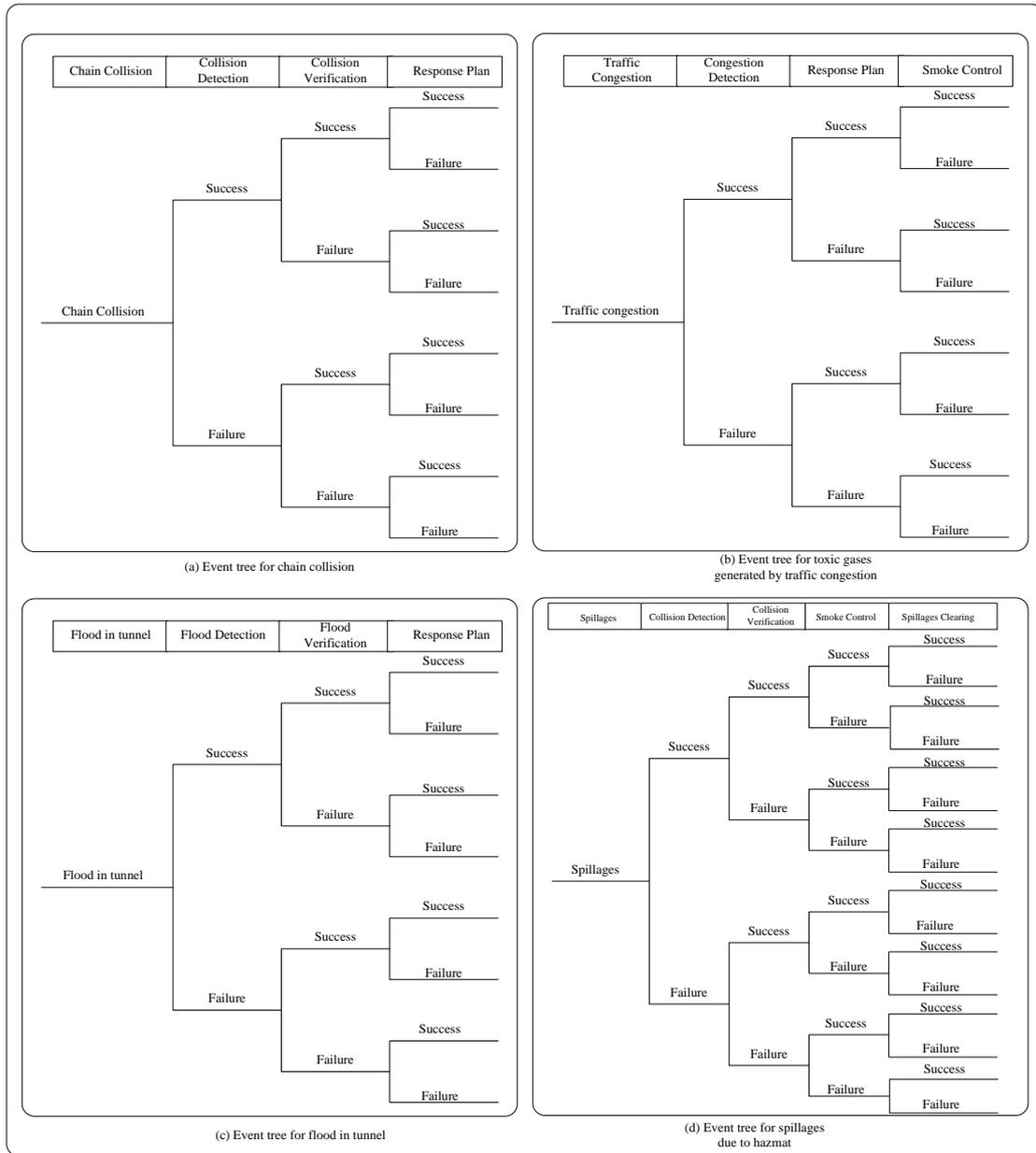


Figure 3 Event Tree for Other Top Events

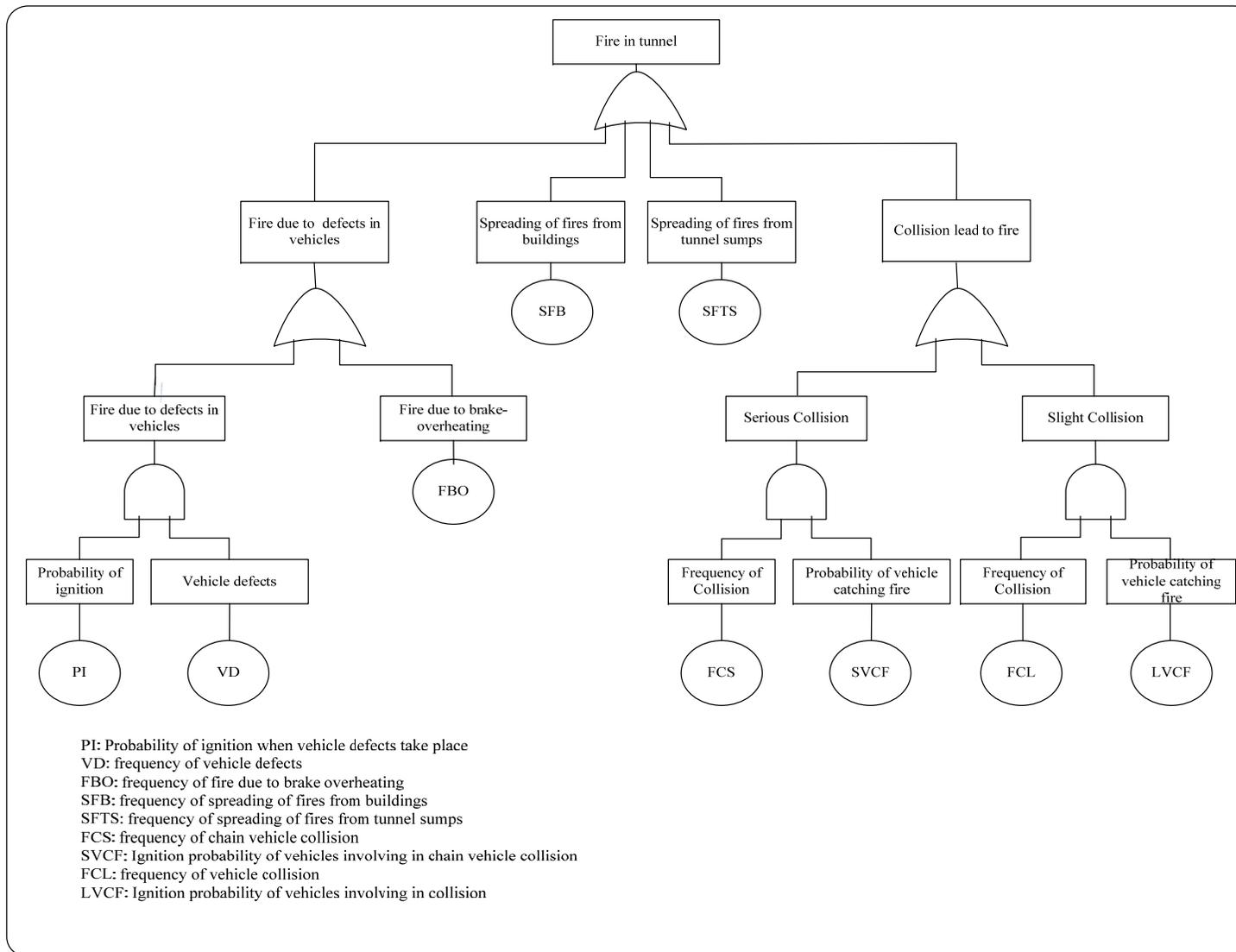


Figure 4 Fault tree for fire in tunnel top event

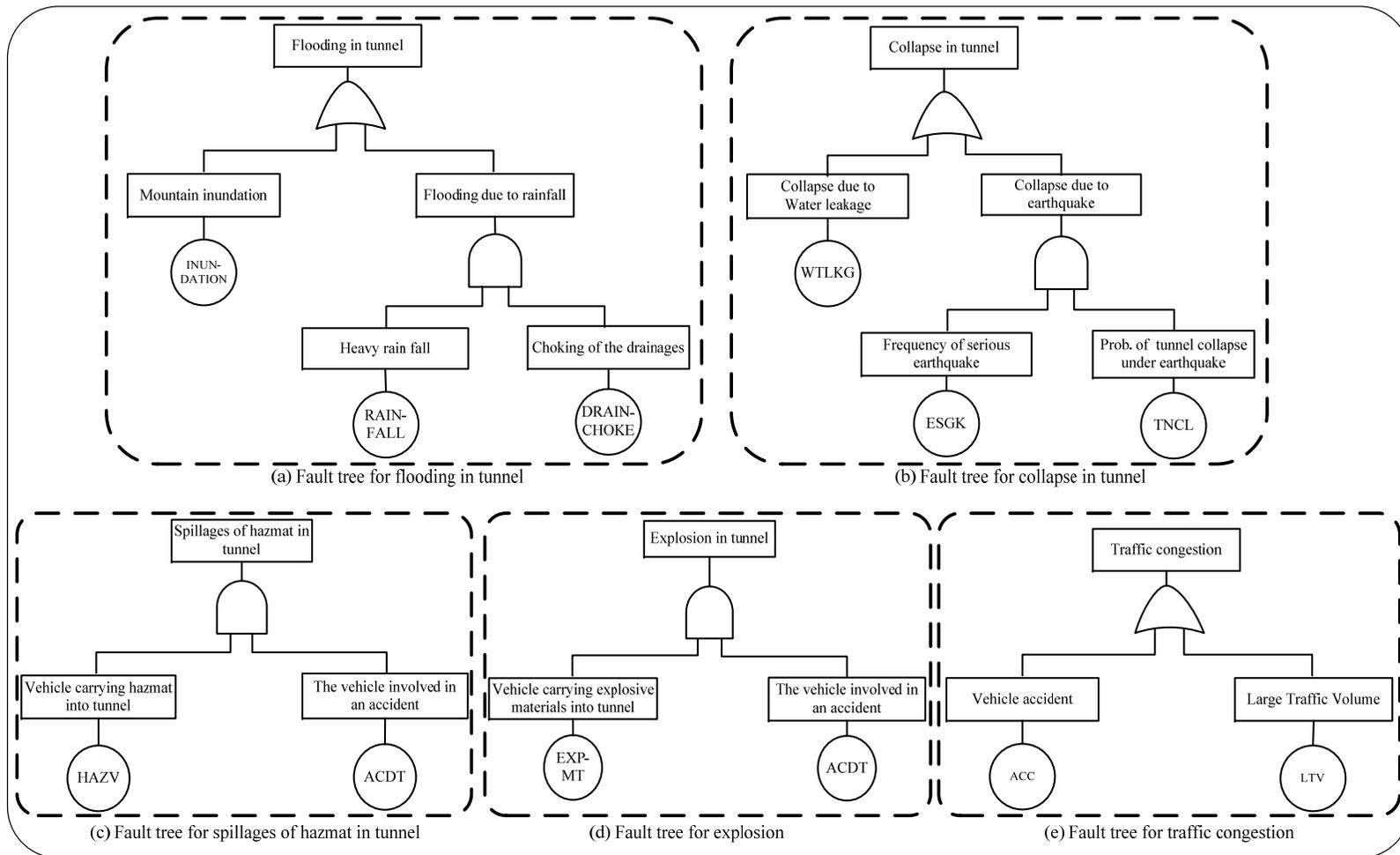


Figure 5 Fault tree for other top events

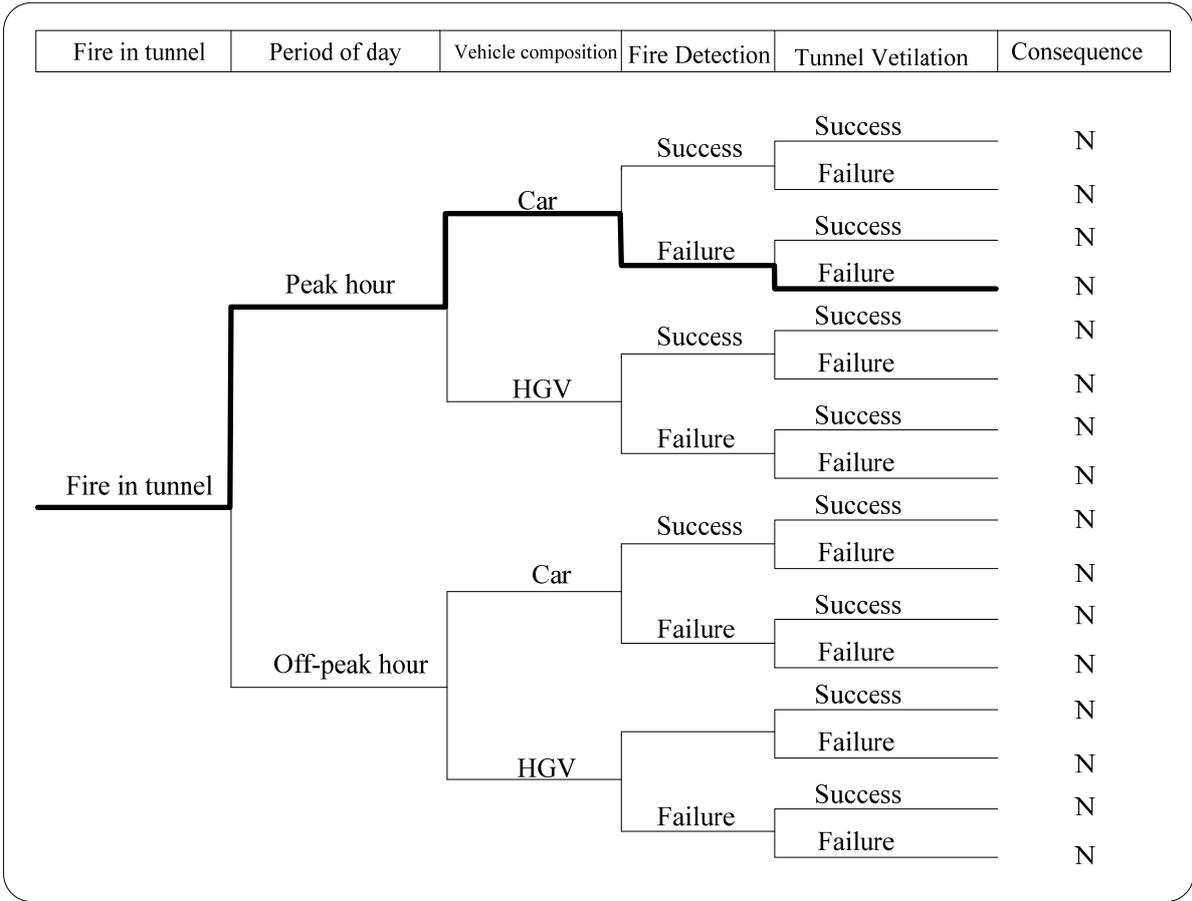


Figure 6 An Event Tree

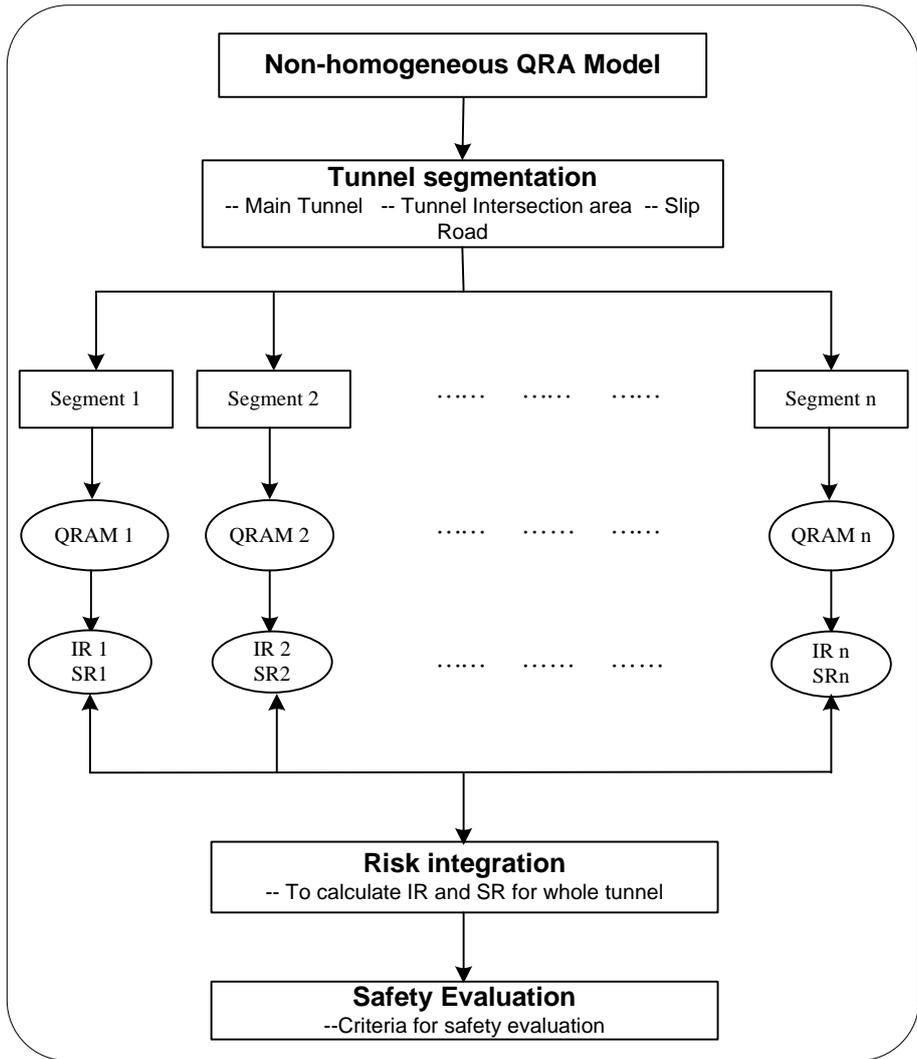


Figure 7 The QRA model for non-homogeneous road tunnels building procedure



Figure 8 MCE road tunnel in Singapore

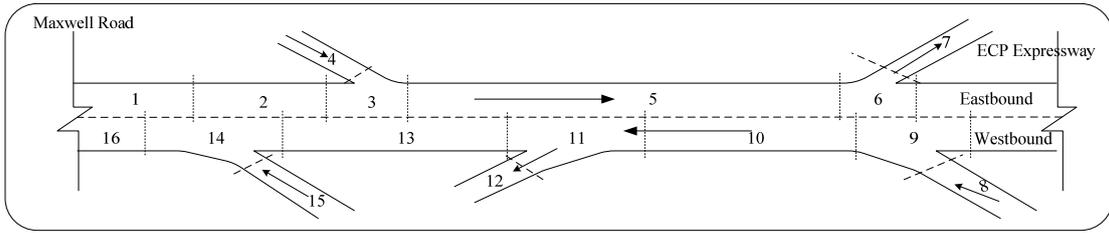
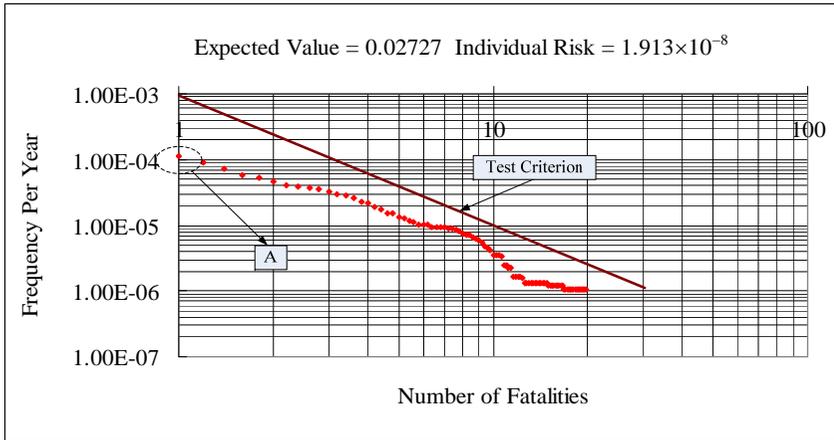
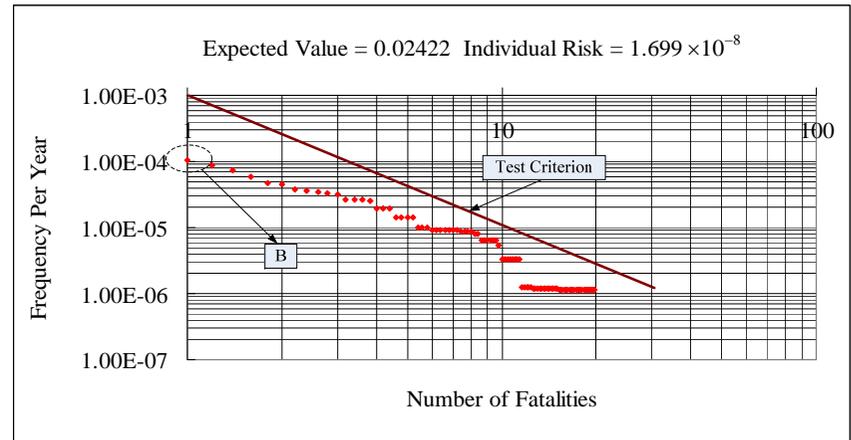


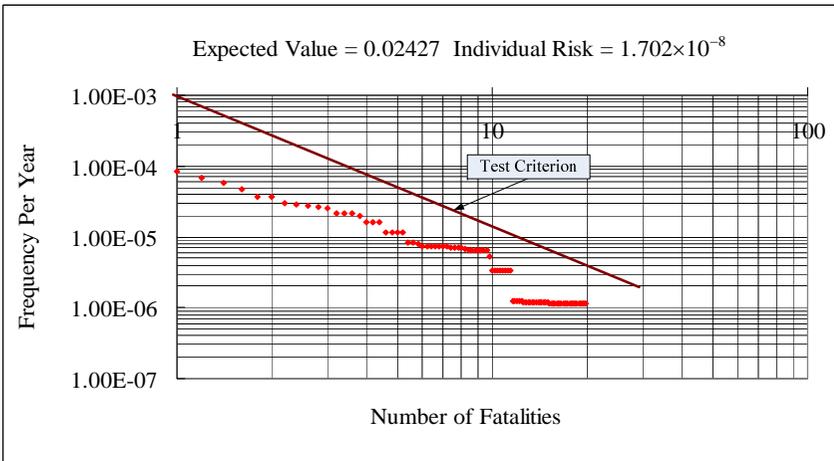
Figure 9 Geometry of MCE tunnel segmentation



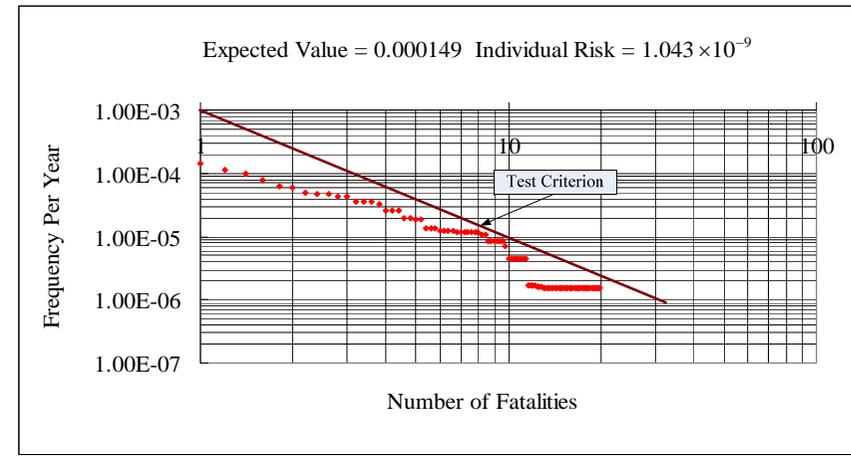
(a)



(b)



(c)



(d)

Figure 10 Risks of MCE road tunnel