CONSEQUENCE ANALYSIS OF FALSE FIRE DETECTION IN ROAD TUNNELS

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ABSTRACT

Regulations for fire detection in road tunnels vary strongly around the world. For example, the required speed of fire detection in Japan is much faster than in Europe. Moreover, the minimum size of fire that must be detected at the required speed is much smaller than in Europe. These two requirements have led to the widespread adoption of different technologies for fire-detection and this, in turn, leads to different probabilities of false alarms. This paper uses both qualitative and quantitative methods of consequence analysis to assess the influence of the different regulations on overall risk for tunnel users. It is found that, for the chosen tunnel type, which is especially common in Japan, the speed of detection is less important than the choice of ventilation strategy. Also, advantages gained from high detection speeds might be outweighed by disadvantages of false alarm rates as small as one per week. These findings are not applicable to all types of tunnel. The relative importance of rapid fire detection might be significantly greater in tunnels with fixed firefighting systems, for instance.

Keywords: fire detection, false fire alarm, risk analysis, consequence analysis

1. INTRODUCTION

In modern road tunnels, the breakout of a fire is detected and monitored by one or more sensors such as flame-detectors, infrared cameras, video cameras, thermal cameras and linear temperature cables. When these detect a fire, various actions are triggered automatically – e.g. changes to the ventilation control regime, smoke extraction, activation of fixed fire-fighting systems and notifications to bodies such as emergency services. Usually, they will also include traffic control and the provision of targeted guidance to vehicle users. The use of automatic responses such as these has big potential advantages for reducing the severity of incidents and the risks for persons caught up in them. However, *automatic* triggering of such responses also has its own risks. For instance, *false* fire detection in tunnels can cause unnecessary traffic jams at tunnel portals and hence possible vehicle collisions causing injury and even fatalities. Accordingly, it is important to minimize the risk of false detection, not only to maximize the effectiveness of valid detection.

This paper presents both qualitative and quantitative assessments of risks associated with valid and false fire detection. It does so by applying formal consequence analysis to a selection of scenarios used as the basis of regulations in three countries, namely Japan, Germany and Austria. The outcomes are summarized in a manner that enables rational judgment to be made of the balance between *rapid* detection and *reliable* detection. Both are highly desirable, but neither can be maximized without compromising the other to some degree.

To ensure adequate focus on the key purposes of the paper, some potentially important factors are addressed in a simplified manner. For instance, the influence of interventions by human operators is modelled partly on published data, but also on wider experience, especially in the case of remotely-controlled tunnels. Other important factors are excluded completely. For example, only longitudinally-ventilated tunnels are considered (these are the dominant type amongst Japan's vast number of tunnels) and no account is taken of the possible availability of fixed-fire-fighting systems (FFFS). These would be included when appropriate in practical design studies, but their inclusion herein would complicate the inference of generic conclusions.

2. REGULATIONS FOR FIRE DETECTION

As fire detection plays such a critical role in tunnel emergency operations, performance criteria for fire detection systems are strictly specified in regulations. However, some strong differences exist between regulations in different countries. Herein, specific attention is paid to requirements in Japan, Germany and Austria.

In ***Japan***, a 0.5m^2 plate, 2 litres gasoline fire must be detected within 30s (NB: the regulation does not place limits on the air speeds for which this must be achieved). Since the prescribed fire is very small, the time taken for temperatures to increase significantly except very close to the fire is such that the criterion tends to favour flame detectors (infrared detectors). Typically, such sensors are installed on tunnel walls at 50m intervals.

In ***Germany***, if the tunnel air speed is less than 6m/s, a 4.0m^2 plate 20 litres gasoline fire must be detected in less than 60s [1]. Typically, this is achieved using a linear temperature cable installed on the center of the tunnel ceiling. In sharp contrast with Japan, flame detector-type sensors are not used in Germany.

In ***Austria***, if the tunnel air speed is less than 3m/s, a fire formed by two 1m^2 plates, each with 10 litres methylated-spirit pools must be detected in less than 90s [2]. As in Germany, this is typically achieved using linear temperature cables on the center of the tunnel ceiling and flame-detectors are not used.

It is noteworthy that the Japanese regulation not only requires the smallest detection time (30s), but also stipulates that it must be achieved for much smaller fires that those prescribed in the European examples. The regulation applies to all expressway tunnels and national road tunnels owned and operated by the Nippon Expressways Companies (NEXCO), the Urban Highway Companies (UHC), and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

Notwithstanding the differing characteristics of the prescribed conditions, the overall aims of the regulations in the three countries (i.e. maximizing safety) are the same. One purpose of this paper is to investigate how well the aims are achieved. For brevity, the three regulations are characterized in the remainder of the paper by 30s, 60s and 90s detection times.

For obvious reasons, the prescribed fires in each of the above cases are capable of being reproduced simply and accurately. However, it should not be assumed that pool fires are necessarily representative of typical tunnel fires. For instance, it was concluded in the ESCOTA report [3] that fire began with flame in only 1% of the actual fires for which data were collected. In most of the fires, smoke was observed before flames. This could have potentially important consequences for the effectiveness of different types of fire detection systems, especially if their effectiveness is assessed solely on the basis of gasoline or heptane fires on open plates.

3. FIRE EMERGENCY RESPONSE

When a fire breakout is detected, a series of measures follows, typically including:

- notifying operators and emergency services and providing information about the fire source
- traffic restrictions; e.g. traffic lights or barriers at the portals (and information displays)
- traffic control; e.g. emergency display boards and radio broadcasts within the tunnel, especially advising on the nearest emergency exits
- ventilation control to facilitate safe evacuation; e.g. zero-flow control in Japan, low-speed flow in the EU
- fire risk mitigation measures, such as triggering fixed firefighting systems to minimize fire growth, protect tunnel facilities and assist emergency personnel

In *supervised* tunnels in Japan, these measures are undertaken manually by human operators after confirmation of fire breakout and its scale with the aid of video cameras in the tunnel. In the large number of *non-supervised* tunnels, however, the emergency responses are initiated automatically by a fire emergency panel.

Within the EU (particulary in Autsria and Germany), the general emergency response in supervised tunnels is broadly similar to that in Japan, but the usual provision in non-supervised tunnels differs from Japan. Instead of having fully integrated emergency and alarm circuits, it is usual to have semi-integrated alarm procedures that, in most cases, notify a human operator who then acts in accordance with information from sensors.

4. MODEL FIRES IN CONSEQUENCE ANALYSES

The main purposes of this paper are (i) to illustrate the power of rigorous consequence analysis modelling for comparing alternative approaches to fire response and (ii) to use the method to make rational comparisons between the distinctively different fire response processes adopted in Japan and typical EU countries. Since this cannot realistically be done for a large number of individual tunnels, it is necessary to undertake the comparisons on the basis of selected tunnel scenarios. Once again, differences exist between the approaches adopted in Japan and the EU.

4.1. Japan: *Qualitative* Consequence Analysis

In Japan, the focus is on qualitative (not quantitative) consequence analysis when designing safety devices and equipment for either new or refurbished tunnels. A “standard” fire is defined with particular characteristics regarding smoke density distribution and heat release rate (HRR). These are based on measurements made in a series of full-scale fire tests conducted to determine smoke densities and HRR that are used in engineering design [4]. **Figure 1** illustrates smoke density distributions s*V(1/m*m3/min) measured in five different fire tests, namely a bus interior fire, a bus undercarriage fire, a passenger car interior fire, a passenger car underbody fire, and a 4m^2 plate gasoline fire. The smoke release rate adopted for a 20MW standard fire is based on the measured smoke distribution of the bus undercarriage fire. This case is used as a standard in engineering tunnel fire emergency responses in Japan and it is used in qualitative consequence analysis in Section 5.1.

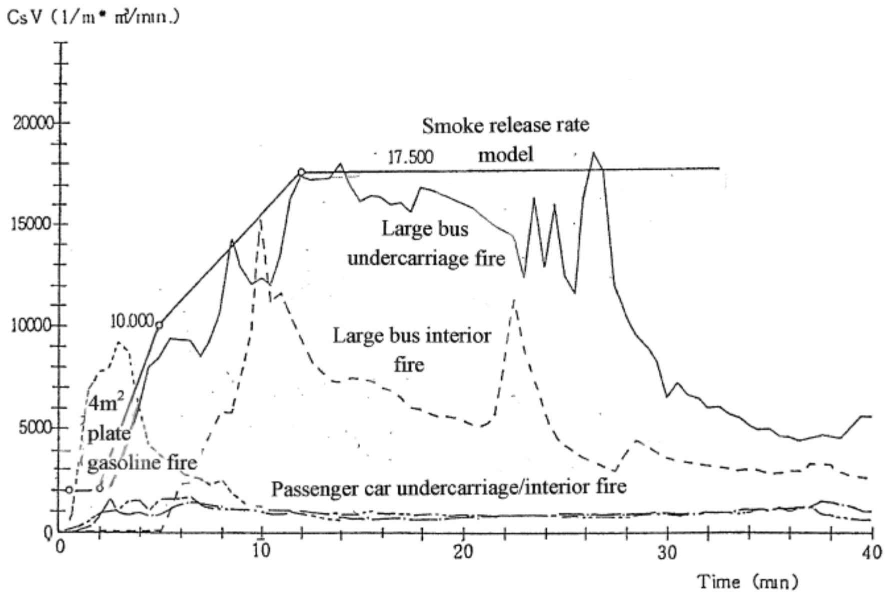

Figure 1: Measured smoke release rates and 20MW standard fire in Japan

4.2. Austria: *Quantitative* Consequence Analysis

The chosen method of quantitative consequence analysis is based on Austrian Regulations. In RVS 09.03.11, published by the Austria Society for Research on Road, Rail and Transport [5], which provides the methodical basis for Tunnel Risk Analysis in Austria, the consideration of three different model fires is officially required. One model fire, characterized with a maximum HRR of 5 MW, represents a median passenger car fire and two model fires, with maximum HRRs of 30 MW and 100 MW respectively, represent HGV fires with different cargo loads. The model fires are based on simplified assumptions, including:

- The increase of HRR in each of the three fire sizes is approximated as linear
- The fire-development times depend only on the maximum heat release rate (Table 1)
- The prescribed HRR development is independent of the longitudinal air flow velocity
- The pollution emissions rates are constant in time and depend only on the maximum HRR. They are stated in RVS 09.03.11 [5].

Table 1: Time required to reach the maximum fire load

Fire Size	5 MW	30 MW	100 MW
Timespan until full development [s]	180	300	420

4.3. Purposes of Japanese and Austrian fire models

Overall, probabilistic approaches to risk assessment are an attempt to represent a variety of tunnel fires in a realistic way through the superposition of different, albeit individually deterministic, models of fire development. The specifications of the individual models inevitably reflect the intended purposes of the regulators. In Japan, the broad purpose is to assess individual tunnel systems explicitly in their own right and the result is a simple “okay” or “not okay”. In Austria, the aim is somewhat broader, nominally enabling a more quantitative outcome that, in principle, can be used to compare the relative degrees of safety of the target tunnel and any other tunnel. This is done by assessing the safety of the chosen systems with reference to a universally defined tunnel as well as to the actual tunnel.

5. CONSEQUENCE ANALYSIS - VALID FIRE DETECTION

Implications of the 30s, 60s and 90s “rules” are now assessed by applying both qualitative and quantitative methodologies to the model tunnel summarized in **Table 2**.

Table 2: Model tunnel and its characteristics

Tunnel length	2,990m
Emergency exits	6
Tunnel cross section	Vaulted, 71m^2 (8.4m diameter)
Traffic volume	25,000 vehicles/day
Traffic mix	60.4% passenger cars 39.6% HGV (incl. bus)
Traffic speed	80km/h
Traffic signals	Traffic signals at both portals
Traffic condition	Asymmetric and symmetric traffic scenarios

5.1. Qualitative Consequence Analysis

Simulations of the standard 20MW fire (**Figure 1**) followed by zero-flow ventilation control have been conducted using a tunnel safety simulator [6]. Although all three detection times have been modelled, only the 90s case is presented here because it is clearly the least safe of the three. **Figure 2(a)** shows the evolution of the longitudinal velocity along the tunnel. Immediately after the fire breaks out, but before it is detected and the zero-flow response control system is activated, the air velocity in the tunnel increases. Zero-flow conditions are achieved approximately 3½ minutes thereafter. The jet fan velocities needed to achieve zero velocity are shown in **Figure 2(b)** as a percentage of the maximum required jet fan capability. The jet fans continue to operate after zero-flow has been achieved because the chosen boundary conditions would cause a net air flow rate if the fans were switched off.

Figure 3 shows the evolution of smoke density predicted by the simulator together with possible evacuation paths from the fire location – assuming rapid responses and average evacuation speeds of 1m/s. Persons evacuating to the left are in a smoke-free environment almost immediately whereas those evacuating to the right are continually exposed to smoke. Nevertheless, the smoke density to which they are exposed is less than the value of 0.4/m that is the approximate limit of densities for which fatalities are a strong risk. Accordingly, the qualitative methodology leads to the conclusion that the tunnel is "okay" even with a 90s detection time.

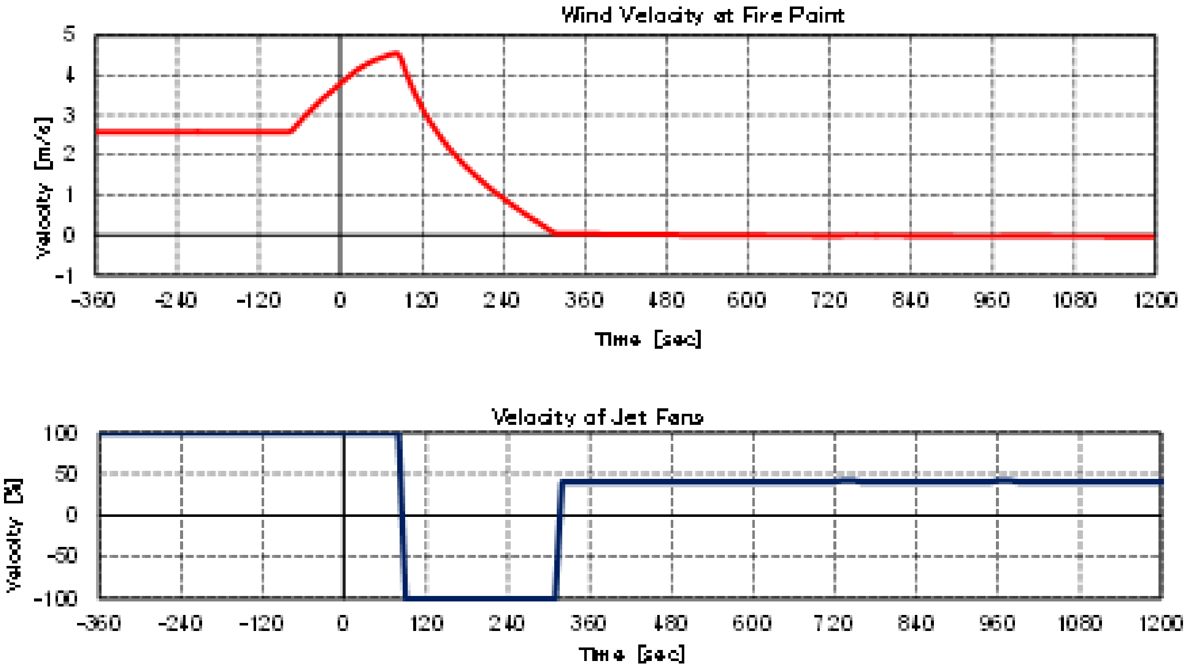

Figure 2: Air-flow velocity and output of jet-fans: 90s delay in fire detection

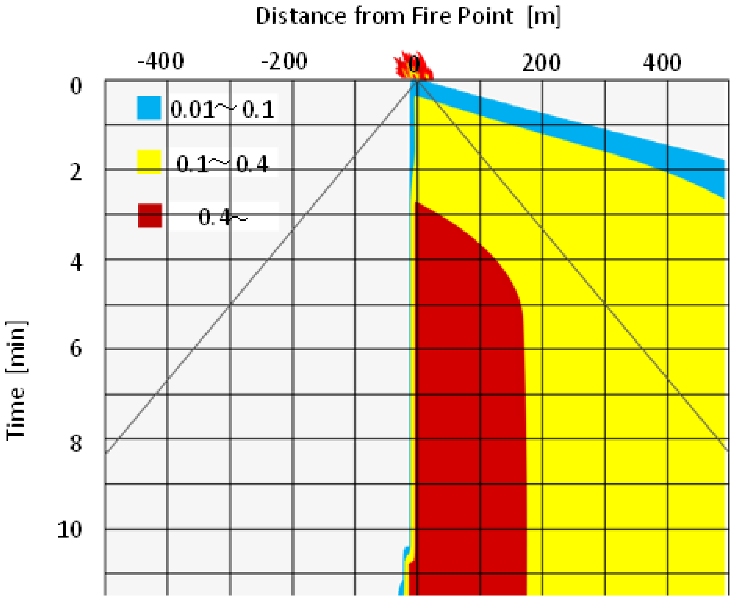

Figure 3: Smoke density and evacuation paths for a 20 MW fire (90sec detection time)

5.2. Quantitative Consequence Analysis

The Austrian methodology for carrying out tunnel risk analysis ("TuRisMo") is now used to evaluate the influence of different fire detection times, i.e. 30s, 60s and 90s, on the expected risk-value of the model tunnel specified in **Table 2**. TuRisMo uses a fully integrated quantitative approach and therefore allows for the implementation and detailed analysis of a broad variety of tunnel characteristics and safety measures. Detailed descriptions of the model and its implementation can be found in [5], [7] and [8]. One specific feature that can be taken into account when applying the Austrian tunnel risk analysis model is the composition of the emergency-response timeline. The general structure of a timeline table is depicted in **Figure 4**. Although the detailed form of the table might seem complicated, the important features for analyzing the impact of different fire detection times/rules are straightforward.

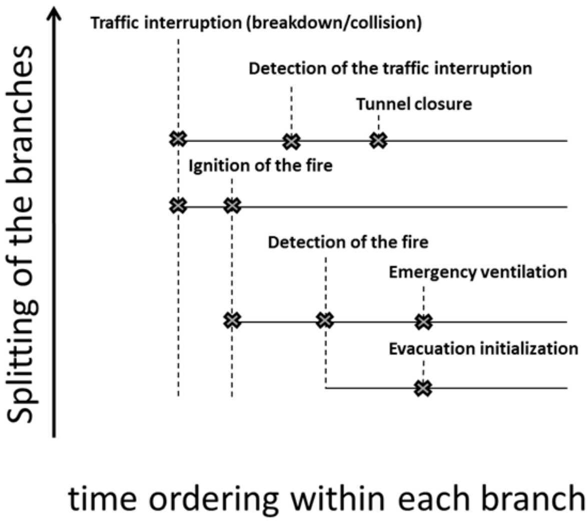

Figure 4: Time table of events for the quantitative risk analysis model

First, the detection of the traffic interruption and the detection of a possible consequential fire are separated and are considered independently of each other. Thus, for example, a variation of the fire detection time does not *a priori* imply a variation in tunnel closure times. This is because traffic interruptions such as accidents are usually detected before a consequential fire and may in themselves trigger closure of the tunnel. The following results for the model tunnel are based on an assumption of a fixed detection of the primary traffic interruption, 37 seconds after the initial incident, for all fire detection times considered.

Second, the transition from normal to emergency ventilation and the initialization of evacuation occur after the detection of a fire and therefore depend on the fire detection time. The ensuing result necessarily depends on many factors, especially the facilities available for use in the emergency response. For instance, if smoke-extraction or FFFS systems exist, their effectiveness will depend not only on their individual activation times, but also on the sequence in which they are activated in relation to each other and in relation to the time of change from routine to emergency ventilation. TuRisMo enables account to be taken of all such factors, but they are not considered herein because the necessary discussion of multiple options would detract from the primary purposes of the paper. Instead, attention is limited to the initiation of the changed ventilation regime and of the evacuation process. The risk assessment has been carried out for six cases, namely all combinations of the three detection times and two ventilation strategies. The latter are defined in **Table 3**. One is indicative of the Japanese zero-flow approach [4] and the other is indicative of a strategy that is more common in Europe [9]. The outcomes are summarized in **Figure 5**.

Table 3: Definition of two different fire emergency ventilations at the model tunnel

Model tunnel	**Ventilation system**	**Ventilation strategy**
Longitudinal Tunnel with Zero-Flow Ventilation	24 jet-fan positions with 2 jet-fans at each position	Longitudinal air velocity between 0.25m/s and -0.25m/s
Longitudinal Tunnel with Standard-Flow Ventilation	24 jet-fan positions with 2 jet-fans at each position	Longitudinal air velocity between 1.0m/s and 1.5m/s

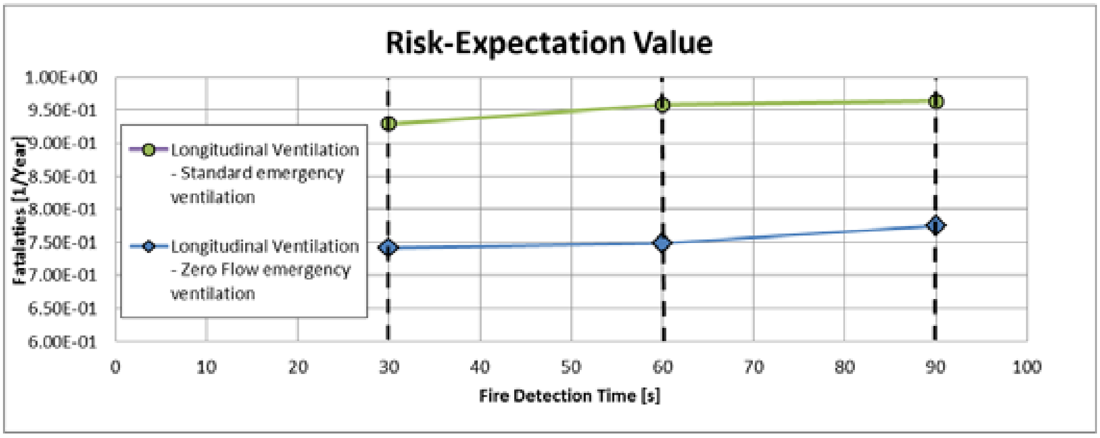

Figure 5: Dependency of the expected risk (fire risk + collision risk) value on the fire-detection time and the ventilation control strategy

By inspection, for the chosen scenario, the choice of the ventilation strategy has a much greater influence than the fire detection time. The “zero-flow” approach leads to a prediction of 20% fewer fatalities per year than the standard European strategy whereas a reduction in the detection time from 90s to 30s reduces the predicted fatality rate by only about 4%. Of course, it should not be inferred that the detection speed is unimportant in general. Indeed, it can be highly influential in other scenarios – e.g. when smoke extraction or FFFS capabilities exist. Nevertheless, the outcomes shown in Figure 5 do provide a clear demonstration that preconceptions can be very misleading. At the very least, it should not be assumed *a priori* that rapid fire detection will always have a significant influence on the eventual outcome even though it will always give some advantage. Similarly, it should not be assumed that the ventilation strategy will always have a strong influence. For example, the existence of smoke-extraction or FFFS capabilities could simultaneously increase the value of rapid fire detection and decrease the influence of the ventilation regime.

6. CONSEQUENCE ANALYSIS - FALSE FIRE DETECTION

In the preceding section, it is implicitly assumed that the information received from all sensors is valid. In practice, however, the possibility exists of false alarms and/or of the false interpretation of signals by a human operator. The false/nuisance alarm rate of a tunnel influences risk in two ways. First, tunnel users who are travelling towards the location of a falsely detected fire might have to stop inside the tunnel if it has internal traffic signals. Similarly vehicles approaching the tunnel might be stopped by external traffic signals or barriers. In both cases, this creates a risk that would not exist in the absence of the false detection, namely rear-end collisions. In tunnels with FFFS, additional risk is notionally possible through unnecessary activation. Such possibilities, whilst small in themselves, can have cumulative consequences for overall risk that change the relative advantages of alternative response strategies. Such effects can be simulated in the event tree according to RVS 09.03.11 in a direct manner. For instance:

- Rear-end collisions between stationary and late-stopping vehicles inside the tunnel define a distinct branch within the event tree, enabling false detection rates to be translated into modified probabilities for the existence of stopped cars within the tunnel.
- The corresponding risk arising for vehicles approaching the tunnel is most conveniently modelled by artificially extending the assumed length of the tunnel so that it includes the external regions in which a collision risk is incurred.

Figures 6 and **7** summarize risk analysis results for the standard European ventilation method and the zero-flow ventilation method respectively. The model tunnel is as defined in **Table 2** and a range of combinations of fire detection times and false/nuisance alarm rates is considered. These parameters are treated independently in this presentation even though they might not be independent in practice. Indeed, it is likely that an inverse relationship will exist between them because rapid detection and, especially, rapid reaction to detection, reduce the time available for reliability checks. For the chosen scenario, false alarm rates of very low frequency have an even smaller influence than that reported above for the speed of fire detection. However, the influence of more frequent false alarms is quite strong. It is therefore potentially important to take formal account of false alarms when assessing overall risk, not simply to regard them as a nuisance.

A subset of the same information is presented in a different format in **Figure 8** which shows selected combinations of the false alarm rate and the prescribed detection time. The general patterns for the two ventilation control strategies are very similar. For obvious reasons, the lowest possible risk would occur with the smallest false alarm rate and the smallest fire detection time. Assuming that these extremes are mutually exclusive, the Figure shows that, on balance, slightly lower risk will ensue from allowing an increased detection time of 90s than from allowing an increased false detection rate of one per week. Significantly greater risk will arise if the false detection rate increases significantly – e.g. to one per day.

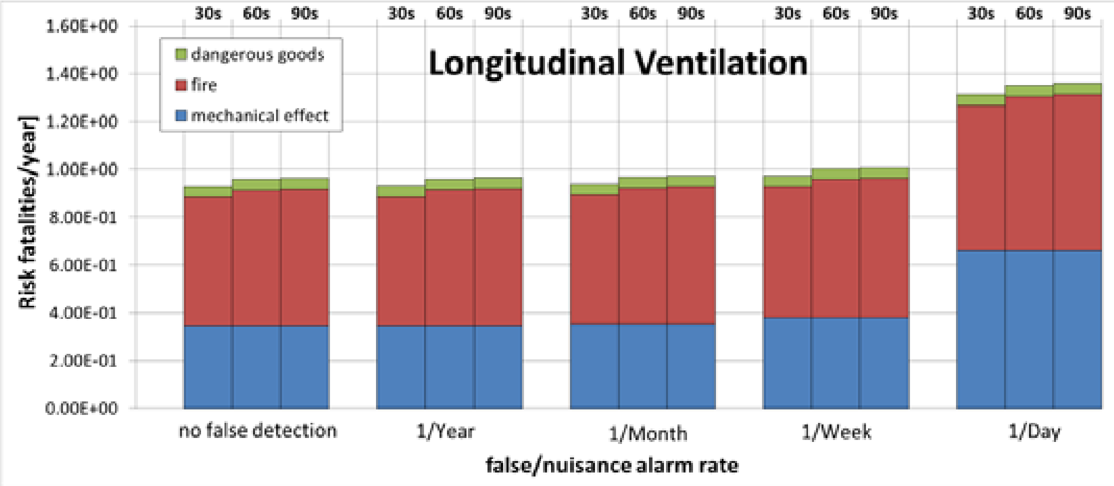

Figure 6: Risk (fire risk + collision risk) dependencies on false/nuisance alarm rate and fire detection time for standard-flow ventilation control

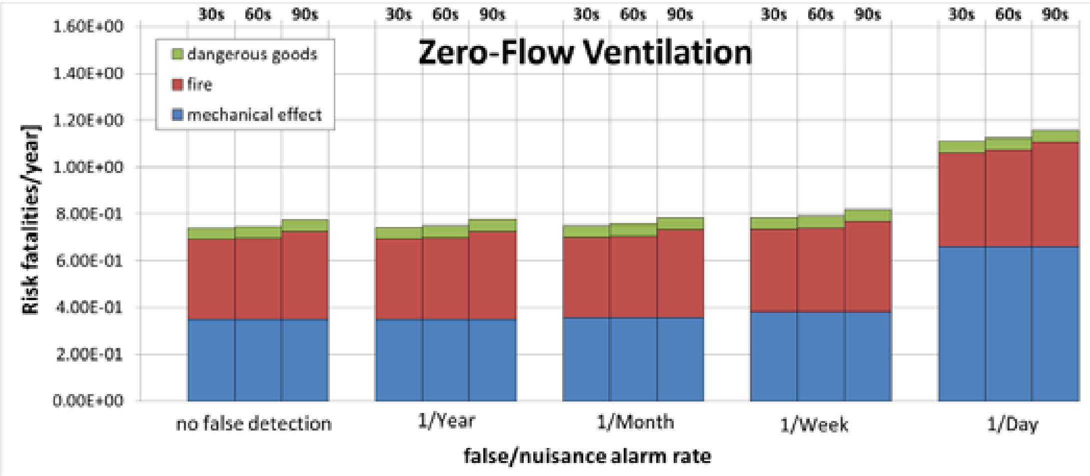

Figure 7: Risk (fire risk + collision risk) dependencies on false alarm rate and fire detection time for zero-flow ventilation control

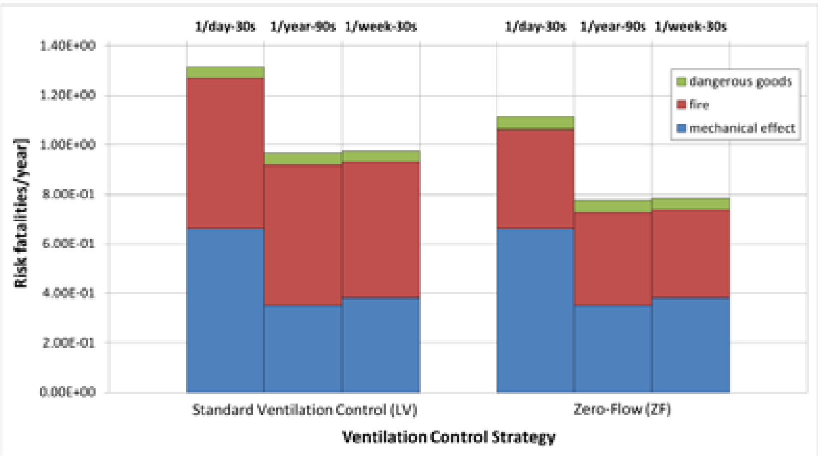

Figure 8: Comparison of selected false alarm rates and fire detection time combinations

7. CONCLUSIONS

Qualitative and quantitative consequence analyses have been used to estimate the relative influence of different requirements for fire detection rates in road tunnels in Japan (30s), Germany (60s) and Austria (90s). The analyses have been applied to the particular case of a longitudinally-ventilated tunnel with bi-directional traffic. This type of tunnel is very common in Japan although it is less common in Europe. The model tunnel does not have FFFS and there is no provision for smoke extraction within it.

For the chosen tunnel scenario, it has been found that:

• Overall risk depends much more strongly on the ventilation control strategy than on the time required for fire detection;

• Overall risk has only weak dependence on false alarms when these are significantly rarer than one per week, but it increases significantly with increasing frequency of false alarms;

• A false alarm rate of approximately one per day can be as important as the difference between emergency ventilation control for zero-flow and the corresponding control for a steady, moderate flow speed;

• In general, there is likely to be an inverse relationship between fire detection times and the frequency of false alarms. Therefore the consequences of false alarms need to be considered carefully when attempting to design fire detection systems that are both rapid and reliable.

Although these conclusions are believed to be valid for tunnels of the type considered herein, it should not be assumed that they are also valid for other types of tunnel.

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