

Risk-Based Evaluation of Longitudinal Ventilation with Enhanced Safety Concept

Göran Nygren

Brandingenjör & Civilingenjör i Riskhantering, WSP Brand & Risk, 111 64 STOCKHOLM, Sweden

Abstract: The longitudinal ventilation strategy is commonly used for road tunnels in urban environment in Sweden. This is partly due to how tunnels in urban environment was planned and designed before the EU Directive [1] (2004/54/EC) came in place. Even in new tunnels both to practical and economic reasons the use of longitudinal ventilation has been an outspoken demand from the Swedish road authority, SRA. Swedish law [2] requires that a risk analysis is carried out to demonstrate that an acceptable level of risk is achieved in the tunnels with longitudinal ventilation if there is a risk of queues. Otherwise transverse or semi-transverse ventilation strategy shall be used. During recent development, or a late awakening, it is clear that dense populated areas in Sweden will experience queues. This threatens the foundation of the Swedish modern tunnel safety concept which calls for enhancement. This paper presents the risk-reducing effect of three alternative strategies, enhancements package, focusing on evacuation safety for road users. It is a combination of traffic management, fixed firefighting systems, reduced distance between escape routes and regulation of traffic with dangerous goods. In addition, it provides a comprehensive review of safety system details, combined with a longitudinal ventilation concept.

Key words: Longitudinal ventilation, queue, risk assessment, risk mitigation measures, safety concept.

1. Introduction

During the last twenty years, a tunnel practice for urban areas has been developed in Sweden, which to a great extent is based on the extensive investigations carried out related to the planning and design of the Ring project in Stockholm. The longitudinal ventilation concept was judged as appropriate during the prevailing conditions. Since then there has been an expressed desire from the SRA to apply the same or similar safety concepts in other tunnels in the urban environment in Sweden. This is due to both practical and economic reasons, e.g., the road users shall recognize the system and to keep design and production costs at a reasonable level.

The longitudinal ventilation concept is in many ways a robust solution that ensures that people are not exposed to hazardous smoke, given that two separate tunnel tubes are included in the design. Furthermore, an

important condition is that queue is not allowed to occur in the tunnel [2]. In such case the tunnel has to be closed according to the safety concept. It has in recent years been shown to be difficult with few limited measures to prevent queues, which poses a potential major problem to the prevailing ventilation concept used.

To close a tunnel due to queues gives a major impact on the surrounding road network, e.g., wide spread traffic congestion, long travel time extensions and a hamstrung infrastructure, which has proven not to be accepted by the City Councils, e.g., in Stockholm. The reality is instead that the tunnels are taken in operation despite the queues, which means that important prerequisites for the safety concept are invalid. In practice, this course results in a poor design of a tunnel system in relation to how the system performs and then adds new problems e.g., increased risk in a traffic system.

The longitudinal ventilation strategy has a major dilemma that complicates the safety further, which is

Corresponding author: Göran Nygren, project manager, research fields: projects in buildings, industry, and urban planning.

that in queue situations and in high traffic intensity the ventilation rate increases in the tunnel to meet the environmental limit values set to air quality. The ventilation rate can be as high as 8-10 m/s at the time of a queue. To detect accidents and slow down the large air masses are important for the safety strategy to work, but then takes long time. Combustion gases at the time of an accident resulting in a fire under these conditions give a very rapid smoke spread. In long tunnel systems there are also problems relating to the piston effect due to traffic movement which can make the decrease of the air flow even more problematic, even when it is forced [3]. Additional problems come with the need to transport dangerous goods in tunnels with high traffic volumes in urban areas are added, which can cause serious and relatively very rapid accident sequence. These aspects are rarely addressed thoroughly.

Based on this problem profile WSP has been involved in evaluating and designing additional safety systems to enhance the traditional one. The additional systems in the safety concept with longitudinal ventilation strategy intends to meet the new safety requirements relating to the EU Directive (2004/54/EC) [1] TEN-road network based on the new conditions with the risk of queues. Swedish law [2], which is linked to the EU Directive (2004/54/EC) [1], requires that a risk analysis is carried out to demonstrate that an acceptable level of risk is achieved in the tunnels with risks of queues. Otherwise transverse or semi-transverse ventilation strategy shall be used. Risk analysis of this kind is complicated for several reasons. There is also little support in Swedish regulations regarding acceptance criteria and the available support is also often qualitative which provides considerable room for interpretation.

The aim of the paper is mainly to present and evaluate active traffic management and fixed firefighting systems as mitigation measures. The purpose of this paper is to explain how different mitigation measure affects the risk level in a tunnel.

2. Legislation

Before 2004 when the EU Directive (2004/54/EC) [1] was in force safety design of tunnels was based on SRA handbook tunnel 99 [4] and later tunnel 04 [5] (EU Directive was first incorporated in to Swedish law in 2007). The acceptable level of risk in tunnels according to tunnel 04 is formulated as a ambitions by politicians rather than as a well-founded design criterion:

“Tunnels shall be designed so that the risks associated with use of the road types containing crossing tunnels are no greater than for road types where no tunnels are included.” [5]

Tunnels risk level was therefore compared with open road and the comparison was made against the public road network at large, e.g., for roads with similar conditions like speed, urban areas etc. Under a few years, however, a change in the statistics regarding the number of traffic deaths has come and that the comparison with a general road network has been questioned. It seems reasonable that comparison should be made against a modern road of similar standard for example. Dangerous goods were earlier excluded from the analysis on weak basis etc.

This means that the risk level for an open road has reduced and that the space that previously existed for the additional risks in tunnels, due to fire and dangerous goods, has decreased. Moreover some statistics point towards that a tunnel cannot be said to be safer in pure traffic terms than the open road [6] and it is expected that risk due to fire and dangerous good is higher in tunnels. This and additional requirements (Swedish law) [2] concerning the ventilation strategy in the tunnels at the risk of queue has led to that the previous design of tunnels does not meet the new requirements.

Swedish regulations on safety in road tunnels (SFS 2006:418) [7] indicates that the safety measures to be taken in a tunnel shall be based on a systematic assessment of the system in all its aspects, i.e. infrastructure, operation, users and vehicles. The law further states a number of risk controlling factors (in the legislation referred to as parameters) to be included in

such assessment. If a tunnel has a special design for this risk controlling factors, should a risk analysis be executed to determine if additional safety measures or additional equipment will be needed to ensure safety in the tunnel [2].

In a systematic assessment of a tunnel system in all its aspects in accordance with regulations on safety in road tunnels with Chapter 2. § 1 [2] can for example the following special characteristic, which need special consideration in the selection of safety measures, appear as specials:

- Tunnel Length (extremely long traffic tunnels)
- Complicated tunnel system containing the main and ramp tunnels, varying number of lanes and weaving sections.
- Traffic flow (extremely high traffic volume over 100 000 vehicles / day in total in both directions)
- High speed (80-100 km / h)
- Risk of traffic jams and queues
- Extensive traffic of hazardous materials (all classes allowed)
- Tunnel slope

In conclusion from a risk point of view these kind of tunnels are very complex and the level of risk, without special attention to extra safety measures, can be expected to be high.

3. Risk Assessment Model

In the current situation there is no simplified method for carrying out the safety design and planning for a tunnel in Sweden and the rules and legislations are varying between specific prescriptive measures to performance-based requirements. The available method for the design of the total safety is the systematic and scientific tool risk analysis.

This section presents the used risk assessment model briefly. The model is based on literature studies, empirical assessments, statistics, calculations and fault- and event tree methodology. The analysis is thus both qualitative and quantitative in nature. Event tree methodology is a tool to systematically develop and

illustrate an accident possible course depending on what barriers and conditions there are and how they work. These barriers may consist of both technical and administrative measures. Active traffic management, fixed firefighting system (FFFS) and reduced distance between escape routes are examples of protective barriers. Event trees can be seen as an illustration of possible accident scenarios that may arise as a result of an initial event, in this case the fire in a vehicle due to vehicle defect or accident (resulting in fire or dangerous goods accident) [8, 9]. The event tree model in the analysis has been divided into a number of smaller event trees that are connected to a network of different event trees. The total number of end nodes in the model is over 1000. An important part of a risk analysis is to do sensitivity and uncertainty analysis to find the sensitivity in the model and to calculate the uncertain parts of the analysis, input data and assumptions. The analysis of sensitivity shows [10] e.g., that the number of hours a queue exist in a tunnel has a significant impact on the level of risk.

In practice, in order to achieve the requirement of the law, it's necessary to carry out a risk analysis on the whole safety concept and then compare the level of risk to a reference tunnel with transverse or semi-transverse ventilation strategy. However, there are not any fixed stipulated requirements detailing how such reference tunnel shall be designed to be acceptable.

WSP has developed a quantitative risk assessment model that has been used in several major projects and analyzes the safety concept from a holistic perspective in which different risks and risk mitigation systems can be analyzed and compared with each other. The quantitative risk assessment model takes into account the following types of accidents presented in figure 1.

In the developed risk assessment model the benefits of active traffic management have been demonstrated effectively reducing the risk for queues and reduce the overall risk.

Focus of this paper is to describe active traffic management as risk-reducing measure and to describe

a couple of other mitigation measures in combination with active traffic management. These are fixed firefighting systems, reduced distance between escape routes and traffic restrictions of dangerous goods, which are described briefly.

4. Risk Level with Previous Designs with Longitudinal Ventilation Concept (Tunnel A)

The overall design and level of risk for a tunnel with the traditional Swedish tunnel design is presented below and represents base-case used for comparison, from now on referred to as Tunnel A.

Tunnel A is designed with parallel tunnel tubes, providing the conditions to evacuate people between the tubes if an accident were to occur and for emergency services to make their way to the accident. The concept of longitudinal ventilation strategy is based on that the vehicle in front of the accident is to drive out of the tunnel and that the people behind the accident to evacuate to the other tunnel tube, in case of fire, which then acts as escape route.

The tunnel tubes are equipped with various safety systems including fire alarms, emergency lighting,

information signs, fire extinguishers, longitudinal smoke control, radio breakthrough, traffic control, cameras, booms and more. Escape routes are equipped with firefighting equipment, help telephones and alarm, see figure 2.

The level of risk has been calculated per km. The proportion of heavy goods vehicles > 3.5 ton, HGV, is about 8 % of the total traffic flow. The proportion of dangerous goods transports is 2,5 % of the total traffic flow of HGV's. The accidents have been analysis in different accident categories in the event tree model. The traffic flow in these calculations is 140 000 vehicles/day.



Fig. 1 Accident risks addressed in the risk assessment model.

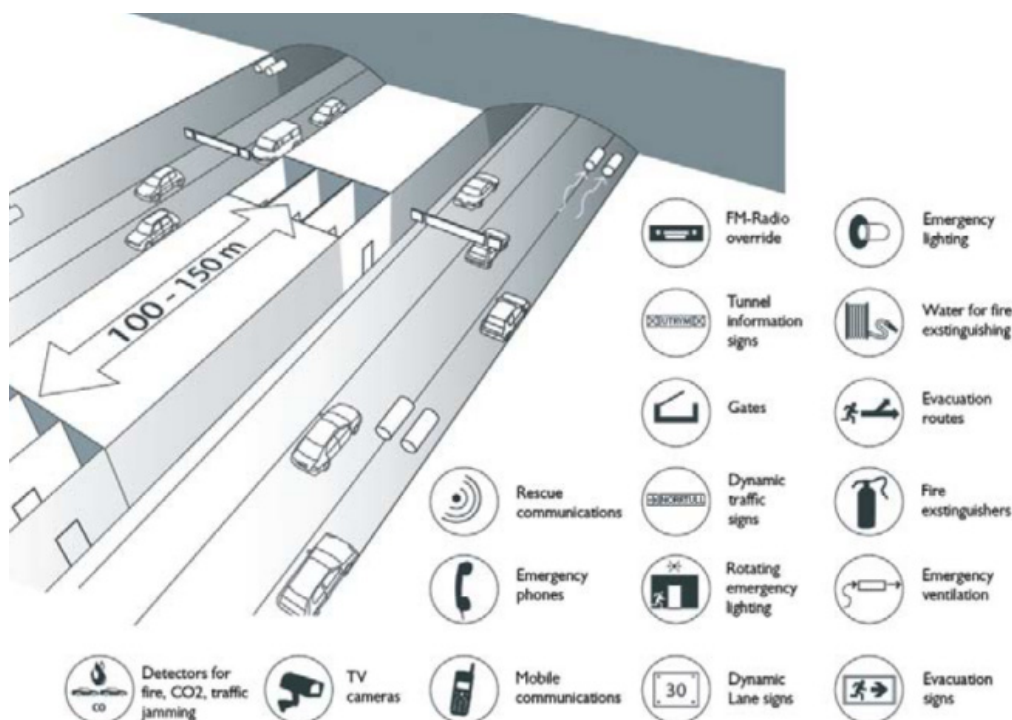
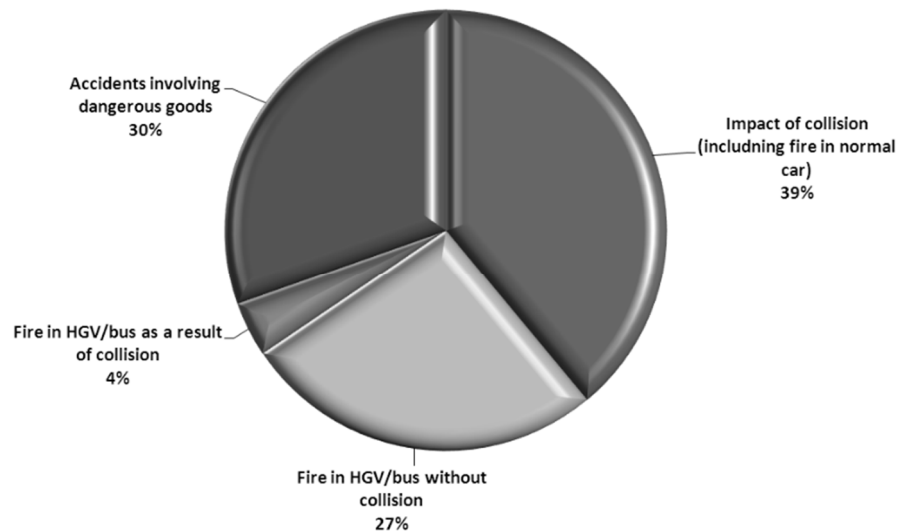


Fig. 2 Basic safety systems.

Table 1 The risk level of Tunnel A.

Accident category Fatalities due to:	Expected number of deaths/year/km	Years between accidents Tunnel A	Expected number of accident/year Tunnel A	Expected number of deaths/year/km 0 hours of queue
Impact of collision (including fire in normal car)	4,47E-02	0	4,5E+00	4,47E-02
Fire in HGV/bus without collision	3,05E-02	10	1,0E-01	0
Fire in HGV/bus as a result of collision	4,63E-03	558	1,8E-03	0
Accidents involving dangerous goods	3,49E-02	809	1,24E-03	1,49E-02
Total accidents	1,15E-01	-	-	5,96E-02

**Fig. 3** Expected number of deaths per year divided between accident categories, Tunnel A with 6 hours queue

This design is based on free flowing traffic. Studies on traffic flow, however, demonstrate that the queues fervently can occur for about 6 hours per day without active traffic management for this kind of tunnel in urban areas [3]. Tunnel A below is calculated with 6 hours of queue. In comparison to this has the risk level for Tunnel A with 0 hour of queue been calculated.

In a tunnel system, tunnel A, without queue the risk difference against tunnel A with 6 hours of is 48% on the total risk level and 79 % without traffic accidents. Queues make a significant difference on the risk level.

The expected number of deaths due to normal traffic accident is estimated at 4,5E-02 deaths per year and km or for a 16 km long tunnel about 0,8 deaths per year. The risk picture indicates that the risk of deaths is dominated by accident relating to fire and dangerous goods accidents in the tunnel, which differs a bit from the general point of view.

5. Risk Mitigation Measures

5.1 Traffic Management

The introduction of traffic management is an attempt to achieve free-flowing traffic in the tunnel. Theoretically, an active traffic management that creates a free flowing traffic gives a low level of risk. This when road users down streams an accident can drive out and the people up streams are in a smoke free environment.

To be able to better understand how incidents and high traffic flow can generate queues and how they in turn can affect the flow of traffic within the tunnel system a traffic model should be used. WSP has in the last few tunnel projects mainly used a mesoscopic model but also a microscopic model should be used to study smaller networks.

Through the use of a mesoscopic model the whole tunnel system as well as much of the surrounding road

network can be modeled. Output such as speed, traffic flow and the buildup of queues and the blocking of junction is result of the modeling. Different hours can be modeled and a number of incidents should be modeled to get an idea of how the queues will build up and what sections of the tunnel system or the surrounding road network is most likely to be affected, or is in fact affecting the buildup of queues within the tunnel.

Different scenarios of traffic disturbance have been modeled to investigate the impact within the system and on surrounding open roads. Studies show that small incidents are usually managed without the need to start major actions. The study also gives good indication on how the traffic system copes with disturbances of the available capacity.

The systems that we generally equip the road tunnels with are: A MCS (Motorway Control System) to help smoothen traffic in case of incidents, automatic barriers to quickly close parts of the tunnel system, a system of microwave and video detectors to detect incidents, queues and stopped vehicles, variable direction signs to direct drivers to alternative routes and to help drivers chose the best route to evacuate the tunnel in case of an incident. At last there is a system of VMS signs to inform drivers about abnormal situations and to inform drivers in case of an emergency in the tunnels.

The traffic management toolbox consists of:

Ramp metering, usually a basic traffic light together with a signal control that can regulate the flow of entering traffic to a main road. The flow can be set to current traffic conditions and can reduce congestion and prevent queues.

Mainline metering, is a control on mainline to a tunnel. It can be used to close the tunnel when the congestion is getting too high. It would also be possible to close the hole or some lanes of the main entrances of the tunnel for shorter periods of time earlier, too prevent congestion and massive queues. In order to make these decisions, however, the operators need some sort of decision making support tool.

Access control, can be used for surface ramps downstream from a tunnel exits that is not adding a lane, but rather is a weaving lane. It will in effect mean that the ramp is closed in the most extreme rush hour period. That could also be the case of some of the ramps leading directly into the tunnel if the congestion levels in the main tunnels would be too high. This option will most likely cause severe congestion on the surface network. It has to be remembered, however, that in case of a fire in the tunnels, all the tunnel entrances will be closed anyway. It is assessed better to let the tunnel control center to have access control than to close the mainline.

Traffic signals, many of the exits from the tunnels end up in a junction, either give way, signalized or a roundabout. In order to control the traffic going into the tunnels during ordinary traffic situations they would need to be signalized. This would be an alternative to access control where one could control the green times for the traffic flows going into the tunnels. It would also be a big advantage in case of a major incident in the tunnels when there's a need to quickly evacuate the tunnels. One could then activate an emergency evacuation program in the traffic signals that would allow the exiting traffic to go out without being in conflict with other traffic flows, in a roundabout for instance.

Hard shoulderrunning, has proven effective when incidents have made it necessary to close an ordinary lane. It requires hard shoulders though, to lead the traffic from the area.

Travel time information, at a more distant point has been proved effective. The Danish road directory selected a system of travel information signs on the roads leading up to the road being refurbished and also gave the travelers the travel times on alternative routes. In order to ease congestion in road tunnels this solution could be used and it would most likely prove to be effective.

Although active traffic management manages to control traffic in a tunnel system so that free flowing traffic can be achieved under normal conditions, is the

Table 2 Risk level of Tunnel with active traffic management.

Accident category Fatalities due to:	Expected number of deaths/year/km	Tunnel A Expected number of deaths/year/km	Risk compared to Tunnel A reduction(%)
Impact of collision (including fire in normal car)	4,47E-02	4,47E-02	0
Fire in HGV/bus without collision	9,88E-03	3,05E-02	68
Fire in HGV/bus as a result of collision	3,31E-03	4,63E-03	29
Accidents involving dangerous goods	2,92E-02	3,49E-02	16
Total accidents	8,70E-02	1,15-01	24

system not capable to prevent queues caused by incidents and accidents. For a 16 km long tunnel statistics and calculations shows that queues will occur somewhere in the system about 2 h/day and is therefore used in the calculation [3].

The result shows a significant difference between the tunnel with an active traffic management and Tunnel A. An explanation of some of the difference in the results: the result shows a difference between Fire in HGV/bus without traffic accident. The accidents are due to vehicle defects and the decrease is calculated to 68 %. With decreased proportion of queue, 2h compared with 6h, the model takes account of the decreased traffic work and that risk reduces for serious accidents with many people in the tunnel. When traffic volume increases, the model also takes into account the number of vehicle defects increases. The proportion of serious accidents resulting in fire at queue situation, in dense traffic, due to traffic accident, has been evaluated leading to an increase in risk. Accidents that lead to severe collision and resulting fire has been assessed occur in situations with queues and overtaking accidents coming from traffic behind.

5.2 Fixed Firefighting System (FFFS)

Expected effect of a fixed firefighting system, FFFS, in tunnels as those presented in this paper does not refer to a system in which all fires can be managed and extinguished.

The purpose of such system is to limit the fire to the start object and handle the fire when it is small and not allow it to become critical, i.e., of about 15 MW, corresponding to a fully developed fire in 2-3 medium-

sized cars. The systems main purpose is to suppress fire. Performed CFD simulations clearly show that under the prevailing conditions, i.e., geometric and other conditions such as ventilation conditions, etc., arise critical conditions regarding visibility and toxicity of combustion gases at the time a fire becomes about 15 MW. Critical conditions of temperature occur mainly in the area around the fire under the evacuation phase.

The fixed fire firefighting system shall result in reducing the total number of fires to not grow above these levels. The completed risk assessment assumes that the system is activated early when the fire is likely to be small, and then control it, which means that the damage to the property will be limited and that life safety is assured. Since all types of vehicles are involved in the risk analysis the level of ambition that the FFFS must meet limit resulting fires from small cars to large trucks. There is no Swedish standard for fire suppression systems in tunnels. Therefore, the evaluation in order to achieve the above functional requirements is that the analysis is based on the standard used for the bus garage, High Hazard Production or design according to the guidelines for storage of separate goods as High Hazard Storage, according to EN 12845:2004. This is based on the storage height of a truck is between 2.5 m to 3.0 m. The system which has been the basis of the risk analysis has been a deluge system, which is a group release system with clusters of open sprinklers, nozzles. One section, which is controlled by a group of release valve when activated emits water from all sprinkler heads. Water releases always in two sections, i.e., normally in both upstream and downstream of the fire. For the risk

analysis, it is assumed that water density is at least 10 mm/min/m² [3]. The risk model results on the risk level are presented below.

The result shows a significant difference between the tunnel with a FFFS and active traffic management compared against Tunnel A.

The likelihood function / availability of the FFFS is assumed to be high to very high, this assumes that the system is well maintained. This is a normal assumption for fixed extinguishing systems in general. These assumptions are made:

- The probability that the FFFS is activated as planned, given that the detection systems work as intended, is assumed to 0,99.
- The probability of the FFFS is activated as planned has been adopted to: 0.97
- The probability that the fire is not too large at the time of activation, given that the fire caused by vehicle defects: 0.95

For fire scenarios with traffic accidents and dangerous goods have similar assumptions been made.

5.3 Restrictions for Dangerous Goods Traffic

The performed analysis is based on statistic of transport of dangerous goods. The analysis is based on

no restrictions of dangerous goods, the tunnel class A is used in accordance with ADR-S framework [11]. Restrictions on transportation of dangerous goods can be varied in many different ways. Everything from that no transport of dangerous goods is allowed to that a reduced number of dangerous goods classes are not allowed during certain time periods to name but a few examples. Below presents the effect on the risk level when a restriction where no dangerous goods is allowed.

Restrictions of transports of dangerous goods will decrease the total level of risk with 30 % for a tunnel under these conditions.

5.4 Reduced Distance between Escape Routes

In comparison object tunnel A the distance between escape routes is 150 m. The risk analysis compared this distance with a reduced distance that is 75 m. Reduced walking distance contributes to an improved evacuation situation by making the time to travel to the escape route less. A reduced distance between the escape routes also contributes making it easier to discover where to evacuate in an accident situation. In case of fire and a smoke filled environment the chance to find an escape route will be higher. To do a deep

Table 3 Risk level of tunnel with FFFS and tunnel with FFFS and active traffic management.

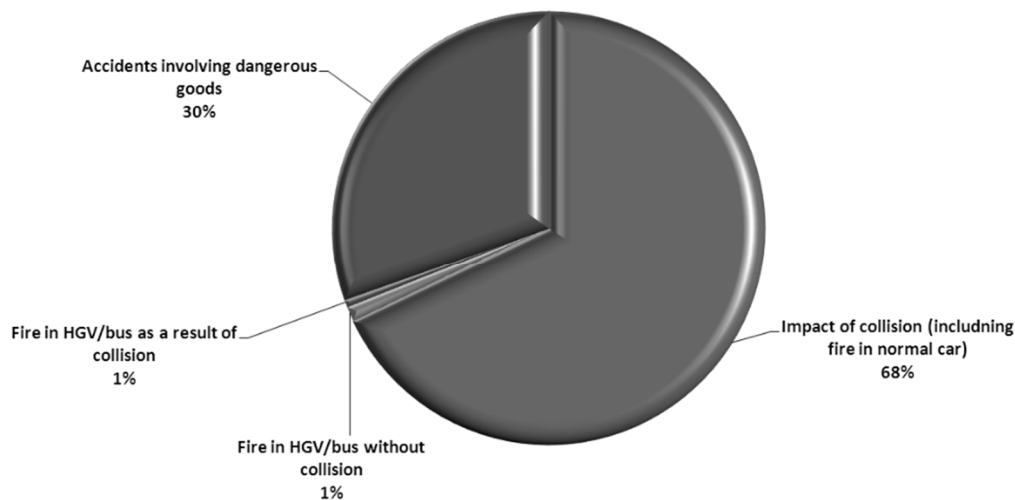
Accident category Fatalities due to:	Expected number of deaths/year/km, with FFFS	Risk difference percentage reduction (%) against tunnel A	Expected number of deaths/year/km, with FFFS and active traffic management	Risk reduction (%) compared to tunnel A
Impact of collision (including fire in normal car)	4,47E-02	0	4,47E-02	0
Fire in HGV/bus without collision	2,75E-03	91	9,05E-04	97
Fire in HGV/bus as a result of collision	6,48E-04	86	4,63E-04	90
Accidents involving dangerous goods	3,09E-02	11	2,50E-2	28
Total accidents	7,90E-02	31	7,11E-02	38

Table 4 Risk level of tunnel with restrictions of dangerous goods.

Accident category Fatalities due to:	Restrictions of transports of DG Expected number of deaths/year/km	Risk reduction (%) compared to Tunnel A
Impact of collision (including fire in normal car)	4,47E-02	0
Fire in HGV/bus without collision	3,05E-02	0
Fire in HGV/bus as a result of collision	4,63E-03	0
Accidents involving dangerous goods	0	100
Total accidents	7,98E-02	30

Table 5 Risk level of enhancement pack 1 and 2

Accident category Fatalities due to:	Pack 1.Expected number of deaths/year/km, with FFFS, active traffic management and reduced distance between escape routes	Risk reduction (%) compared to tunnel A	Pack 2.Expected number of deaths/year/km, active traffic management, reduced distance between escape routes and restrictions of transports of DG	Risk reduction (%) compared to tunnel A
Impact of collision (including fire in normal car)	4,47E-02	0	4,47E-02	0
Fire in HGV/bus without collision	7,24E-04	98	7,90E-03	74
Fire in HGV/bus as a result of collision	3,70E-04	92	2,65E-03	43
Accidents involving dangerous goods	2,00E-02	43	0	100
Total	5,69E-02	50	5,53E-02	52

**Fig. 4** Expected number of deaths per year divided between accident categories, enhancement pack 1.

analysis of who a reduced distance affects the total risk level is a very hard to do. A estimation is adopted and the assessment is that it reduces the risk for evacuees with about 20 %. This when the closeness to an escape route raise awareness about where to find it and in the event of an evacuation in smoke filled environment increases the probability to find an escape route. The value was determined in an expert group and is presented in this paper as an example of qualitatively managed parts. It has in all parts of the analysis regarding the consequences of an accident taken into account if a reduced distance between escape routes makes a benefit or not [12].

5.5 Combination of Risk Mitigation Measures

Three alternative combinations of risk mitigation measures are presented below. Enhancement pack 1

has FFFS, active traffic management and reduced distance between escape routes. Enhancement pack 2 has restriction of dangerous goods, active traffic management and reduced distance between escape routes. Enhancement pack 3, not in the table, is a combination of pack 1 and 2 i.e. has restriction of dangerous goods, FFFS, active traffic management and reduced distance between escape routes.

The two different combinations, pack 1 and 2, of risk mitigation measures show nearly the same level of risk. The one with restriction of dangerous good, pack 2, shows a slightly better risk reduction. What this number is not showing is that the reduction of catastrophic accident is much bigger in pack. 2.

Further the FFFS in pack. 1 reduces more of the severe fire scenarios. The combination of pack 1 and 2, pack 3 will give the tunnel with a risk level at 4,58E-02

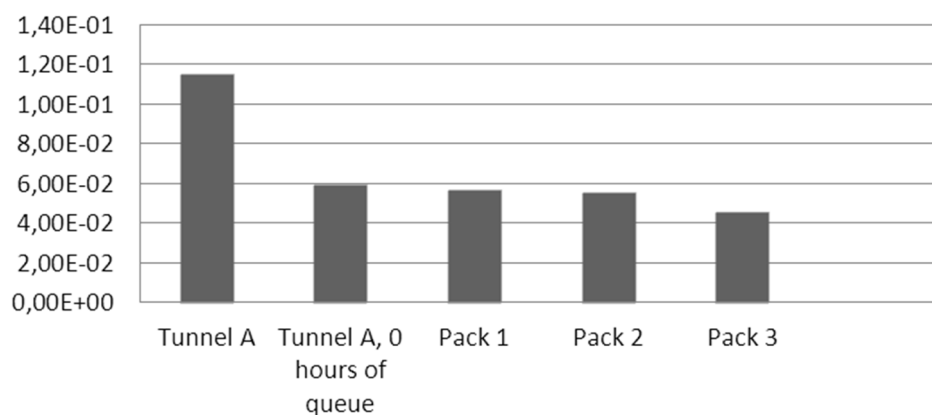


Fig. 5 Total risk level of Tunnel A compared against the different enhancement pack, expected number of deaths/year/km.

death/year and km, which is only 2% over a risk level for an assumed open road/km and reduction of “Total Fire and Dangerous goods accidents” with 98 % in comparisons to Tunnel A (60 % reduction of the total risk).

6. Conclusions

The analysis shows that the contribution of risk in queue situations in the safety concept with longitudinal ventilation is significant. The analysis also shows that the entire contribution of risk due to queues cannot be dealt with active traffic management. The reason is that in tunnels with high traffic volumes, with up to 2000 vehicles per lane and per hour, will have regularly incidents (e.g. engine failure, fuel state, disease, punctures, etc.) and pure accidents in varying severity resulting in queues.

In a tunnel for example, with 140 000 vehicles per day, the analysis shows that about two hours a queue will occur due to the above contributions of incidents and accidents. This is despite active and roving road assistance with a response time of about 5 minutes. To reduce the risk associated with this type of situation and the overall level of risk, additional risk mitigation systems must be deployed. The additional systems consist of a fixed firefighting system, reduced distance between the escape routes or restriction on transportation of dangerous goods and reduced distance between the escape routes. The systems and the

restriction are showing a significant reduction of the risk level in tunnel systems of this type. Transports of dangerous goods in tunnels make a big contribution on the risk level, regulations on dangerous good traffic under high traffic hour is judged to lower the risk level significant. The analysis also shows that huge demands are set on the mitigation systems that are deployed. Active traffic management is likely to affect the surrounding road network on daily basis to keep the tunnel without queues.

The legislation gives very little support for which ventilation strategy to use. In fact as long as tunnels have no acceptance criteria for tunnels, regardless of ventilation strategy, the risk level will be varied for different tunnels and the requirement to use transverse or semi-transverse ventilation strategy useless.

References

- [1] Boverkets föreskrift och allmänna råd om säkerhet i vägtunnlar, BFS 2007:11. (in Swedish)
- [2] Besluts PM Säkerhetskoncept (0S148202), E4 Förbifart Stockholm, Trafikverket, 2010.
- [3] Allmän teknisk beskrivning för vägtunnlar, Tunnel 99, VV Publ 1999:138.
- [4] Allmän teknisk beskrivning för vägtunnlar, Tunnel 2004, VV Publ 2004:124.
- [5] Föreskrifter för hög trafiksäkerhet (0T14S0000), E4 Förbifart Stockholm, Arbetsplan, Vägverket, 2010.
- [6] Lag om säkerhet i vägtunnlar, SFS 2006:418.
- [7] Brandskyddshandboken, Rapport 3134, Brandteknik, Lunds Tekniska Högskola, 2005.

- [8] Riskanalysmetoder – Delprojekt 2.2, bilaga till regeringsuppdrag Personsäkerhet i tunnlar, Boverket, 2005.
- [9] Riskanalys för driftskedet - Bränder i fordon och farligt gods-olycka i tunnel (0S148201), Trafikverket, 2010.
- [10] ADR-S, Statens räddningsverks föreskrifter (SRVFS 2006:7) om transport av farligt gods på väg och i terräng, Statens Räddningsverk, 2006.
- [11] Konsekvensanalys - Brand i fordon (0S149401), E4 Förbifart Stockholm, Trafikverket, 2010.