ON THE ROAD TO SAFER TUNNELS

[1]F. Zumsteg, [1]U. Steinemann, [2]M. Eisenlohr
[1]US+FZ Consulting Engineers, Lenzburg/Wollerau CH
[2]Swiss Federal Roads Office (FEDRO), Bern CH

ABSTRACT

The fatal fire events around the turn of the millennium led to the amplified efforts to make tunnels safer. Due to the strong traffic increase and as a result of increased social claims and expectations, the pressure has increased prominently for higher tunnel safety with corresponing bigger investment and maintenance efforts. The legal pressure for the identification of persons responsible for incidents also contributes to it. This is reflected on the extent of the requirements in standards and guidelines and has an effect on the inventiveness of manufacturers and engineers as well as on the complexity of the systems in tunnels.

Keywords: tunnel safety, ventilation, complex systems

1. INTRODUCTION

With regard to ongoing developments we recapitulate successful innovations of the tunnel equipment with their benefit and cost in this paper as well as illutions and dilusions. It turns out that man as the element of uncertainty often limits the use of the systems.

In theory many of the developments are plausible. In reality, however, difficulties lead to necessary modifications and compromises.

2. MEANING OF TECHNICAL ACHIEVEMENTS

A topic at this year's SWISSBAU was: Is modern technology our rescue or do we have to rescue ourselves from it? The following examples show that this question also has significance for the tunnel equipment. Besides technology in an incident the often unpredictable human behaviour is decisive for success or failure.

2.1. Fire and smoke detection

Thermal detection is the standard of fire identification in many places. Today thermal linear sensors are used in all Swiss tunnels with a length over 600 m. With sufficient temperature or sufficient temperature rise the sensors react quickly and locat a fire exactly. An experience of the years well before 2000 was that the turbidity measurements often detected a fire in the Gotthard road tunnel earlier than the thermal sensor although turbidity sensors were mounted at intervals of more than 1 km. Only in 2005, thus 25 years after the opening of the Gotthard tunnel, the Swiss Federal Roads Office FEDRO published a draft for the guideline Fire Detection [1] which prescribes the smoke detection. Today smoke detectors are used in Switzerland in most tunnels at intervals of 100 m, in special cases even at intervals of 50 m.

As engineers we have to ask the question how it was possible that this change was carried out so late. The fact that smoke represents the primary peril for the tunnel users seems obvious today.

The specifications in [1], which were accompanied by the further development of smoke detectors led to the euphoric feeling to have solved the problem of the smoke and therefore fire detection. There was even the hope to be able to go without supplementary systems. Fortunately such simplifications were not introduced immediately because the real time evaluation of the smoke signals proved to be more complicated than expected. Ventilation systems with point extraction by controllable dampers need a precise indication of the fire location. Otherwise the operation of the exhaust air can endanger the tunnel users additionally by transferring the smoke at remarkable speed through the driving space. Moving and pulsating smoke sources confront the developers of the software with fiddly questions. Moreover, it cannot be excluded that a smoke detector is faulty. Again and again, at the check of the functionality of the systems in the tunnel one discovers new scenarios and sequences which show that a reliable fire locating detection takes its time even with smoke detectors. At a smoke test recently carried out with an initially moving smoke source we had to notice that the automatic ventilation mode yielded a place discrepancy between fire place and location of detection of 300 m. It can be stated that smoke detection leads to a quick alerting and in the large majority of all cases to an exact determination of the fire location. The thermal linear sensor installed furthermore ensures a system redundancy, offers the possibility of a manual justification of the ventilation operation and can serve the advancing fire brigade as a useful basis for their attack.

2.2. Congestion detection for a correct ventilation reaction in the case of a fire

Smoke extraction right downstream the incident or longitudinal ventilation blowing the smoke in driving direction through the tunnel are means to keep smoke away from people in a tunnel with one-directional and initially free flowing traffic. Since the ventilation operation shall happen automatically and in general without a manual intervention, the set value of the flow corresponds to the approaching air flow of at least the critical velocity according to the design fire.

With a fire within congested traffic the above mentioned ventilation operation is unreasonable. The attempt to grasp congestion reliably to determine the appropriate ventilation operation proves to be very difficult. On the one hand, the question arises how congestion has to be defined for this need for multi-lane tunnels and, subsequently, whether the recordings at certain cross-sections suffice, e.g. in front of the exit portal, or whether a recording is indispensable over the total tunnel length. The complexity of the system and particularly the interpretation of the recorded signals are very high for the latter.

A pragmatic approach consists in putting the focus onto the phase of self-rescue. An approaching flow speed lowered to 1.5 m/s allows people in the congestion downstream to escape. A transverse system operates at full extraction capacity and a symmetrical flow toward the fire is installed in the case of traffic congestion (cf. section 2.4).

2.3. General behaviour rules and alerting of the tunnel users

The quick alerting of the persons in the tunnel is a prerequisite for their adequate behaviour. While the alerting concerns persons mainly who do not have any view on the event, behaviour instructions are for everyone of importance. The experience shows that the behaviour of the persons can be chaotic despite of quick alerting and correct information. The aim is therefore "giving the people a fair chance for the escape". The safety means such as detection, alerting, ventilation and positioning of emergency exits have to interact properly.

With regard to adequate alerting the opinions differ considerably although their investment is low in comparison with systems like ventilations or fire extinguishing systems. The temporal optimization of the processes of ventilation scenarios deals with time spans of 10 seconds. If one can encourage persons to escape on foot, we can win several minutes. The results of the thorough research and the positive experiences with loudspeakers, e.g. in Holland and in

Germany, should be perceived also in other countries and the use of loudspeakers should be considered.

The general information of the road users about the behaviour is of great importance for a fire incident in a tunnel. The fatal fire events around the turn of the millennium have led to considerable reinforcements of these activities and the appreciation of the road users of these requests has increased at the same time.

2.4. Arrangement of emergency exits

Thirty years ago the necessity of emergency exits for tunnels with transverse ventilation was questioned. With the understanding that transverse ventilation alone cannot ensure the safety of the tunnel users in a fire incident, the knowledge of the importance of short distances of the emergency exits grew. In the year 1980 the Gotthard road tunnel was opened to the traffic and it is equipped with emergency exits at intervals of 250 m. With this it fulfills the Swiss norm [2] presently in effect. Due to the civil engineering costs, exponents warned until the year 2004 of the "inflation of emergency exits".

Short and steep bi directional tunnels for wich ventilation in the case of a fire is not suitable, [3] [4], are today planned with emergency exit intervals of down to 60 m. Short distances of the emergency exits are a substantial motivation due to their visibleness and obvious accessibility to begin the escape besides the theoretically calculable shorter escape time. With difficult tunnel geometries and for cut and cover tunnels short emergency exit distances often offer an effective and - regarding investment and maintenance - favourable measure for the achievement of the requested safety standard.

2.5. Doors and ventilation of emergency exits

A general principle is to open emergency exit doors in escape direction and sometimes by means of a crash bar. This principle was and partly still is applied so stringently that certain doors were no more openable with physical strength against the excess pressure in the incident ventilation operation.

The pursued methods of resolution are:

- opening aid for wing doors with external power
- opening aid for wing or sliding doors with mechanical strength transmission (e.g. tunnel Flüelen, CH)
- double doors with different opening directions (RABT [5])
- sliding doors (FEDRO [6]).

Figure 1: Sliding door seen from pressurized safety tunnel to the deriving space

The approach to use sliding doors as it is pursued as consistently as possible in Switzerland gives cause to serious discussions. Altogether, the advantages predominate, however, clearly: The escape routes including the safety galleries can robustly be ventilated and well designed sliding doors with the dimension B x H = 1.25 m x 2.1 m can be opened with 60 N at a pressure load over the door well up to 300 Pa (Figure 1). The various experiences during the last 10 years with constructional lacks have led to mature door constructions by now.

It is plausible that railway tunnels are equipped with motor-driven openings of the escape doors due to a high number of persons approaching the door and the consequently large area of the doors.

2.6. Automatically controlled dampers for smoke extraction

In the year 1987 the Rosenbergtunnel was opened in the city of St Gallen. It was the first Swiss tunnel with automatically controlled ventilation dampers in the intermediate ceiling. However, until the year 2000 most transvers ventilated tunnels in Switzerland had no controllable dampers but distributed exhaust openings. Reasons against controllable dampers were doubts about sensors needed for the determination of the fire location, the complexity of the facilities and the so-called "mechanized intermediate ceiling" with its maintenance effort. Moreover, there was the expectation that smoke is generally warm, rises to the ceiling and can be extracted from there even over longer distances. This assumption arose from fire tests which were not able to cover the reality extensively due to lacking disturbancies of the air flow. In the meantime the experiences show that the stability of stratified smoke hardly ever meets this expectation in a real fire scenario. A chaotic event like a vehicle fire in a tunnel is mastered only with a massive use of ventilation.

An earlier argument cannot be wiped off the table, though: Inadequately maintained extraction dampers can be more dangerous for persons than the earlier distributed exhaust openings in the case of a fire in the tunnel. In theory it may seem as a trifle. In practice, however, the maintenance of the dampers is not always sufficient. Reasons for it can be: lacking appreciation of the danger of a malfunction and missing financial and personnel resources subsequently. No country is known where this is not a issue.

2.7. Frequency controlled fans

Speed controlled fans make the life easy for the ventilation designer. He can fix the desired volume flow exactly even without big risk of calculation errors. Frequency converters are additional electronic and thus failure-prone components which have a considerably shorter life cycle in comparison with fans and cables. Due to the required coordination of frequency converter, cable and motor a partial replacement represents an increased risk with regard to the fault-free operation of the safety facilities ventilation.

With few exceptions only one reason stands for speed control for exhaust air fans which are operated only in the fire case: the limitation of the starting current. This is required for weak power supplies.

Usually large axial fans are tested sequencially to safe peak energy costs. It has to be noted that axial speed controlled fans working in parallel have to be tested contiguously to guaranty a proper start-up.

A more important use can arise from speed control for jet fans. But even here theory promises more than what practice with all unpredictabilities can offer.

The demand of FEDRO in [7], to use frequency converters only if power supply or aerodynamic reasons require it makes sense.

2.8. Manual interventions in the ventilation control

Manual interventions in the ventilation operation during a fire require a detailed knowledge of the complete system as well as the current situation in the tunnel. While due to their computational simulations the designer of the ventilation systems and the developer of the ventilation programmes regard a manual intervention as feasible, this is understandably enough a hot potato for most operators who are multiple charged particularly in a first phase of the incident. In certain areas of Switzerland operators explicitly wish that the possibility for manual interventions is omitted. In general, automatic operation cannot be activated any more after a switchover to hand operation without endangering the persons in the tunnel. An operator should manually intervene only according to 4 eye principle and preferably according to on-site demand.

A meaningful approach is to offer ergonomically clear manual transitions to pre-programmed scenarios, e.g. to shift the extraction point or to change to the appropriate traffic mode.

2.9. Complexity of systems, open and closed-loop control

Computer simulations of ventilation controls can mislead to implementing complicated and strongly differentiated procedures. It does not increase the safety of the tunnel users if under special conditions a dedicated ventilation scenario is assigned to a 60 m long portal near section. In the example mentioned here with only one single smoke detector in the concerning section the scenario would not have been testable. A basic principle must be:

What is not properly testable must be avoided.

The inclusion of experienced operators in the conception of controls has proved of value. This might lead to more intensive discussions, in general, however, to more robust systems which operators understand even without very effortful training and without support of the developers. This is of special importance under the aspect of the fluctuation of personnel.

2.10. Safety and availability during refurbishments

It is essential that during the renewal of existing tunnel systems the safety standard does not fall below the minimal specifications. This requirement is plausible particularly for older systems with considerable safety backlog demand. It can be drastic, however, for the sequence of the refurbishment.

One has to consider whether a short phase with partial fulfilment of an individual system can be accepted to be able to quickly obtain a higher safety level. For short work phases and hardly assignable states, quantitative risk analysis is not suitable for this evaluation.

2.11. Thermal requirements on components

High thermal requirements give the impression that the feasible gets implemented. If high requirements seem necessary, concept and layout of the components have to be analysed. In general, the temperature resistance of 250°C over 2 hours of the ventilation components, like exhaust air or jet fans, suffices to cover the effective requirements of the rescue phases. The results in the bast publication [12] for fireloads up to 50 MW confirm widly the indications in the directive [9].

2.12. Risk analyses

The request of the EU in the guideline [7], article 13, for the creation of national methodologies for a risk analysis was also heard in Switzerland. The corresponding FEDRO guideline [8] was put into effect in 2014. The target to use gainfully the limited means is plausible. The requirements to master fire incidents in tunnels are high today. Hopefully these requirements are not increased further purely due to new technical developments of safety facilities for mastering the rare fire events with serious consequences.

Certain refurbishing concepts show a great and not plausible discrepancy between the approaches according to standards, like [9], and according to quantitative risk analysis, QRA, like [8]. While the disadvantage of the application of the standard requirements is the not object-specific distinction of safety facilities, crucial points of the QRA are:

- Missing basic data and statistics due to the few events.
- Difficulty of parameter definitions, two exemples:
  The economic costs, in [8] with CHF 21 per person and hour, drive up the congestion consequence and affect the result strongly.
  Non-zero escape velocities in dense smoke overestimate the benefit of emergency exits and reduce the fatality rate.
- Complexity of the methodology, versatility across the trades: The methodology requests the knowledge in all trades, the ability to carry out an assessment coordinated integrally and the critical questioning of the results.

The plausibility of the results of the QRA must in any case be checkable and be checked. Parameters must, if necessary, be analysed and adapted. This can be required also object-specifically which means that one leaves the official specifications and with that the legally stable terrain what sacrifices a great advantage of the method.

An example of an implausible result from the QRA is the long permitted distance of emergency exits in railway tunnels. From events in vehicular tunnels it is known that an initially moving smoke source leads to an extensive area with smoke and therefore represents a considerable peril. A train fire in a tunnel starts almost always from an initially moving smoke source and even in the self rescue phase the smoked area is mutual. Moreover, the fleeing people's density in a rail tunnel is much higher than in a road tunnel.

2.13. Geometry of lay-by niches

In the fatal bus crash in the tunnel Sierre of March 13th, 2012, 28 persons, among them 22 children, were killed. The accident started an intense discussion about the shape and arrangement of lay-by niches. Should the end walls be at an angle or can it be right-angled? Depending on the incident scenario the one or other solution proves to be more favourable. It is not possible in the end to realize the optimal safeguard for all scenarios. As long as a man steers the vehicle, the variety of his reactions is unfathomable.

2.14. Kerb height in tunnels

There is a great disagreement with regard to the kerb height. Kerb heights of 12 to 18 cm are commonly realized with a lowering in front of emergency exits. Quoted reasons are the safety of pedestrians on their way to the next emergency exit, the high intake capacity of the slit gutters, the protection of signals on the margin of the clearance profile and the function of spur keeping. The latter was often specified as a main reason. One can doubt whether this goal really is accomplished. In the outline of the new RABT a kerb height of 3 cm is provided on both sides of the complete tunnel length. Thus it becomes easily walkable especially for handicapped persons but at the same time it is also drivable. The low frequency of walking persons on the kerb while traffic is running makes it difficult to give reasons for higher kerbs. The experience will have to show which consequences this modification in Germany will have. A direct transferability of statistics from other countries is hardly possible.

2.15. Developments on the vehicles

The predominant number of accidents arises from a human misconduct. Safety facilities, like seat belts, crush zones or ABS, is a matter of course today. Distance and lane hold systems are already just as ordinary. Further developments, such as self steering cars are in the test phase and will contribute prominently to the diminution of accidents within a few years. The more complex the systems the higher their maintenance needs. The developpement leads to a shift of responsibilities from the individual vehicle driver to the system manufacturers and the servicing shops.

Reports about spontaneous fires of electric vehicles because of short circuits or battery problems have lowered the hopes concerning a positive effect, on the fire frequency and fire load of electric cars already. The initial fire performance is possibly smaller but the cargo load which is decisive in great events remains the same. In a fire where large batteries are involved a new danger from poisonous substances can arise. However, the already approved vehicle-bound extinguishing systems are desirable for a wider use.

2.16. Measures against recirculation

According to [9] recirculation of polluted air between exit and entry portal has to be reduced with measures like portal offset or partition walls at twin-tube road tunnels. In reality it looks differently.

Figure 2: Naturally ventilated tunnel with portals in a deep cut and with potential recirculation of smoke and polluted air

Sometimes the local situation is taken into account too little, architecture is placed over the function or this requirement simply gets forgotten. It has to be stated that a recirculation is unwanted in normal and in emergency operation and shall be reduced with suitable measures. Passive measures against recirculation work without further technology and without time delay.

2.17. Cross border harmonization of safety measures

International activities have already achieved a considerable degree of harmonization in the area of signalization of the safety facilities and partly of safety requirements. One of such basic documents represents [10]. The World Road Association, PIARC, has created substantial bases in all sorts of areas. The report [11] stands as a fundamental document in the field of ventilation. Further coordinations are necessary particularly at areas like Europe in which one can pass through several countries within a few hours. The facilities which directly concern the tunnel users like the way of the alerting, the behaviour instructions, the driving education or the signalling, are most important. Moreover, it would be useful to harmonize issues such as adequate information of the tunnel users, handicapped person suitability, detection systems, kerb heights and emergency door opening concepts.

3. CONCLUSION

The examples in this paper show that there is no direct road to safer tunnels. New theoretical findings and technical developments prove in practice to be demanding, delicate on disturbances and intensive in maintaining.

The specifications and requirements in standards and guidelines should permit a sufficient flexibility for an object-specific distinction, however without disturbing the uniformity of the systems to such an extent that the understanding of the operation is afflicted. This is a balancing act which cannot be avoided. As a principle, simple and checkable systems should guarantee a proper interaction with the other facilities. The simplicity of the systems has to be stressed according to servicing effort and corresponding servicing costs. If servicing and maintenance are inadequate, safety systems can mutate to hazards.

Steep tunnels are still planned with ventilations whose positive safety effect is overestimated clearly. It lays in the responsibility of the engineers to show and explain the bounds of the feasibility to the builder-owner. An attempt to solve this problem consists in giving passive systems increased weight such as emergency exits and structural design which reduce smoke recirculation. Higher investment costs relativize with reference to the life cycle.

4. LITERATURE

[1] Swiss Federal Roads Authority: Directive 13004, Branddetektion in Strassentunneln, V2.10, 2007

[2] Standard SIA 197/2, Design of tunnels – road tunnels, 2004

[3] Zumsteg F., Steinemann U., Berner M.: Ventilation and distance of emergency exits in steep bi-directional tunnels, Conference "Tunnel Safety and Ventilation", Graz 2006

[4] Bettelini M., Seifert N.: On the safety of short road tunnels, Conference "Tunnel Safety and Ventilation", Graz 2010

[5] Richtlinien für die Ausstattung und den Betrieb von Strassentunneln, RABT, 2006

[6] Swiss Federal Roads Authority: Directive 13011, Road tunnel doors and gates, V1.05, 2009

[7] Swiss Federal Roads Authority: Fachhandbuch 23001, Betriebs- und Sicherheits-ausrüstungen

[8] Swiss Federal Roads Authority: Directive 19004, Risikoanalyse für Tunnel der Nationalstrassen, V1.01, 2014

[9] Swiss Federal Roads Authority: Directive 13001, Lüftung der Strassentunnel, V2.03, 2008

[10] Council of the European Union, EU: Directive on Minimum Safety Requirements for Tunnels in the Trans-European Road Network, 2004/54/EG

[11] PIARC: Fire and smoke control in road tunnels, PIARC Committee on road tunnels C5, Report 05.05.B, 1999

[12] Bundesanstalt für Strassenwesen bast: Forschungsprogramm Strassenwesen, Anforderung an die Temperaturbeständigkeit von lüftungstechnischen Bauteilen, FE 15.0514/2011/ERB, 24.5.2013