# Chapter 14
# Fire Safety in Road Tunnels


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**Abstract**  Modern industrial societies need efficient and safe transportation systems for their existence and progress. Tunnels form an important component of road transportation systems in many countries. However, significant fire incidents within them have highlighted human safety as a major concern, resulting in considerable changes to the safety requirements to be satisfied during the design and assessment of new and existing tunnels, respectively. This chapter discusses state-of-practice related to the implementation of risk analysis methods in road tunnel projects. It reviews relevant safety criteria in standards and describes basic aspects on risk acceptance and decision-making with respect to the choice of the safety measures to be implemented. This contribution presents the determination of human safety consequences for use in risk analysis by considering design fires, the development and spread of effects of such fires and emergency evacuation of people. The methodology is illustrated via a case study that deals with the re-qualification of an existing road tunnel in Wales.

## 14.1   Introduction

The worldwide road network has grown steadily over the last century due to the increase of traffic volumes. There are many tunnels longer than 10 km. The longest road tunnel worldwide is currently the Laerdal Tunnel in Norway; with bidirectional traffic and a total length of 24.5 km.

Life safety is a major issue in the design of a new tunnel and in the assessment of an existing tunnel, especially for those with a considerable length (e.g. greater

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than 1500 m). Past incidents such as the fire in the Mont-Blanc Tunnel in France, the accident in the Tauern Tunnel in Austria and the fire in the Gotthard Tunnel in Switzerland have led to significant changes in safety requirements in applicable regulations and standards.

The difference between safety in a tunnel and an open road is related to the rarity of intersections, the smaller influence from climatic conditions such as fog, rain, ice, or snow, the more difficult conditions for rescue and clearance in the tunnel and the potentially more severe consequences of fire incidents due to the significantly confined environment. Some important factors influencing tunnel safety in general are for example traffic type and volume, tunnel configuration, dimensions and alignment.

Additional factors affect fire safety within a tunnel: for example the fire safety measures provided within it, including means of escape, detection and warning systems, fire and smoke control measures and facilities for emergency services personnel. Also the tunnel lining material, the shape and dimensions of the tunnel cross section, the exposure of portals to high winds, air/smoke flow through cross passages in twin-bore tunnels and the altitude of the tunnel are important factors.

The scope of this contribution is to illustrate how risk and decision-making methodologies can be applied to fire safety in road tunnels. Safety criteria in standards and regulations are reviewed in Sect. 14.2. The analysis of the human consequences in case of a tunnel fire are presented in Sect. 14.3. A case study dealing with the re-qualification of an existing road tunnel in Wales is discussed in Sect. 14.4. Concluding remarks are provided in Sect. 14.5.

## 14.2  Safety Criteria in Regulations and Standards

### 14.2.1  General

As mentioned above, incidents involving fire can lead to significant life safety consequences. Fires in tunnels have been discussed in various publications (e.g. [2, 11, 18, 29]) and have been considered in the development of the standards, guidelines and recommendations (e.g. [8, 19, 24–26]).

Owing to the issues described in the previous section, there has been considerable activities to improve tunnel safety, including:

- The development of tunnel fire safety standards such as that of the UK [3];
- The development of risk-informed methods and associated computation tools (e.g. [16, 21])
- Research projects related to tunnel safety, especially with respect to the fire hazard (e.g. [10, 29]); and
- The development of a European regulation in terms of EU Directive [8] on the minimum requirements for tunnels longer than 500 m on the Trans European

Road Network and their local implementations such as the Road Tunnel Safety
Regulations [25] of the UK.

## 14.2.2  Prescriptive Versus Risk-Informed Approach

Two approaches to tunnel safety can be distinguished as summarised below.

(a)  **prescriptive approach**
     The traditional approach to design of the built environment is based on prescrip-
     tive standards. They usually are developed over many years and represent a
     rich seam of knowledge. In a prescriptive approach a tunnel is considered
     sufficiently safe if it is designed in line with the standards; which means that
     the tunnel and its safety devices fulfil the minimum requirements given in the
     regulations. The standards specify particular safety features, actions etc. to
     be implemented. Such minimum requirements were provided, for example, in
     British Guidance of 1999 [3], European Directive [8] and German Standard
     [24].

The safety checks in this approach can be performed based on the code require-
ments, with tunnels classified on the basis of their configuration and length, traffic
volume and direction(s) and type of goods allowed. For each category a set of safety
measures is recommended; with their technical specifications also provided in some
standards. This approach is simple but not fully transparent since the fire risk in the
tunnel is not determined. The prescriptive methods encompass tunnel safety manage-
ment during maintenance periods when, for example, traffic can be restricted and
potentially on contraflow.

(b)  **risk-informed approach**
     Risk-informed approaches to the design and assessment of structures and
     infrastructures have been in use since the 1970s, starting with the nuclear
     industry. Such methods were later applied to assess risks in both new and
     existing tunnels. In this approach a tunnel is considered sufficiently safe if
     predefined risk acceptance criteria are satisfied (e.g. [6, 16, 20]).

The application of a risk analysis requires appropriate methods and tools and input
data on accident frequencies and consequences. The analysis allows a structured,
harmonised and transparent risk assessment also in the case of fire. The approach can
be used for the comparison of alternative tunnel solutions, hence also to demonstrate
the safety of a tunnel in case of its deviation from prescribed requirements, and for
the cost-optimal selection of safety measures.

Generally, the risk-informed approach includes hazard identification, risk analysis
and risk evaluation (risk appraisal) and risk mitigation. It requires users to posses
specific knowledge related to the safety hazards, risk analysis methods and tools and
many input data for which in some cases only limited information may be available.
Typical examples of the last item are branch probabilities in the development of an

accident, effectiveness (risk reduction) of modern safety measures, development of fires and consequences in case of fire in a partially confined environment, effects of applied active safety measures and behaviour of users in emergency situations. Therefore, it appears necessary to consider uncertainties in risk analyses by using appropriate statistical models and/or by performing sensitivity analyses. EU Directive [8] recommends the use of risk analyses where necessary and the World Road Association [21] provides tools for such purposes (also see [17]).

Risk analyses for tunnels have been performed for road tunnels in the last decade and results are reflected in the literature [e.g. 13, 27, 31], and in unpublished studies not available to the wider community. The studies deal with different types of tunnels and with different hazards. Since fires in tunnels are particularly hazardous to life due to the potential concentration of smoke and heat radiation, the human risk for a group of persons (societal risk) is thereby applied as the main criterion. For this, different fire sizes are considered, e.g. from fire in a passenger car, a bus, a heavy goods vehicle (HGV) with combustible goods and even a petrol tanker, in order to assess the risk. Risk analysis procedures and associated tools have been analytically described by the World Road Association [21–23].

### 14.2.3  European Directive 2004/54/EC

The European Directive 2004/54/EC [8] is a current major legislative text that sets a minimum fire safety level for road tunnels in the Trans-European Road Network. Utilising results of recent investigations, it specifies safety measures based on a classification of tunnels according to their.

1.  annual average daily traffic (AADT) volume given in terms of vehicles per lane:

    (a)   ≤2000 vehicles per lane
    (b)   >2000 vehicles per lane; and

2.  length:

    (a1)   500–1000 m and (a2) >1000 m for traffic volume of case (a)
    (a2)   500–1000 m, (b2) 1000–3000 m and (b3) >3000 m for traffic volume of case (b).

On this basis different fire safety measures such as emergency walkways, distance between emergency exits, fire resistance of structures, natural and mechanical ventilation, firefighting water supply, monitoring systems etc. are specified as minimum requirements for each tunnel class. Where the prescribed requirements cannot be satisfied or where it is desired to achieve a more economical facility, a fire risk assessment can be carried out to asses and demonstrate sufficient safety. The latter is undertaken when, for example, specified requirements can be achieved only at a disproportionately high cost and it is necessary to examine and demonstrate the suitability of more economical alternative risk reduction measures. The assessment

of risk and the evaluation of possible safety measures should be accomplished based on quantitative acceptance criteria.

Neither specific risk analysis methods nor quantitative risk acceptance criteria are described in the EU Directive. Hence, the member states of the European Union shall ensure that, at national level, a detailed and well-defined methodology, corresponding to the best available practices is used. The risk analyses shall be carried out by a body which is functionally independent from the tunnel manager, i.e. from the public or private body responsible for the management of the tunnel.

### 14.2.4   Human Risk Criteria

The calculated risk needs to be compared to well defined risk tolerability criteria. Although there are no universally accepted risk criteria for road tunnels, there are established criteria in use in some countries for specific applications [22].

In case of fire risk in tunnels, the potential harm to people (fatalities and/or injuries) is a risk with two important points of view [5, 14, 22]:

- The point of view of the individual who decides to undertake an activity, weighing the direct and indirect personal costs against benefits (*individual risk*).
- The point of view of the society, which considers whether an activity is acceptable in terms of the cost–benefit trade-off for the affected population (*societal risk*).

In case of societal risk, two types of criteria are applied to tunnel fire safety [22]: (a) the expected value (EV) and (b) the frequency versus number of fatalities (F-N) curves. Both these criteria are briefly described below.

(a)   **Expected value (EV) or risk value**
A simple measure of societal risk is the risk value or expected value EV i.e. the expected value of all consequences caused by considered accidental events. It is the long-term average number of statistically expected fatalities per year for a tunnel. For the particular event of a fire, it is equal to the sum of the expected consequences of $n$ different fire hazard scenarios $i$:

$$EV = \sum_{1}^{n}(p_i C_i) \tag{14.1}$$

where $p_i$ is the probability of a specific fire hazard scenario and $C_i$ are the associated human consequences (fatalities, injuries or weighted fatalities by representing a particular type of injury as equivalent to a fraction of a fatality). [Note: The probability of hazard scenarios can be obtained using Bayesian methods, Apostolakis [1]]. Expressing risk in terms of the *EV* has the advantage of allowing the total risk of the tunnel to be expressed as a single number which treats all consequences, i.e. fatalities, as equally important irrespective of the number of lives that maybe lost simultaneously in a major accident such as

fire [21]. The application of absolute criteria is simple, but the determination of thresholds as a basis for decision making is not straightforward. In some countries a limit value for EV of $10^{-3}$ fatalities per year is recommended for the transportation of dangerous goods [22]. In many cases relative criteria are used by comparing results of the investigated tunnel to the results based on the same methodology for a reference tunnel that complies with all requirements of the guidelines. The result of the comparison of two singular values is clear and easy to interpret and communicate.

(b) **Frequency versus number of fatalities (F-N) curves**
In this criterion graphical information is provided by relating the number of fatalities $N$ and the frequency of accidents $F$ with more than $N$ fatalities (see, for example, [5, 12, 15, 22, 32]). The cumulative frequency $F$ is commonly compared with a target value $F_t$ [5, 28]. Thus the risk criterion may be expressed as an inequality:

$$F \le F_t = AN^{-k} \tag{14.2}$$

The criterion of societal risk is usually shown in a graph with logarithmic scale for both the number $N$ (within the interval from 1 to 1000) on horizontal axis and the cumulative frequency $F$ on the vertical axis (within the interval from $10^{-8}$ to 1). Then the frequency curve is represented by a straight line having the slope $-k$ ($k$ is commonly given by the values within the interval from 1 to 2 [5, 28]. The parameter $A$ reflects the intercept of the line (on the vertical axis). Example bounds for tunnel human risk in the F-N space are provided in [12]. Based on the *F-N* curves, the so-called ALARP—as low as reasonably practicable—region can be defined by implementing two limits (i.e. lines) [5]. The area above the upper limit represents conditions not tolerable under any circumstance, while the safety region below the lower limit is considered sufficiently safe and, thus, of no practical interest. In the domain between upper and lower bound, various extra safety measures are to be considered and selected to provide a set of available options for risk treatment. The selected risk treatment will be so as to optimise the expected utility that has to be achieved, as shown in the next Sect. 14.2.5.

Acceptability curves such as the above have been also developed and applied in various industrial fields, including the chemical and the transportation industries. It is to be noted that *F-N* risk acceptance criteria can be obtained also from *F-N* curves calculated for a compliant tunnel that can be considered as a reference tunnel.

### 14.2.5 Decision Criteria

Total safety related costs can be optimised via a cost–benefit approach which either is constrained by limits on human consequences given in regulations or, where it is not considered unethical, incorporates a valuing of human life in the optimisation. Once

the optimum solution is obtained, risk treatment is implemented through appropriate prevention and mitigation measures.

In a cost–benefit analysis for human consequences, for each possible safety measure *i*, the related costs are considered. In the first step all costs are related to the decision point using the net present value method. This implies that either the net present value or the net value at the time of the optimisation is calculated. If an interest rate $\gamma$ and an inflation rate $\delta$ are considered, the annuity factors $A$ and $T$ can be derived. Then the cost–benefit information for each individual safety measure can be evaluated based on the utility reflected in the risk reduction due to the safety measure *i* and using the following inequality:

$$A(n, \gamma, \delta)C_{Ii} + T(n, \gamma, \delta)C_{Mi} < SWTP\Delta R_{Hi} \qquad (14.3)$$

where:

| | |
|---|---|
| $C_{Ii}$ | investment costs for the safety measure i |
| $C_{Mi}$ | annual maintenance/operation costs for the safety measure i |
| | [Note: The use of an annual maintenance cost here is a simplification as a safety measure is likely to require more involved additional maintenance activities over longer intervals during its service life]. |
| $n$ | service life in years of the potential safety measure including the effect of obsolescence |
| $\Delta R_{Hi}$ | reduction related to human risk in terms of weighted fatalities |
| $SWTP$ | societal willingness to pay (to save a human life, see for example [14]). |

## 14.3  Consequence Analysis Methods

### 14.3.1  General

The following description is limited to the determination of human safety risks as a direct effect of flames, heat and smoke within a tunnel and does not consider risks due to structural failure and traffic disruption.

The usual analysis methods and related computer modelling to assess tunnel fire safety risk has three stages:

- Modelling of the fire and smoke conditions within the tunnel, usually using computer-based methods such as Computational Fluid Dynamics (CFD);
- Modelling of evacuation during a fire emergency; and
- Determination of potential casualty numbers.

## 14.3.2   Fire Propagation: CFD Analysis

CFD analysis is carried out to simulate fire and smoke propagation within a tunnel and determine how that could detrimentally affect the evacuees. The results of an analysis, here carried out using the computer program [9], are used to estimate boundaries of the tenable regions within a tunnel under various adverse heat and smoke conditions.

A CFD analysis, to be carried out by specialists, consists of steps such as the geometrical modelling of the tunnel, the thermal modelling of boundaries, the determination of the fire size and its growth model, the consideration of adverse wind pressure between portals, the presence of active control measures such as mechanical ventilation via jet fans, etc. The output from a CFD analysis includes prediction of flame temperatures, hot gas temperatures characterising radiative and convective heat fluxes, surface temperatures of the tunnel walls and soffit, temperatures at jet fans, smoke visibility etc.

For ventilation design to cope with a fire emergency, design fire sizes (given in terms of the heat release rate HRR) for common vehicles are recommended for example by Highways Agency of the UK in its guide [3]. According to this guidance:

- A car produces an HRR of 10 MW;
- A bus, a coach or an HGV produces an HRR of 30 MW; and
- An HGV that contains highly combustible goods is able to produce an HRR of 100 MW.

[Note: For structural fire design of a tunnel, a higher HRR such as 300 MW from a petroleum tanker is used.]

The CFD analysis of smoke and heat conditions within a tunnel is carried out under a given differential pressure between its portals. This difference in pressure occurs due to environmental conditions: mainly wind that usually predominates. The probability of various pressure differentials can be determined using either raw wind data or a wind rose for the site.

An example set of results from a CFD analysis of a curved tunnel is shown graphically in Figs. 14.1 and 14.2. The fire is assumed to occur at the location shown in Fig. 14.1 that also illustrates the vehicle entry/inlet and exit/outlet portals of this tunnel with uni-directional traffic. The horizontal contour plots of ambient temperature along the tunnel at a particular height above the road level are shown in Fig. 14.2 for three occasions since the ignition of the fire. The shown plots in the example are for conditions after jet fans, acting in the direction of the exit portal, have been started to ventilate the tunnel. In the contours blue colour is used to represent
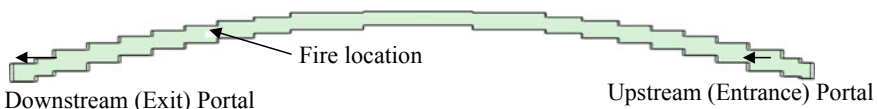


Fire location

Downstream (Exit) Portal                                    Upstream (Entrance) Portal

**Fig. 14.1**   The assumed location of a fire, shown in a plan view of the computer model of a tunnel
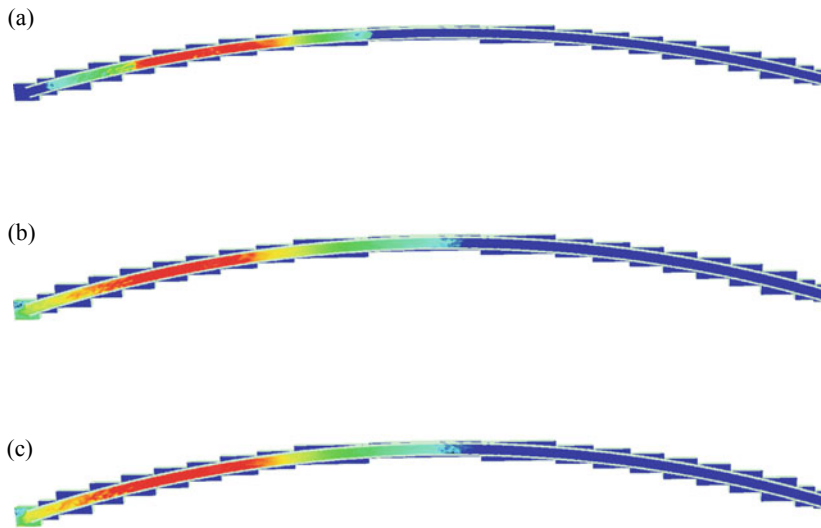
(a)

(b)

(c)

**Fig. 14.2** Example of how jet fans help to control smoke and heat during a 30 MW fire with no pressure differential between portals. Blue colour denotes smoke at 20 °C. Smoke is hotter as the colour becomes redder. **a** At 70 s from ignition and 10 s since the four considered banks of fans reached full power. Hot smoke has spread both upstream (i.e. to the right) and downstream of the location of the fire indicated by an arrow in Fig. 14.1. **b** At 190 s from ignition and 130 s since the four considered banks of fans reached full power. The fans have pushed the hot smoke towards the location of the fire, making the region upstream of it to be of lower temperature. **c** At 280 s from ignition and 220 s since the four considered banks of fans reached full power. The fans that earlier pushed the hot smoke towards the location of the fire maintain this condition (i.e. back-layering is controlled)

colder temperatures while the red colour is used for hotter temperatures, with colours in-between representing temperatures in between. Such information, when expressed digitally, can be used to determine tenability conditions within the tunnel for use in casualty analysis.

### 14.3.3  Evacuation Analysis

On having determined temporal information on fire conditions within the tunnel for different fire loads, subject to the considered portal wind pressures and necessary assumptions, the next step is to determine the exposure of individuals to heat and smoke as they evacuate. For this Monte Carlo simulations are carried out based on information available from the European Research Project UPTUN on cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels [30].

In accordance with the UPTUN method, it is considered that a set of people (group a) would start to evacuate immediately after the ignition of a fire, before an evacuation
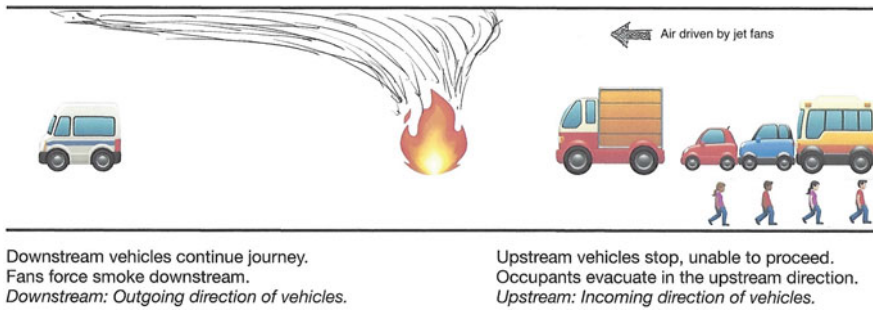
Downstream vehicles continue journey.
Fans force smoke downstream.
*Downstream: Outgoing direction of vehicles.*

Upstream vehicles stop, unable to proceed.
Occupants evacuate in the upstream direction.
*Upstream: Incoming direction of vehicles.*

**Fig. 14.3** The movement of evacuees during a fire in a tunnel with single direction traffic, as assumed in the UPTUN model [30] and used in this work

order is issued. Another set (group b) also would evacuate before an evacuation order has been received (for example, via a public address system available within the tunnel), but they would do so only after the first set of people. A third set (group c) would wait until an evacuation order is received. The time evacuees take to come out of a vehicle is considered random with a prescribed probability distribution. The evacuees who come out vehicles are considered to hesitate and wait for another short period before starting to walk towards safety. This hesitation time also is considered as a random parameter.

The speed with which the evacuees walk has a random probability distribution. The people are considered to be safe once they reach an emergency exit (e.g. a cross-passage door) or the upstream (i.e. entrance) portal. (Here upstream and downstream refer to the flow of traffic.) It is assumed that nobody walks downstream past a fire as shown in Fig. 14.3 for a tunnel with one traffic direction; however, it may happen in real life during the initial stages of a fire if the exit portal or any other downstream emergency exit is only a short distance away from the evacuee and the path to it is not considered hazardous.

In evacuation and casualty analyses, all vehicles downstream of a fire are assumed to move away leaving the fire behind. This is a valid assumption for tunnels where no traffic congestions can be expected beyond its exit portal. However, congestion may occur during a period of heavy traffic, for example if there are traffic control lights downstream of the exit portal, and this should be given consideration.

It is assumed that a fire event will be always detected via a video surveillance system (either manual or automatic), supplemented potentially by other means such as linear heat detectors. It is also assumed that an announcement ordering evacuation will be made always on detection of a fire (or the likelihood of a potential fire). Provision can be made in the evacuation model to consider situations where there is no non-video based fire detection, or where such detection has failed.

The time to detect a fire is determined as the lesser of that by video surveillance and, if provided, linear heat detectors. The probability distribution of the video based detection times can be based on information provided by the tunnel manager/operator because it is very much dependent on the local systems. The detection and alarm

**Table 14.1** Tolerability limits for various tenability conditions

| Mode of heat transfer | Source | Tolerance time |
|---|---|---|
| Radiation | Smoke layer at 160 °C<br>4 m above person's head | 6 min |
|  | Smoke layer at 160 °C<br>0.5 m near person's head | 5 min |
|  | Smoke layer at 200 °C | 30 s |
|  | Flame surface at 370 °C<br>Emissivity assumed 0.9 | 6.5 s |
| Convection | Smoke layer 0.5 m above person's nose at 1.5 m | 1–30 min |

times for linear heat detectors are available in [2], given as to be in the range of 30–60 s from ignition. Accordingly, a probabilistic distribution of detection and alarm time for linear heat detectors can be considered as a uniform distribution between these two limits.

At the start of a fire, the evacuees are considered to be uniformly spread in the tunnel length upstream of the fire, between it and the last vehicle in the stranded queue of traffic. The location of the last vehicle can be determined based on the average number of vehicles and their average length, together with, for example, a uniform gap of 2 m assumed between vehicles in the example presented here.

### 14.3.4 Determination of Casualty Numbers

On having determined the evacuation conditions for each evacuee during his evacuation as simulated by a Monte Carlo simulation, it is necessary to determine how that person can be affected by heat and smoke within the tunnel. This requires tenability criteria beyond which a person may be adversely affected by such products of a fire.

The human body tenability criteria related to the effects of heat of flames and smoke are for example provided in British Standard [4] and reported here in Table 14.1. Based on these values and the exposure of each person, the number of casualties can be calculated.

## 14.4 Case Study

### 14.4.1 General Description

The case study presented here is with respect to the Penmaenbach Westbound Tunnel on A55 in North Wales, which is a 658 m long two-lane existing highway tunnel with uni-directional traffic and a speed limit of 70 mph. This tunnel did not comply with a

prescriptive safety measure required by an EU Directive [8] which was implemented in the UK as Road Tunnel Safety Regulations [25], specifically the requirement for emergency exits along the tunnel at a spacing of 500 m. Providing an emergency exit retrospectively had to be discounted because of its complexity and the consequential impact the work would have upon the road network availability, reliability, delays and environmental issues. However, this tunnel had jet fans for providing mechanical ventilation during a fire; which was not required by the EU Directive because the tunnel was shorter than 1000 m. As the regulations allowed an equivalent level safety to be provided by alternative means, with their effectiveness demonstrated via a risk assessment, the tunnel's owners (the Welsh Government) decided to examine the sufficiency of the available provisions against an equivalent compliant tunnel (which is the 'relative' or 'comparative' method indicated in Sect. 14.2 and used in [17]).

The tunnel has a curved soffit and also is curved in the horizontal plane. It has slight gradients that were too low to affect the walking speed of evacuees [30]. The tunnel portals are open to significant variations in wind conditions, making its consideration in CFD analysis important. Depending on the direction of the wind, it would aid or (mostly) tend to counter the performance of the jet fans. There were six banks of jet fans, with two fans in each. These fans were started in a particular order, instead of simultaneously, to prevent significant electrical surges during the process.

A commonly accepted procedure to determine the fire incident rate, or an annual probability of fire, within a tunnel is to use the average rate of incidents per vehicle-mile in similar open roads in the country as the basis for calculations. The open-road value is converted to a tunnel value based on its length and the traffic volume (i.e. AADT). The particular tunnel's predicted fire accident rates, in terms of the fire return periods, derived from available statistics of the road network were 400 and 3400 years for 30 and 100 MW fires, respectively.

The AADT of the tunnel is 22,000 and a factor of 1.25 was considered to account for future increase in traffic. The vehicle population consists of 75% cars, 23% HGVs and 2% buses. Although this can be considered as random, here it is considered as deterministic and fixed. Vehicles lengths were considered as deterministic with values of 4.12 m for cars, 12 m for buses and 16.5 m for HGVs, respectively. The average number of occupants is 1.6 for cars, 50 for buses and one for HGV.

### 14.4.2 CFD Analysis

The CFD analysis of fire conditions within the tunnel was carried out using the software (FDS 2014). Design fire sizes, in terms of the peak heat release rate (HRR), were 30 and 100 MW (see Sect. 14.3.2). The fires of cars (10 MW) were not considered as was the 300 MW for a petrol tanker. The former was small enough to be easily controlled by the existing jet fans and the latter is considered unrealistically severe for ventilation/life safety design.

Statistics for adverse wind pressure at the tunnel portals were determined from wind data for the site. The pressure difference between the two portals is considered

positive when opposing the movement of traffic and the fan blast. The CFD analyses were carried out with different adverse pressures between portals, ranging from zero to 30 Pa, with the upper limit being advised as the most credible for the location when under high winds. The results from such analyses contributed to the determination of weighted averages of casualties that reflected the probability of various wind conditions. The CFD analyses included situations where no fans operated (in the 'compliant' solutions). In analyses where mechanical ventilation was provided, two banks of fans were considered unavailable due to breakdown and fire damage (see [3]), resulting in the use of only four of the six banks.

### 14.4.3  Evacuation Simulation

The evacuation simulation was based on information available in [30], supplemented with local information available from the tunnel manager, as reported in Table 14.2. During evacuation simulation, a fire is considered equally probable to occur anywhere along the tunnel and the fire location for each simulation is randomly generated based on a uniform distribution. The evacuees are considered to be in place of relative safety once they reach an emergency exit (e.g. a cross-passage door) or the upstream (i.e. entry) portal.

The UPTUN information were supplemented, for example as follows in relation to the particular analysis:

- The fire detection method available (initially) was video cameras (CCTV) installed throughout the tunnel and monitored by staff. Provision has been made in the model to consider situations where there is no fire detection, or where detection has failed.

**Table 14.2**  Input data, including probabilistic data, for the evacuation analysis

| Parameter | Standard | Conservative |
|---|---|---|
| Heat detection time [s] | Uniform (30, 60) | Uniform (30, 60) |
| Video detection time [s] | Uniform (17, 40) | Uniform (17, 40) |
| Tunnel closure time after detection [s] | Uniform (30, 60) | Uniform (30, 60) |
| Time to announce evacuation | Uniform (5, 10) | Uniform (30, 60) |
| Walking speed [m/s] | Uniform (0.44, 1.12) | Uniform (0.30, 0.75) |
| Limit on distance to fire group a [m] | 15 | 1 |
| Limit on distance to fire group b [m] | 30 | 1.5 |
| Hesitation time for group a [s] | 1 | 5 |
| Hesitation time for group b [s] | 5 | 10 |
| Maximum time to evacuate vehicle group a [s] | 10 | 20 |
| Maximum time to evacuate vehicle group b [s] | 30 | 60 |

- The order from the public address system (PAVA) to evacuate the single bore tunnel is (always) made following the detection of a fire (or the potential for a fire) and receipt of authorisation from the relevant manager.
- The walking speeds of evacuees are random, with a probability distribution as reflected by UPTUN. However, in some cases, all generated UPTUN-based evacuee speeds were reduced to 2/3 of the corresponding value of to reflect unforeseen difficult conditions, for example in the absence of mechanical ventilation and the presence of less mobile people.

The described method for assessing types of casualties is efficient and quick as desired by a study that uses a large number of computer simulations. However, it is unable to determine the situations where an evacuee is subject to significantly higher radiation or temperatures than the tenability criteria and, consequently, could have only a shorter tolerance of hazardous exposure. Nevertheless, sensitivity studies conducted using very high safety factors and, consequently, very short tolerance limits, indicated that the analyses are sufficiently robust to allow a comparison of risks in compliant and non-compliant tunnels. It can be also considered robust to a certain extent for absolute risk studies because of the significant dominance of the flame tolerance limit of 6.5 s when determining the casualties.

The methodology described so far determines the expected indicative number of casualties from each simulation for a particular fire location, fire load and an adverse wind pressure, which are the major random variables considered. These individual values were probabilistically combined to determine the expected number of casualties for a one-year period. However, in the following, the annual results for each fire size are presented separately because they provide insights into the differences between them unlike when they are summed probabilistically to obtain overall annual casualty figures.

### 14.4.4  Results

Representative results for indicative life safety consequences in the considered existing tunnel and a compliant equivalent tunnel, given a 100 MW fire and a 30 MW fire under particular wind conditions, are shown in Figs. 14.4 and 14.5, respectively. These results are for two sets of simulation parameters, viz. a '*standard*' set which are considered to reflect a normal situation and a '*conservative*' set that reflect a situation with much longer evacuation times (and, hence, potentially higher life safety risks). The results are for the existing tunnel with two jet fans in each of the four banks of fans and for an equivalent compliant tunnel with no mechanical ventilation but possessing an additional exit from it. The casualty numbers shown in the figures are the expected values under either 30 or 100 MW fires anywhere within the tunnel, with the probability of occurrence of a fire considered uniform along the tunnel. In addition to the above, the results from analyses that investigated the benefit of replacing the two existing jet fans of each bank with three more powerful fans are
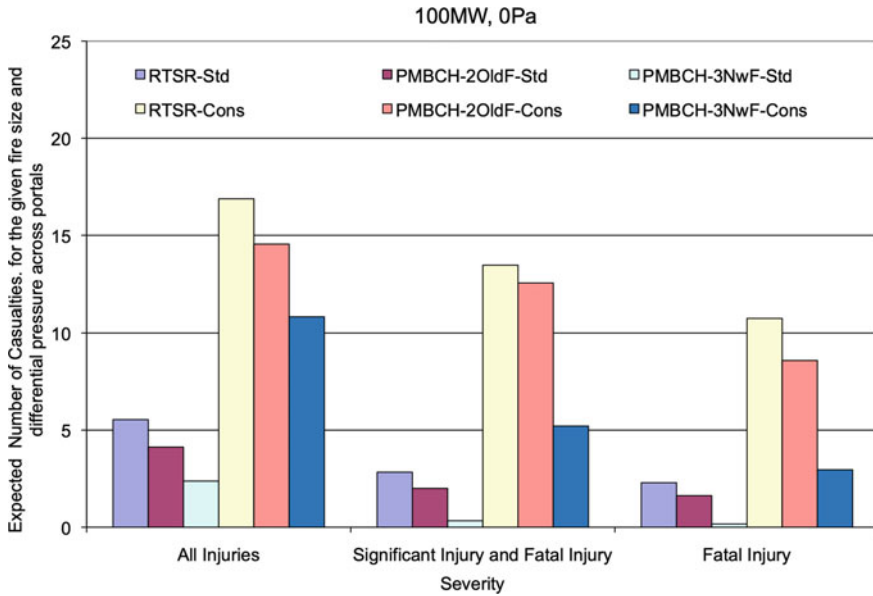
**Fig. 14.4** Expected human consequences given a 100 MW fire with equal occurrence probability along the tunnel and with no adverse pressure differential across the portals. See Sect. 14.4.4 for details on abbreviations used in the legend
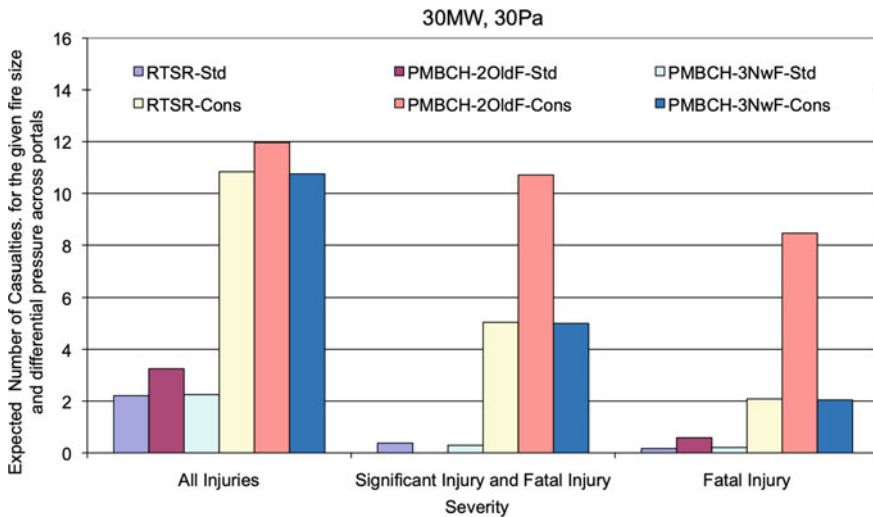


**Fig. 14.5** Expected human consequences given a 30 MW fire with equal occurrence probability along the tunnel and with an adverse pressure differential of 30 Pa across the portals. See Sect. 14.4.4 for details on abbreviations used in the legend

presented in the Figs. 14.4 and 14.5. The following abbreviations have been used in Figs. 14.4 and 14.5 in order to distinguish the different results in them.

- Std = Standard Parameter Case
- Cons = "Conservative" Parameter Case
- 3NwF = With three new more powerful jet fans per bank
- PMBCH = The existing tunnel
- RTSR = Equivalent [25] compliant tunnel, with a new exit and without jet fans.

In the presence of existing jet fans the expected casualty numbers for a 30 MW fire under a 30 Pa pressure differential are higher in the existing tunnel than in the considered equivalent compliant tunnel with no mechanical ventilation (Fig. 14.5). The opposite behaviour is seen for a 100 MW fire with no adverse pressure differential (Fig. 14.4). However, the existing tunnel was seen to pose a lower risk than the compliant tunnel when the results for each fire size under all different wind conditions were probabilistically combined to determine the expected casualties under a particular fire size.

Notwithstanding the above positive results, in order to improve the margin of safety between the two considered tunnel configurations, the effect of replacing the existing two jet fans in each bank with a set of three more powerful fans was additionally investigated. Also the results of this new design condition are presented in Figs. 14.4 and 14.5 and 14.6. The following observations and conclusions can be made with respect to the results shown in these three figures:

- With three new more powerful fans per bank, under the 30 MW fire and a very high and extreme adverse wind pressure differential of 30 Pa, the risks in the existing tunnel are similar to that of the considered compliant tunnel. Therefore, when upgraded, the overall risks in the existing tunnel over all wind conditions will be lower than in the considered compliant tunnel (see Fig. 14.6). This is because the jet fans are more effective against the more common lower adverse pressure differentials across portals.
- With the upgraded tunnel showing lower overall conditional risks (under all adverse pressure differentials) for each of the two fire sizes considered, also the annual risk obtained by probabilistically combining these results as given in expression (14.1) will be lower for it than for the considered compliant tunnel.

Following this work the Welsh Government chose to implement a variation of the suggested solution by providing two extra fans at each of the six banks of fans, to give a total of four fans per bank, to similarly improve the performance. In this way, using the alternative safety measure of mechanical ventilation, the existing tunnel satisfied the requirements of [25] to a higher level than the considered equivalent compliant tunnel.
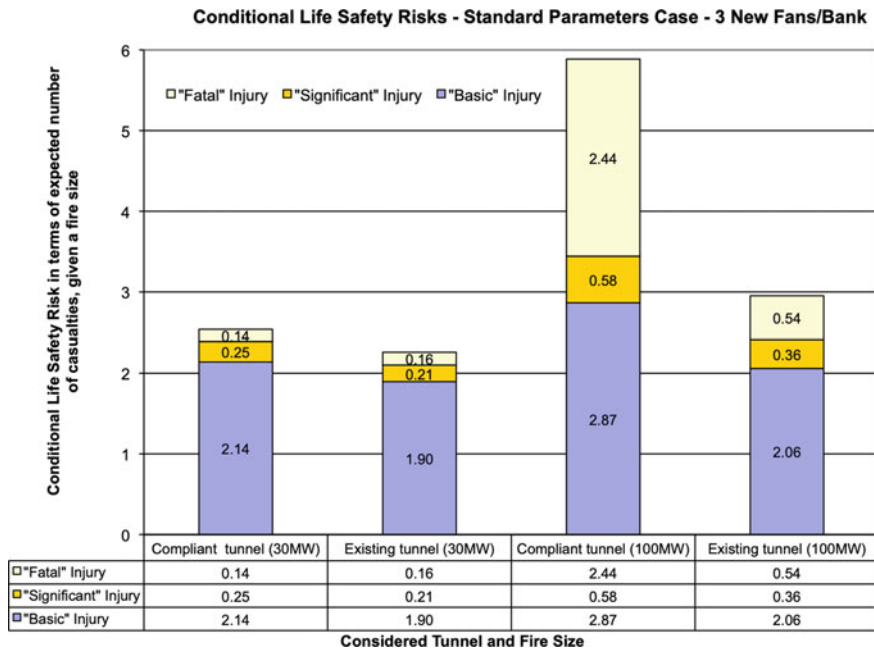
**Fig. 14.6** Conditional life safety risks in terms of the expected number of different types of casualties, given a 30 MW fire and a 100 MW fire. Fires considered here are within a compliant tunnel and the existing tunnel with three new and more powerful fans per bank. Standard parameter case

## 14.5 Concluding Remarks

Vehicle fires in road tunnels represent an extreme hazard to the users, manifested through significant accidents in the past. This chapter provides a critical review of provisions in standards and regulations and summarises state-of-the art methodologies to assess related human risk. It also examines and discusses decisions related to respective safety measures in the light of uncertainties.

The analysis of fire life safety in a tunnel is a complex process involving several parties. The results of the case study of an existing tunnel show the practical usefulness of the presented methodologies that involved computer simulations comprising CFD analysis, evacuation modelling, casualty analysis and statistical analysis.

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