The Importance of Exit Spacing to the Choice of Tunnel Ventilation System

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ABSTRACT
Smoke control in tunnels is often considered from a performance based approach with each tunnel assessed against a number of parameters. Current guidance [1] indicates that the main factors in determining an appropriate emergency smoke ventilation system are the expected traffic volume, the length of the tunnel and whether there is uni-directional or bi-directional traffic flow.

Typically for high traffic volume, significant tunnel length and bi-directional traffic, smoke extraction near the fire location will be incorporated. However for low traffic volume and short tunnels it is generally considered that a longitudinal ventilation system without local extract would be sufficient.

The use of local smoke extraction instead of a purely longitudinal system tends to increase the cross-sectional area of the tunnel. In most tunnel projects the cross-sectional area is proportional to the construction cost and therefore minimising the cross-sectional area is paramount.

This paper presents a quantitative risk analysis suggesting that, in addition to the factors listed above, another important parameter for consideration when designing the ventilation system is the exit spacing. Through varying the distance between emergency exits this paper demonstrates that the differences in the risk to life safety between different ventilation systems can be outweighed by the appropriate choice of exit spacing.

In a real world application the correct choice of exit spacing could minimise the reliance on a ducted ventilation system thus saving cross-sectional area and ultimately cost without increasing the risk to life safety.

KEYWORDS: tunnel ventilation, quantitative risk assessment, exit spacing, ventilation reliability

INTRODUCTION

Different standards and guidance documents recommend varying parameters for the design of tunnel emergency ventilation systems. Mechanical ventilation for a short, low traffic tunnel may not be deemed necessary however in most instances some form of mechanical system is generally provided comprising longitudinal impulse fans and/or transverse ventilation ducts.

Tunnel ventilation systems are rarely designed in a consistent manner due to dissimilar guidance and experience across different jurisdictions. The purpose of this paper therefore is not to address specific nuances of ventilation design but instead to look at the use of a local smoke extraction system versus providing a purely longitudinal system particular in the context of the overall fire strategy and life safety risk.

Separate to this the two systems also both have advantages and disadvantages in respect to asset protection. The choice of tunnel systems for asset protection is the subject of an entirely separate paper as a significant incident may have various societal, political and financial impacts. This is an important note since tunnel designers will typically also consider asset protection for significant infrastructure however the risk assessment presented in this paper focuses solely on life safety.

Life safety in a tunnel can be affected by a number of factors. This paper focuses on the inter-relationship between four specific areas:

- The ventilation design i.e. local smoke extraction or longitudinal ventilation
- The ventilation system reliability
- The frequency of congestion
- The travel distances between emergency exits

In an ideal world a simple flow chart addressing these bullet points would result in the correct decisions. There is however significant overlap making the decision much less clear cut. The remainder of this paper presents a model risk analysis combining these four factors.

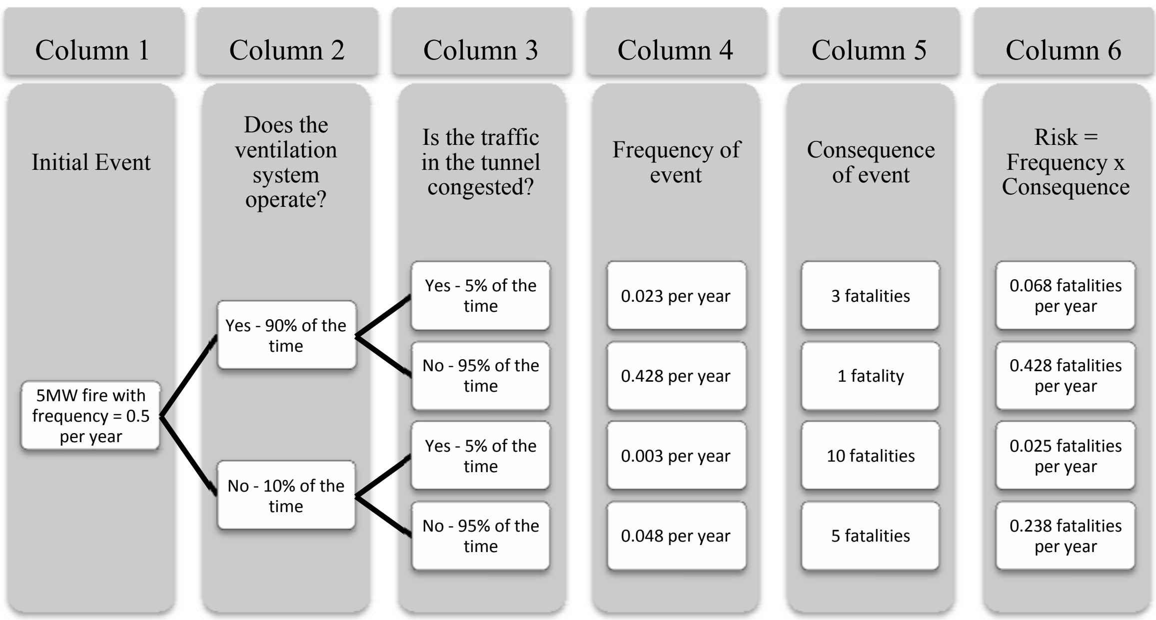
The model risk analysis can be used to determine the impact of the ventilation system design, congestion in the tunnel and the emergency exit spacing and subsequently demonstrate how the same level of risk can be achieved using different combinations of these parameters. Alternatively if the acceptable level of risk is pre-defined this model risk analysis can be used to find the balance between all these factors in order to achieve that stated level of risk.

MODEL RISK ANALYSIS

The risk analysis undertaken in this paper follows a fairly typical approach whereby event trees are constructed to determine the frequency of specific events. The consequence of each event is separately determined and the risk of a single event or combined events can then be calculated through the product of the frequency and the consequence.

A simplified event tree is shown in Figure 1. The numbers within the event tree are all fictional to demonstrate the approach. For any given tunnel the frequencies and consequences will depend on the specific design and ultimately influence the overall risk. In other words since the risk is a product of the frequency of an event and its consequences it is clear that the risk can be affected by controlling either or both of these parameters.

Figure 1 Typical event tree

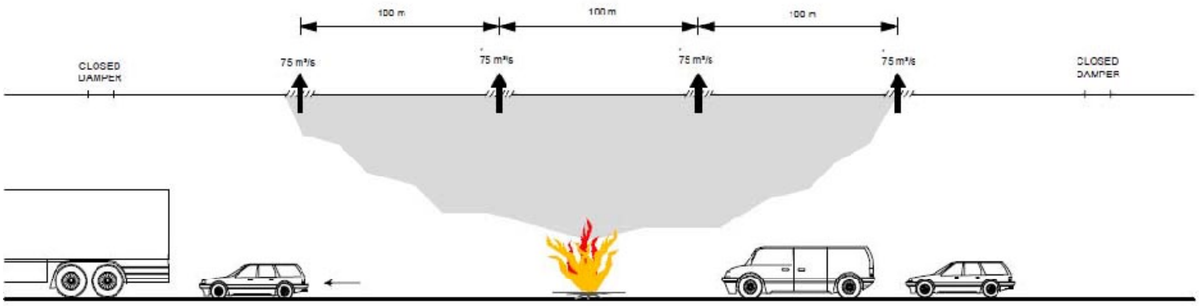


The following sections of this paper firstly outline a longitudinal ventilation system design and a ventilation design incorporating local smoke extraction. Subsequent sections address sequentially each “branch” of the event tree to provide a step by step approach to implementing this model risk analysis in a real world application.

VENTILATION DESIGN

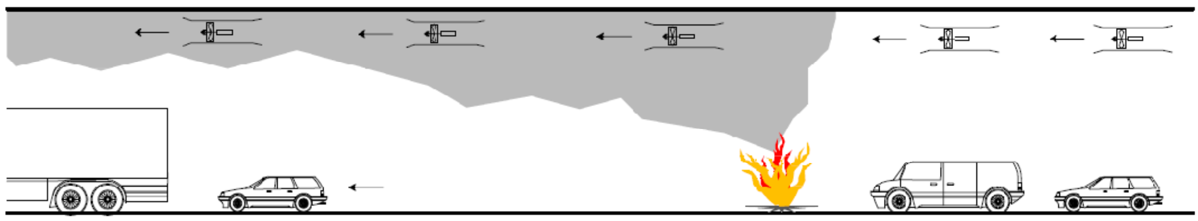
In order to provide a benchmark system the author proposes to use the German approach adopted in the RABT [2] as the basis for the ventilation system with local extraction. In this concept the smoke clearance is achieved by utilising a high level duct and opening a number of remotely actuated mechanical dampers that are evenly distributed along the length of the tunnel. Extract points are located approximately every 50m to 100m and the smoke contained within a zone of approximately 200m to 300m. This system is indicatively shown in Figure 2 and it is noted that additional systems (such as longitudinal jet fans) may also be required in order to provide sufficient make-up air and adequate airflow along the tunnel to maintain the smoke within the extract zone.

Figure 2 Indicative RABT mechanical ventilation system with local extract



The alternative to local extraction is to provide an air flow along the tunnel in order to clear the smoke through the tunnel portal. This can be achieved using a simple longitudinal ventilation system comprising longitudinal jet fans along the tunnel length. The system is designed to provide a minimum air flow through the tunnel driven by the requirement to minimise back-layering of smoke. The calculation is based on many different factors but typically air flow of the order of 3m/s is generally considered sufficient.

Figure 3 Indicative longitudinal ventilation system



INITIAL EVENT (COLUMN 1)

To provide a complete risk analysis for the life safety of tunnel users a wide range of incidents need to be considered including:

- Breakdowns
- Collisions (without fire)
- Fires (without dangerous goods)
- Dangerous goods incidents
- External influences (e.g. environmental disaster, terrorism etc.)

This paper focuses specifically on the third bullet; a fire incident but excluding at this time any involvement of dangerous goods. The frequency of these initial events will depend on the specific tunnel in question and ultimately the method presented in this paper can be adopted on any given tunnel project.

In order to provide a relevant example, the frequency of initial events presented below are based on the Waterview Connection in New Zealand which is currently under design and soon to be under construction. By way of a disclaimer, at the time of writing the author of this paper has no involvement with the design or construction of the Waterview Connection and all facts and figures presented in this paper are based on information available in the public domain.

The Waterview Connection tunnel is 2.5km long and is expected to carry 90,000 vehicles per day. The tunnel is uni-directional and there are no entry or exit junctions within the tunnel.

Vehicle fires within the tunnel are expected to occur as a result of two initial events; firstly a collision leading to a fire and secondly a technical fault leading to auto-ignition.

Based on a 2007 German report on the safety of road tunnels [3] the estimated number of fires is 0.06 fires per year due to collisions and 0.25 fires per year due to technical faults. This gives a total of 0.3 fires per year (accounting for rounding errors in the individual figures) or roughly one fire every three and half years.

In a road tunnel no two fires will be identical and as such some assumptions must be made particularly regarding the maximum heat release rate. For the purpose of this analysis the simplified distribution Table 1 is assumed.

Table 1 Distribution of heat release rates as a percentage of the expected number of fires [3]

Maximum Heat Release Rate (MW)	Percentage of Fires	Number of Fires per Year	Approximate Fire Return Period (years)
5MW	90.00%	0.27	4 years
30MW	9.90%	0.03	33 years
50MW	0.09%	~0.00	3700 years
100MW	0.01%	~0.00	33,000 years

DOES THE VENTILATION SYSTEM OPERATE? (COLUMN 2)
This branch of the event tree incorporates two separate factors; firstly the choice of ventilation system and secondly the reliability of the chosen ventilation system. The two options in regard to ventilation design are the longitudinal approach and local extraction approach presented earlier.

Both of these are designed and maintained to provide a certain level of reliability between 0% and 100%. A reasonable expectation would be for the reliability to be close to 100% however this need not or may not always be the case.

Assuming that all other variables in the event tree are equal, and that the inclusion of the ventilation system reduces the overall risk, then the reliability of the ventilation system directly impacts on the risk to life safety.

IS THE TRAFFIC IN THE TUNNEL CONGESTED? (COLUMN 3)
Traffic congestion in a tunnel can be influenced by a number of elements but will typically depend on the number of vehicles and whether there are any disruptions to the flow such as junctions within the tunnel or close to the tunnel portals. For example a rural tunnel carrying 10,000 vehicles per day is unlikely to experience congestion while an urban tunnel carrying 100,000 vehicles per day may expect to experience congestion particularly during peak hours.

Estimating how likely congestion is to occur can be a difficult for a tunnel under construction. Traffic planners may be able to provide some useful insight however if it is likely that congestion will occur then a range of frequencies, again between 0% and 100% of the time, should be used. In reality congested traffic for more than 5% of the time (equates to approximately two hours per week day) is unlikely to be acceptable and if this is occurring highlights potentially bigger problems with the traffic network or the proposed design.

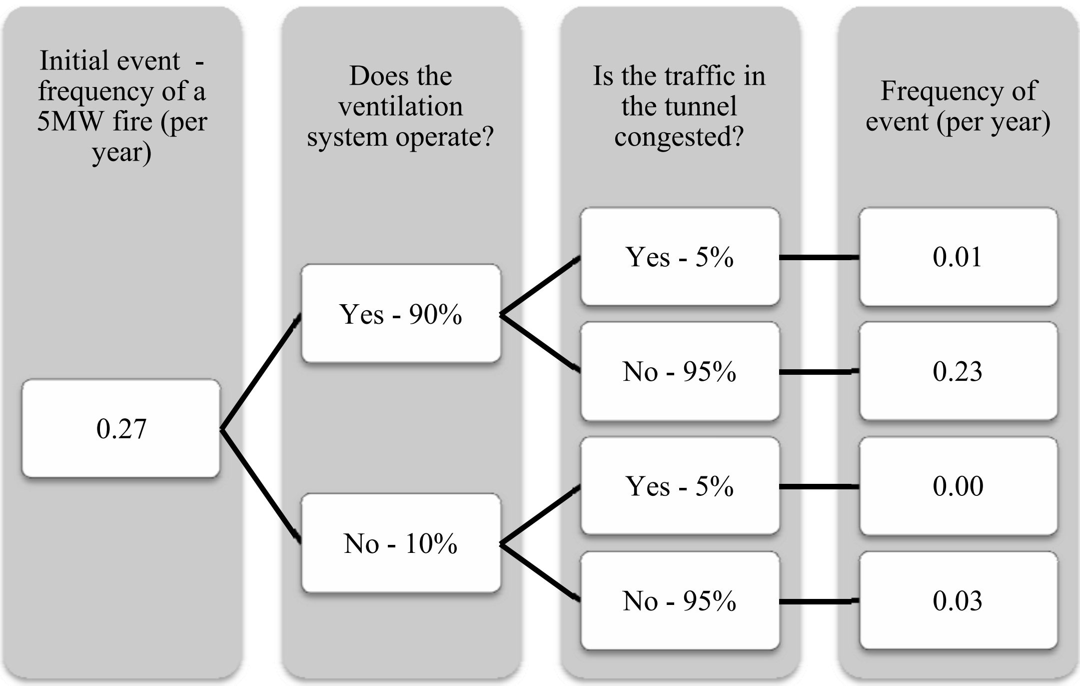
Congested traffic has a number of influences on life safety in a fire specifically in the context of the choice of ventilation system. The tunnel used in this example is uni-directional and therefore it is assumed that in the event of a fire all vehicles upstream of the incident are prevented from travelling any further while in uncongested flow vehicles downstream are able to drive out of the tunnel. As such the ventilation system should be designed to protect occupants upstream until they are able to reach an exit on foot. Of the two systems presented in this paper both, when operational, should achieve this performance objective.

Now consider the congested traffic case whereby vehicles downstream of the fire are unable to drive out of the tunnel. Occupants of these vehicles must also evacuate on foot and as such the ventilation system should also afford these occupants some protection. Using a ventilation system with local extract means that in general occupants within a zone of 200m – 300m downstream of the incident may be affected by smoke. Using a longitudinal system, occupants much further downstream may be affected. While the impact is expected to drop the further occupants are from the fire source it is clear that there is the potential for more occupants to be at risk.

Note that bi-directional tunnels will require different assumptions however this does not preclude the use of this model but will strongly favour a ventilation system with local smoke extraction.

FREQUENCY OF EVENT (COLUMN 4)
Once the ventilation system reliability and the expectation of congested traffic are determined the frequency of a given event can be estimated as per the example in Figure 4.

Figure 4 Example event tree for a 5MW fire with 90% operational ventilation and congested traffic over 5% of the time



CONSEQUENCE OF EVENT (COLUMN 5)
For each scenario there will be a consequence. In this context the consequence is considered to be the number of fatalities. In general relatively fewer fatalities are expected with smaller fire sizes than with larger fire sizes. Similarly to the frequency of each event the number of fatalities is considered to be based on the following factors:

- Local smoke extraction v. Longitudinal ventilation
- The ventilation system reliability
- The frequency of congestion

The point of difference between frequency and consequence is that in addition the consequence of an event is considered to be based on the travel distances between emergency exits. The underlying assumption here is that the longer occupants are within the tunnel the longer they are potentially exposed to fire and smoke and hence the higher level of risk to life safety.

Ignoring for the moment the influence of the travel distance between emergency exits, Table 2 presents a matrix of scenarios for which consequences are to be determined.

Table 2 Scenario definition for variable ventilation and traffic congestion

Scenario*	Ventilation Operating?	Tunnel Congestion?
L1/T1	Yes	No
L2/T2	No	No
L3/T3	Yes	Yes
L4/T4	No	Yes

* L1 – L4 represent scenarios with a longitudinal ventilation system and T1 – T4 represent scenarios with local smoke extraction.

Consequences with Longitudinal Ventilation

For scenario L1 (operational ventilation and no tunnel congestion) the expected number of fatalities is given in Table 3 for each fire scenario. The number of fatalities is based on weighting factors presented in [3] which should be multiplied by a model value appropriate to the particular tunnel. For the purposes of this paper the model value is not important since the risk analysis is comparative. In essence for the remainder of this paper the model value is assumed to be 1.

Table 3 Expected number of fatalities for scenarios L1 – L4

Heat Release Rate		5MW	30MW	50MW	100MW
Expected Number of Fatalities	L1	0.02	0.14	0.69	0.79
	L2	0.05	0.25	0.69	0.79
	L3	0.05	0.25	0.69	0.79
	L4	0.07	0.36	0.69	0.79

Table 3 also gives the expected number of fatalities for scenarios L2, L3 and L4.

Comparing scenario L1 to L2 the ventilation failure results in occupants upstream of the incident being at greater risk. Note that occupants downstream are able to drive clear of the tunnel and are considered to be at no greater risk.

Comparing scenario L1 to L3, the traffic has changed from uncongested to congested and therefore occupants downstream of the incident are now at risk since they must evacuate by foot. Note that occupants upstream of the incident are no more at risk in scenario L3 than scenario L1.

Finally in scenario L4 the ventilation system has failed to operate and the tunnel is congested leading to occupants both upstream and downstream of the incident being affected.

Consequences with Local Smoke Extract Ventilation

Similar expected number of fatalities can be calculated for the local smoke extraction scenarios as presented in Table 4. In general the fatalities follow the same trend between scenarios with one notable exception. In scenario T3 the traffic is congested however the ventilation system is operational. In this scenario occupants downstream are only considered to be affected within a period of 200-300m from the fire. Outside of this distance occupants should not be exposed to smoke unlike in the equivalent longitudinal scenario (L3) where smoke is spread downstream for a much greater distance.

Table 4 Expected number of fatalities for scenarios T1 – T4

Heat Release Rate		5MW	30MW	50MW	100MW
Expected Number of Fatalities	T1	0.02	0.14	0.69	0.79
	T2	0.05	0.25	0.69	0.79
	T3	0.02	0.11	0.69	0.79
	T4	0.07	0.36	0.69	0.79

Impact of distance between emergency exits
The final factor which is considered to influence the expected number of fatalities is the distance between emergency exits. Crudely the further emergency exits are apart the greater the expected number of fatalities.

Under the German RABT guidance the exit spacing is set at 350m. Therefore for scenarios L1 – L4 and T1 – T4 the expected number fatalities in Table 3 and Table 4 are given based on an exit spacing of 350m.

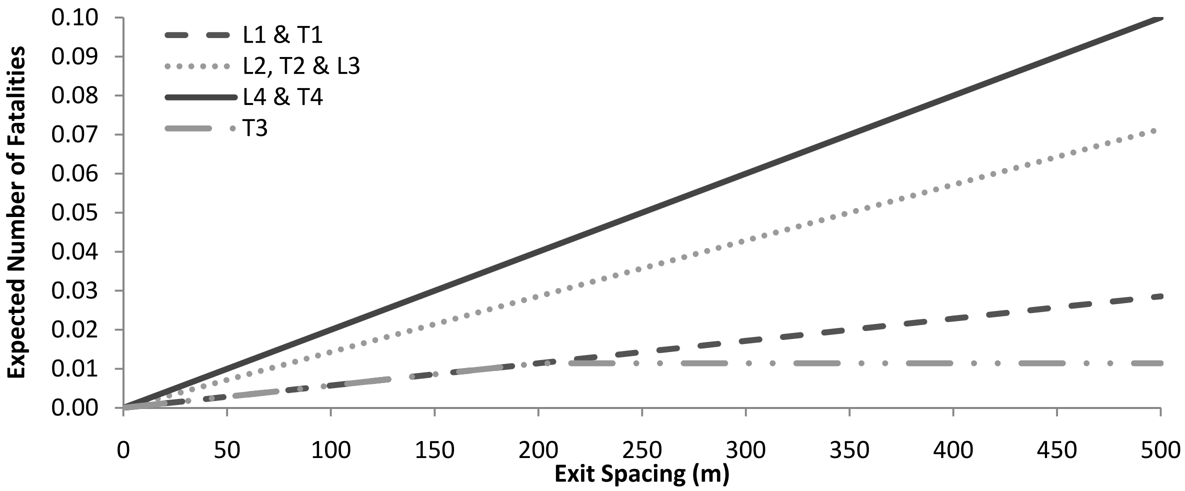
For scenarios L1 – L4 the number of fatalities is assumed to scale based on exit spacing. For example if the exit spacing is reduced to 250m the expected number of fatalities scales by a factor of 250/350. Conversely if the exit spacing increases to 450m the number of fatalities scales by a factor of 450/350.

In reality it is unlikely that the exit spacing will linearly affect the number of fatalities. A rigorous approach would involve a fractional equivalent dose (FED) analysis. While this is outside the bounds of this paper and will be considered as an extension to this work, the general trend is expected to be such that the number of fatalities reduces proportionally with the exit spacing.

For scenario T1 – T4 a similar logic is followed with one exception. For scenario T3 the ventilation system is assumed to control the spread of smoke to within 200m downstream of the fire. As such the maximum distance occupants may have to travel through smoke is considered to be 200m. Therefore an exit spacing less than 200m is considered to reduce the number of fatalities while an exit spacing greater than 200m is considered to be no worse than an exit spacing of 200m.

The trend in expected number of fatalities for each scenario is shown graphically in Figure 5.

Figure 5 Trend in expected number of fatalities against exit spacing



RISK (COLUMN 6)

The risk to life safety is calculated by multiplying the frequency of an event by the consequence of the same event and the outcomes of the model are best demonstrated with a number of examples. Consider in the first instance the proposed tunnel is designed with a longitudinal ventilation system (scenario A) which is 98% reliable and secondly that the tunnel is designed with a local smoke extraction system (scenario B) which is also 98% reliable. In both instances congested traffic is expected 2% of the time and the exit spacing is set at 350m.

As shown in Table 5, Scenario B with the local smoke extraction results in fewer fatalities. This is because in the event of congested traffic the local smoke extraction system minimises the number of occupants exposed to smoke. Logically this is the correct outcome.

Note that with this combination of ventilation reliability and frequency of traffic congestion it is not possible to change the exit spacing such that a different conclusion is reached. In all instances the local smoke extract system is considered to present a lower risk than the longitudinal ventilation system.

Table 5 Scenario A v. Scenario B

	Scenario A	**Scenario B**
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	98%	98%
Frequency of Traffic Congestion	2%	2%
Exit Spacing	350m	350m
Expected number of fatalities per year	0.01133*	0.01110*

* the accuracy of the results to five decimal places can be debated as to their statistical significance however for the purposes of a useful result it is necessary to be able to identify which scenario results in the greater number of fatalities.

Assume now that the local smoke extract system is less reliable than the longitudinal system. This is not an inconceivable assumption and based on a fault tree analysis of the design of the two systems is a fairly likely outcome. The expected number of fatalities with the longitudinal ventilation system remains as before. However the expected number of fatalities with a local smoke extraction system increases by a small percentage as shown in Table 6.

Table 6 Scenario C v. Scenario D

	Scenario C	**Scenario D**
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	98%	96%
Frequency of Traffic Congestion	2%	2%
Exit Spacing	350m	350m
Expected number of fatalities per year	0.01133	0.01129

Now assume that the exit spacing is in fact 100m. If everything else is kept consistent it is calculated by the model that the number of fatalities is expected to be lower with the longitudinal system than with the local smoke extraction system as shown in Table 7.

Table 7 Scenario E v. Scenario F

	Scenario E	**Scenario F**
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	98%	96%
Frequency of Traffic Congestion	2%	2%
Exit Spacing	100m	100m
Expected number of fatalities per year	0.00324	0.00326

Scenario C to Scenario F indicate that, all other variables being equal, by reducing the exit spacing from 350m to 100m the ratio of fatalities between the longitudinal ventilation system and the local smoke extract system changes from 1.004 to 0.994. In other words by reducing the exit spacing the longitudinal system changes the risk from being greater than with the local smoke extract system to less than with the local smoke extract system.

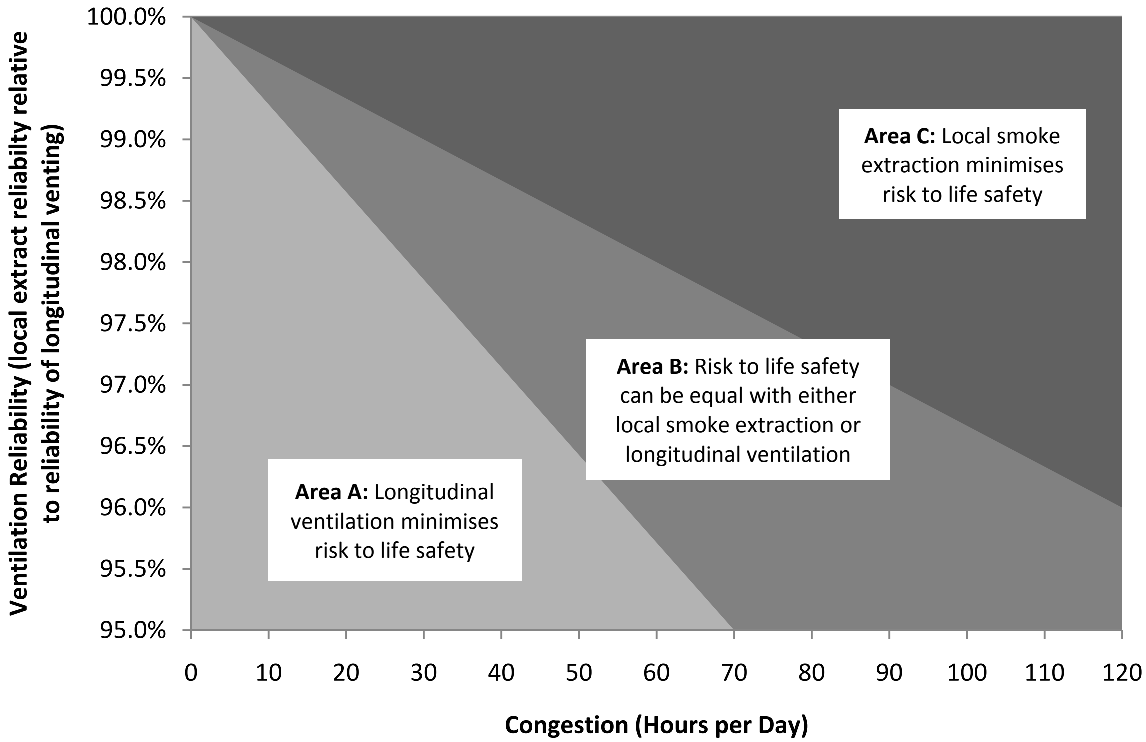
Continuing this further there is logically an exit spacing at which the risk to life safety is identical for both the longitudinal ventilation systems and local smoke extraction system for every tunnel. In this case the answer is approximately 288m for which the model predicts 0.00931 fatalities regardless of the choice of ventilation system as shown in Table 8.

Table 8 Scenario G v. Scenario H

	Scenario G	Scenario H
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	98%	96%
Frequency of Traffic Congestion	2%	2%
Exit Spacing	278m	278m
Expected number of fatalities per year	0.00931	0.00931

There are in fact an infinite number of scenarios which can be calculated by varying the reliability of the two systems, the frequency of traffic congestion and the exit spacing. The results of all these calculations can be used to develop a plot as shown in Figure 6 which, for different ventilation reliabilities and congestion frequencies, can be used to determine which ventilation system would present the lowest risk to life safety.

Figure 6 Plot highlighting choice of ventilation system as a function of the frequency of congestion and the system reliability



Within the central shaded area (Area B) both ventilation systems can be shown to present a similar risk subject to the appropriate choice of exit spacing. The example calculated above (scenario G and scenario H) sits within this range.

In Area A and Area C changing the exit spacing within reasonable bounds will not change which ventilation systems presents the lowest risk to life safety.

An example of a scenario in the range marked Area A would be as given in Table 9. For the expected number of fatalities to be the same in both scenarios the exit spacing is tending towards infinity or more practically the extent of the tunnel. The reason for this is that the unreliability of the local smoke extraction system relative to the longitudinal system far outweighs the additional risk posed to occupants downstream of a fire during the 1% of time in which the traffic is congested.

Table 9 Scenario in which longitudinal ventilation minimises the risk to life safety

	Scenario J	**Scenario K**
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	99%	96%
Frequency of Traffic Congestion	1%	1%

Alternatively an example of a scenario in the range marked Area C would be as given in Table 10. In this instance the frequency of congestion and the small relative reliability of the two ventilation systems means that the exit spacing must tend towards zero for there to be an equal risk to life safety. This is of course impractical.

Table 10 Scenario in which local extract smoke ventilation minimises the risk to life safety

	Scenario L	**Scenario M**
Ventilation System	Longitudinal	Local Extract
Ventilation Reliability	99%	98%
Frequency of Traffic Congestion	5%	5%

SUMMARY

The risk analysis model presented in the paper outlines an approach for determining the balance between choice of ventilation system, traffic congestion and exit spacing in order to minimise the risk to life safety. The key conclusion from the risk analysis model is that with the appropriate choice of exit spacing a longitudinal ventilation system can be shown to present an equal or lower risk to life safety than if a local smoke extraction system is provided even assuming a reasonable level of congestion.

Often the cost and time associated with tunnelling can be significantly reduced if a local smoke extraction system is not required. This is both as a result of the reduced cross-sectional area, through minimising the ventilation ductwork, and the reduced complexity due to the simplified ventilation system design. In a number of cases this risk analysis model can show that a ducted system is not necessary to achieve the required level of life safety and as such this approach has the potential to improve the financial viability of tunnel projects, reduce the construction risk and lower the maintenance requirements.

REFERENCE LIST

[1] Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.
[2] Guidelines for the Equipment and Operation of Road Tunnels (RABT 2006), Forschungsgesellschaft für Straßen- und Verkehrswesen.
[3] Assessing the Safety of Road Tunnels (FE 03.378/2004FRB), Bundesanstalt für Straßenwesen (BASt), November 2007.