CLEAR AIR, CLEAR CONSCIENCE

Limited resources and administrative uncertainty can throw up some difficult safety decisions. The directors of *Pospisil & Ilg Associated Engineers* provide some advice

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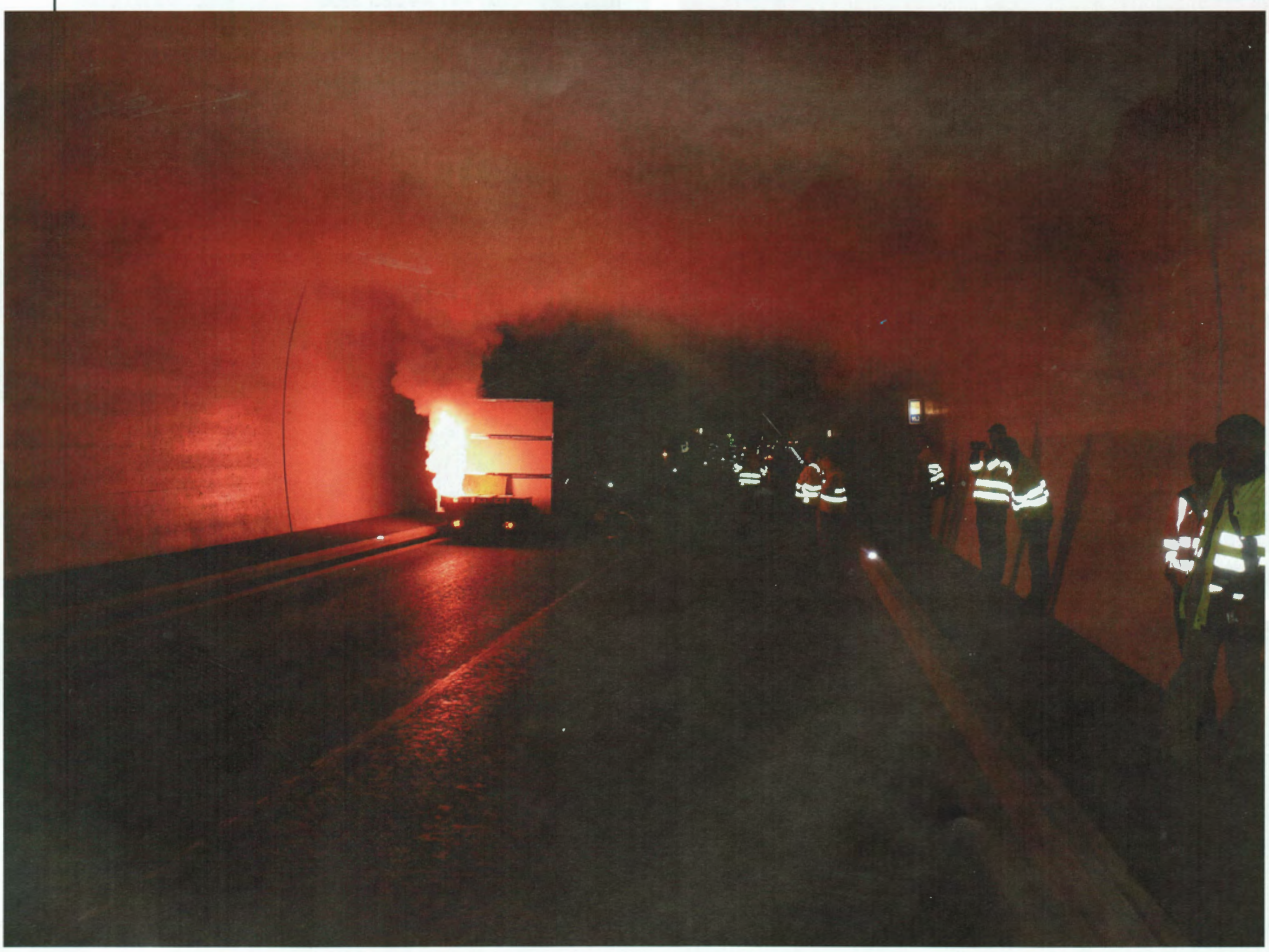
WHEN TALKING with employees of tunnel investors and operators, as well as the responsible government bodies, an uncertainty over the correct course of action sometimes emerges. Doubts about having taken the right decision on safety systems, and fear of possible personal consequences from failures and tunnel disasters can haunt the decision maker's sleep.



For investors, operators and the designers of road tunnels – who bear a responsibility for the safety of persons, as well as for important investment decisions – ventilation is one of the most important systems that enhances the safety of a tunnel. Particularly for long tunnels with high traffic volume.

Lessons have been learned from several road tunnel fire disasters 15 years ago, and a number of new safety requirements have been introduced since then [3]. Today most ventilation systems are designed primarily for an emergency situation, i.e. the fire ventilation, and many are hardly ever used in normal operation. Improvement is a continuous progress, and after more than a decade of practical application of those new safety standards, new findings and the actual state of the art of technology should be taken into account.

Another sleep-depriving fear for tunnel stakeholders is the fact that the excessive costs of road and rail infrastructure are being brought into question in many countries. Political pressure leads to cuts in budgets, and many tunnel projects are postponed or even cancelled for this reason.

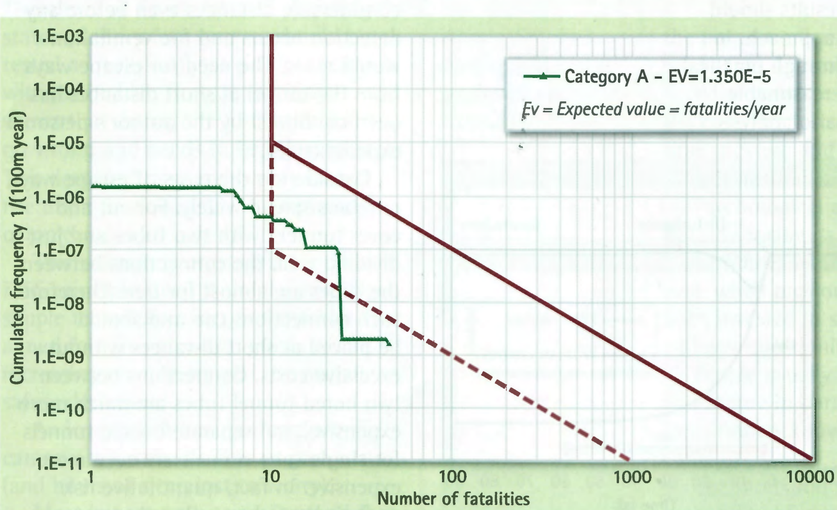
Prescriptive guidelines for tunnel safety equipment, particularly for ventilation, do not always lead to useful solutions. When safety requirements lead to the construction of a tunnel being delayed, or even cancelled due to financial restraints, then those requirements might be questioned and compared with the primary benefits of the tunnel itself, like improving traffic safety and capacity by optimising road alignments, or reducing the environmental impact in comparison with an open road. Considered from this perspective tunnel safety regulations that delay or prevent projects do indeed decrease the road safety in the long term.

Two important measures to increase safety and reduce costs of road tunnels are described in this article. The first is a proper risk assessment, based on scenario analysis, to support useful conceptual decisions. The second is rigorous and continuous testing to ensure that those costly safety measures fulfil their purpose in practice. Only testing allows us to identify systems with limited or not even existent usefulness. It enables us to improve or omit that kind of technology in the future.

These aspects have been more or less ignored in many prescriptive design codes that have been revised in the aftermath of the 1999 tunnel fire disasters. In fact, any requirement in a guideline is useless when its fulfilment cannot be proven.

Recent guidelines, for instance the new Czech methodical instruction for road tunnel ventilation [4] include risk based decision-making and requirements for testing procedures in order to achieve an acceptable level of reliable functionality.

Below: Figure 1, Sample frequency-consequence diagram with lines of acceptance



That guideline was worked out for the Czech ministry of traffic, but has been based on practical experience from more than 100 tunnel ventilation projects worldwide.

RISK ASSESSMENT AND SCENARIO ANALYSIS

Cost-benefit considerations should be part of any decision about safety of human lifes and investment of billions of Euros. The often-heard statement "each life has to be saved at whatever expense" is practically infeasible given limited funds [9].

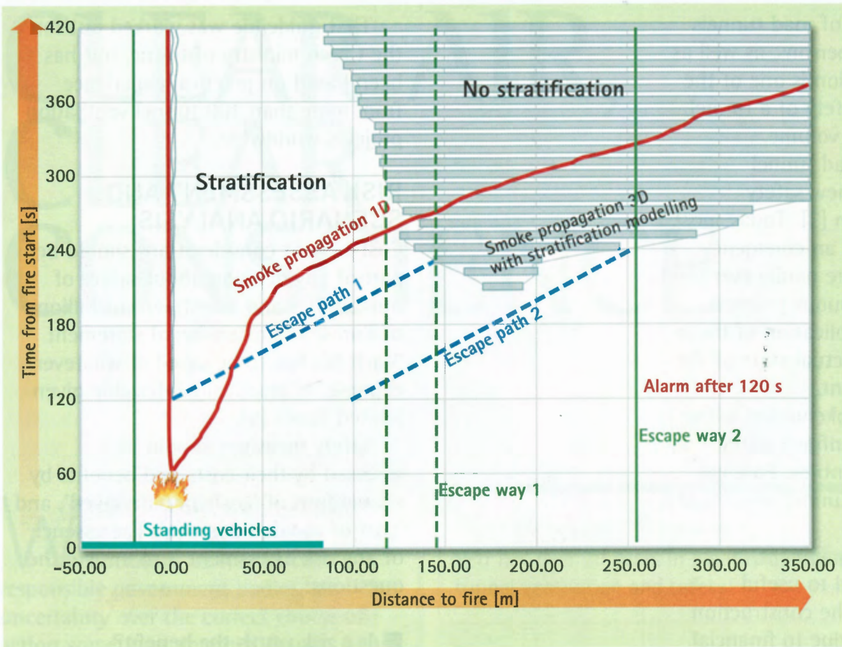
Safety measures should be assessed by their costs and benefits by estimations of 'costs per life saved', and 'cost of avoided damage'. The essence of any risk assessment is to answer the questions:

- Is a risk worth the benefit?
- Are risk mitigation measures worth the resulting risk reduction?

Many risk analysis studies for road tunnels have been worked out in the recent years, a number of simulation models have been established and a lot of literature has been written about the issue. A good overview can be found in the PIARC document [2]. One of the major findings is that the safety in a road tunnel is governed in first order by the risk of collisions and only in second order by fire risk. There are only a few tunnels where fires occur with a statistically relevant frequency, and the vast majority of fire incidents do not lead to casualties. In fact, in comparison with overall road traffic casualties, those from fires in tunnels are negligible. In 2012 , there have been approximately 28'000 fatalities on roads in the European Union [11], while the fatalities due to road tunnel fires worldwide in the last 100 years sum up to a number in the order of 150 (at least in peace times) [8]. Approximately 25 per cent of those died in one single event, the 1999 disaster in the Mont-Blanc tunnel between France and Italy, and many deaths were caused by the accidents leading to the fire rather than by the fires or the smoke.

Obviously the new safety regulations may contribute to a higher level of fire safety in tunnels, but this is not a guarantee that a huge disaster could not happen just the next day.

For an applicable risk assessment, first of all the main goals of any safety measures must be defined, and clear criteria must be stated whether those goals are met. In this way, limiting lines



in a frequency-consequence-diagram (F/C) are created.

For risk mitigation, measures that prevent accidents are much more effective than measures that affect only the consequences. In this aspect, the purpose of tunnel ventilation to provide clear visibility in the tunnel could have a higher importance than fire ventilation. This aspect is important for long tunnels with bi-directional traffic and high traffic volume.

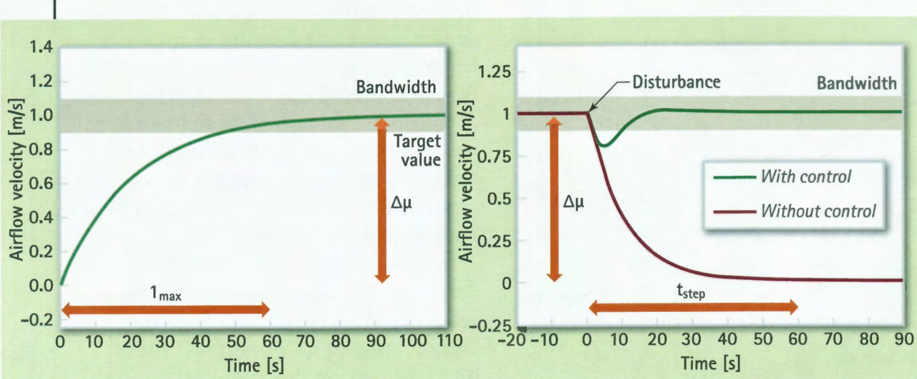
The key element to assess fire risk in a road tunnel is a scenario analysis based on dynamic simulation of smoke spread and escape of persons. Different variants and boundary conditions lead to dozens or even hundreds of simulations to be conducted. 1-D models are useful for fast computations, but for the assessment of smoke stratification, which might be essential in certain cases, 3-D modelling of the airflow in the tunnel is required.

Assumptions on useful boundary conditions may have a strong influence on the results. Particularly sensitive to this is the longitudinal airflow and spread of smoke in the first phase of a fire, before the fire is detected and the fire ventilation is started.

Any risk analysis is based on simplification. The result of even complex, detailed risk analysis is still a rough estimation, taking into account the limited data, unknown probabilities and simplifications of modelling. Simulation results should be double checked by using a common sense approach. In that aspect, common sense can be achieved through practical experience. Expert knowledge can assure that reasonable assumptions are applied. Therefore, such scenario analysis

Above: Figure 2, Example diagram of smoke propagation and escape paths

Below: Figure 3, Acceptance criteria for control of longitudinal airflow



An additional tube to allow unidirectional traffic is much more efficient than an escape tunnel

should be conducted or at least supervised by experienced engineers. Such can be identified by having a proven track record of planned, realised and successfully tested reference projects, with focus on thorough testing.

Even when the underlying probabilities and models are to be understood only as rough estimations, the instrument risk analysis provides a good idea about the magnitude of the risk that is to be expected. It may serve as basis for decisions about useful risk mitigating measures.

As an example, escape ways rank among the most important safety measures. They significantly improve the ability of the tunnel users to escape in case of a fire. For instance, the European guideline [4] requires escape ways in distances not exceeding 500m for tunnels on the trans-European road network.

However, the determination of useful distances between escape ways is very dependent on the context. Scenario analysis based on simulations of smoke propagation and escape of persons have shown that to be effective in tunnels with bidirectional traffic, the distance should not exceed approx. 150m, when the tunnel is going to be filled with smoke. Particularly in connection with strong longitudinal airflow, smoke is spread quickly over considerable distances even before any detection occurs and fire ventilation would react. The need for escape ways from the tunnel at short distances has been confirmed by the author's personal experience [8].

Considering the costs of escape ways, numbers spread widely. For cut and cover tunnels, with two tubes and just a dividing wall, the connections between the tubes are almost for free. Therefore, such connections can and should be placed at short distances without excessive costs. Connections between two bored tunnel tubes are much more expensive, and separate escape tunnels for single tube tunnels are even more expensive. In fact, quantitative risk analysis have shown that the cost per life saved for separate escape tunnels lies in the magnitude of billions of Euro. In terms of cost per life saved, the construction of an additional tunnel tube to allow unidirectional traffic is much more efficient than any parallel escape tunnel, because it significantly reduces the collision risk and subsequent fire risk.

Of course, such considerations are subject to political decisions. However, you cannot always predict the future by taking into account past experience. Using the term 'worst case' is questionable. In practice, worst case scenarios always occur, ones of which nobody has previously thought of. It is usually only after such an incident that public opinion may criticise the lack of appropriate measures. The decision process requires some courage from the authorities when looking for useful solutions. Maximum provisions cannot be relied upon just to avoid blame [9]. In this aspect, sleeping well cannot be justified by spending excessive money on safety measures with questionable usefulness.

THE IMPORTANCE OF TESTING

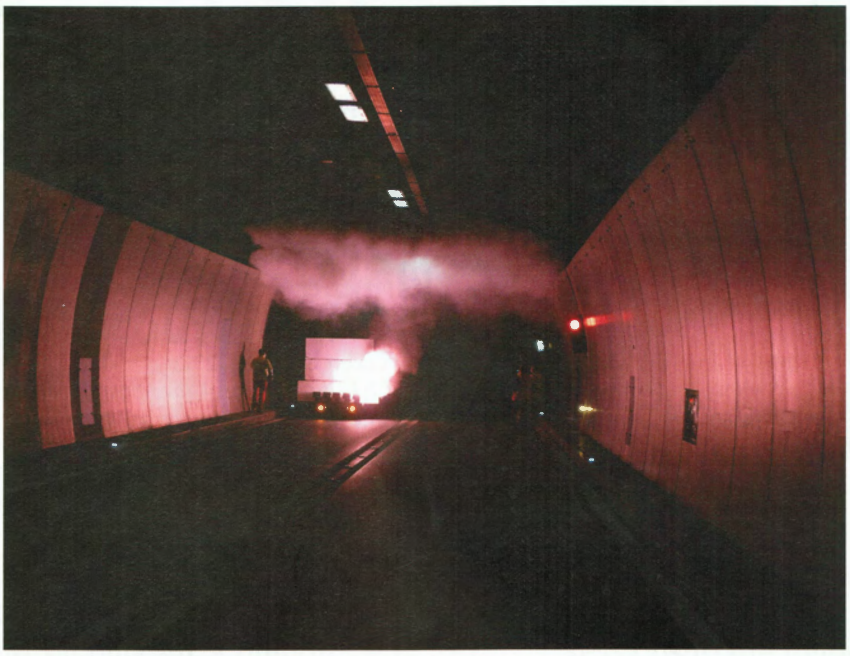
A concept or system which is completely inapt might last for long time as long as it is never really tested. That is the case for many safety systems (e.g. tunnel ventilation equipment) that are built for extraordinary events, which probably never happen. In fact, most tunnel ventilation systems as designed before 1999 were not useful for fire ventilation.

Defects in safety systems that are practically never in operation become first visible when an incident occurs, but then it is too late - the failure can have disastrous consequences. Uncertainties about this issue rightly cause bad sleep. Therefore, all functions and operating states of the safety systems should be tested as realistically as possible but with justifiable efforts. Experience shows that during the tests a lot will go wrong and needs to be corrected. This demands time and costs which rise disproportionately with increasing complexity.

This is a strong argument for the KISS principle (keep it simple, stupid): simple technical concepts should be aimed for. The error rate grows with increasing complexity and the overall safety decreases.

An investment in smart engineering can save a hundredfold in project costs (and hours of sleep lost to worry).

Most important is to understand that the purpose of testing is not to demonstrate that everything works fine, but to find faults that are to be eliminated.



Above: Smoke testing exercises underway in tunnels

What is not tested cannot be assumed as safe. Although the costs for tests are comparably low, due to continuous time pressure and financial shortcuts in the final stage of any project, testing is often neglected.

Psychological aspects counteract safety considerations. Because incidents occur very rarely, the common attitude is that nothing would happen, and there is no money for testing, even when previously dozens of millions of Euros might had been invested in safety equipment and structural provisions without questioning.

People usually assume that everything would work fine and ignore in particular their own mistakes. Experienced practitioners know better. To err is human and errors always come up.

The more and profound you test, the lower becomes the probability of unpleasant surprises in operation. Investment in testing lets you sleep well as a tunnel investor, operator or safety officer.

The control of the spread of smoke is the main goal of the fire ventilation. To achieve this, detailed test scenarios for all possible states of the control system must be defined, including failure modes, breakdown and malfunction of equipment.

For each of these scenarios, acceptance criteria should be defined. Tests probe the function of single systems – like the ventilation – as well as the integral cooperation of all tunnel safety systems.

The key element of state of the art fire ventilation in tunnels is an effective control of the longitudinal airflow. With or without smoke extraction, a fast stabilisation of the airflow at low flow velocities, lower than the assumed walking speed of persons, assists escape and enables smoke stratification. This is important in tunnels with bidirectional traffic or where congestions are common. However, this does not apply to highway tunnels with free flowing unidirectional traffic.

Acceptance criteria for the control of longitudinal airflow, based on realised ventilation systems, have been proposed [7].

Calibration of instruments and testing of equipment and control systems should also be repeated in regular intervals for tunnels in operation, together with proper service and maintenance work. This is often neglected however, leading to expensive equipment becoming inoperative after only a few years.

An important part of testing procedures are realistic smoke tests. From the two main effects of fire, smoke and heat, the latter leads to significant structural damage and cannot be simulated without extensive, costly protection measures. On the other hand, the smoke kills and injures most people in fire incidents, and it´s propagation can be simulated and visualised relatively easily.

Realistic smoke tests to be applied for testing of tunnel safety equipment should fulfil the following requirements:

- The physical characteristics of the test smoke, especially the optical density should be similar to that in case of a real vehicle fire.
- The produced heat must not damage the structure and equipment in the tunnel but should induce thermal buoyancy and smoke stratification.
- The test smoke must be harmless with regards to toxicity and possible health hazards.
- The test smoke must not be corrosive and must not leave behind any deposits on the installed equipment in the tunnel, particularly on measuring instruments and cameras.
- Influencing boundary conditions for the longitudinal airflow in the tunnel (traffic, wind, buoyancy) must be simulated.
- The smoke detection must react reliably, even with an active fog suppression.
- Tests should be carried out simply and quickly, to carry out tests for many different scenarios.

Realistic smoke tests show the function of the automatic smoke detection and the performance of the fire ventilation. A realistic view of the situation in a fire emergency is given to the present professionals, including investors, designers, operators and fire brigade. Most importantly, you often find issues that nobody has thought of previously.

Through this, precious findings for a continuous progress and improvement are achieved, which should be considered in the concept and design process. This is important where requirements in actual design guidelines were based mostly on mere theoretical considerations.

Finally, when decisions, particularly about appropriate ventilation and safety systems, are based on careful considerations and risk analysis, and proper function with sufficient reliability of those systems has been achieved by a process of thorough testing and improving, then the stakeholders like tunnel investors, operators and designers can sleep well with a good conscience

Below: Smoke exhaust damper in action

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