MANAGERIAL AND TECHNICAL ASPECTS OF TUNNEL SAFETY REGARDING NORMAL AND EMERGENCY MODE

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ABSTRACT

The safe operation of a traffic tunnel may be compared, in a certain way, with the operation of a production plant. Here the employees expect a safe work environment just as people passing through a traffic tunnel is expected to have a firm believe in the tunnel’s safety and in the responsibility of the tunnel’s operators. System analyses of traffic tunnels, as well as the latest catastrophes show that the tunnel’s operation does involve a variety of risks. Among these risks, (besides traffic accidents with hazardous materials) a tunnel fire is certainly one of the most dangerous ones.

Due to the stochastic character of such risks the question is not if a tunnel fire could start or not but when. Whenever a tunnel fire occurs, it has the real potential to endanger persons in the tunnel, in the form of smoke inhalation, heat exposure and confined spatial conditions, as many tragic events have showed us. Therefore a modern operation of traffic tunnel-systems requires a safety management-system that integrates technical- and organizational aspects. This provides a safer operation and it prepares one for adequate reactions in unexpected incidents (small or large).

Such a management-system must be prepared to cover unexpected events with its own resources, up to a certain level. Above this level, which certainly must be (politically) discussed and defined, the management must be able to provide a functional interface between a variety of agents, services and other organizations, in order to counter even the largest of incidents.

A generic element of such a management-system is the fact, that at the top a single person becomes responsible for safety. Further generic elements are an adequate organization, tailor-made standardized practices and procedures and a functional method to supervise the whole management process.

Due to the steady reduction of vehicle emissions by new technical developments the air flow requirements in normal tunnels were recently decreased. Whereas the ventilation system was designed for normal operations (to dilute and remove vehicle emissions from the tunnel itself) now, in a case of a fire, it has however, to ensure a smoke-free evacuation route for tunnel users. The tunnel ventilation system has now become an elementary and vital function for the tunnel users, but also for key personnel and emergency services responders. In other words, a potential fire scenario is now the determining factor, when designing tunnel ventilation systems.
1. **INTRODUCTION**

The number of extended street and railway tunnels increases continuously. Consequently we have to cope with much more traffic which might cause fatal accidents such as release of dangerous substances or (major) tunnel fires. The recent fire disasters in the European Alps focused the public interest on problems concerning traffic and safety. Shortly after the fire in the Mont Blanc Tunnel the Deutsche Montan Technologie GmbH (DMT) having its origin in mining has been caring for safety and people and equipment in mining for about 100 years. DMT as an expert body for tunnel safety carried out a preliminary audit for twenty tunnels on the most important holiday routes in Austria (12), Switzerland (4), France (2) and in Germany (2) on behalf of the Allgemeine Deutsche Automobil-Club (cf. [4], [10]). Thereby a comparative picture concerning the state-of-the-art of particular tunnel systems, in other words of safety practise and of single safety elements has been worked out in an objective manner. That time almost the half of them were assessed as “risky” or even “sub-standard”. Only 5 tunnels were quoted “good” and the best mark “very good” was not awarded at all. However several organizational and/or technical safety elements could be identified in all cases, there was an indication to improve the state-of-the-art due to the implementation of a safety management system (SMS). Due to the implementation of a SMS in particular the risk caused by major fire disasters can be reduced for a new tunnel as well as for an existing tunnel to a small acceptable level. Therefore the integral approach proposed by DMT and RISC RUHR GmbH considers a tunnel more as a living organ than as a static building. This is why the individuality of a tunnel system and the financial effort to maintain the safety technique and the safety management system are taken into account.

2. **MANAGERIAL ASPECTS**

2.1 Analysis of the DEPOSE-System

In terms of safety engineering and safety science every tunnel can be interpreted as a DEPOSE-system (Design, Equipment, Procedures, Operators, Supplies and Materials, Environment) within a certain system-environment. The system itself may contain several sub-systems containing units and parts. Dependent on the quantity and individual character of the components of a particular system there is a certain degree of coupling and interaction between the components of a system. Perrow (cf. [13]) examined various types of systems an rated them in this concern. For example a nuclear power plant system was rated “complex” concerning interaction and “close” concerning coupling in comparison with a coal mine system which was rated “less complex” and “loose”. In this concern the interaction of a traffic tunnel system can be rated less “linear” compared to railway transportation systems and the coupling may be rated as “close” as for railway and maritime transportation systems.

The more complex the system is the more difficult it is e.g. to foresee its reaction in case of a failure or emergency mode (e.g. a fire in the tunnel). Related to this it has furthermore to be taken into account, that safety (sub) systems may contribute to an increase the complexity. The closer components are linked together in the system the more a transfer of unintended processes to other components may occur. This coherence may decide on whether the operational personnel may deal with a small initial event (e.g. extinguishing a burning tire) or if this exceeds and finally results in the failing of the whole system (e.g. uncontrollable tunnel fire). Thereby the system analysis of the DEPOSE tunnel system is of essential importance.
2.2 Hazard Analysis and Safety Concept

Based on this system analysis further methods can be used for a systematical investigation and assessment e.g. concerning identification of hazards and assessment of its probabilities and consequences.

Following this a safety concept containing adequate safe guards and a corresponding safety organization can be designed, implemented and maintained. The safety concept must be designed tailor-made for each individual tunnel system and its system environment. Furthermore it must be revised frequently and adopted e.g. whenever the technical and/or organizational character of the system changes, legal requirements are modified or an unintended emergency mode took place.

2.3 Safety Management System

Traffic tunnels contain the risk of a major fire. This risk results from the probability and the consequence of the fire. A look at risk statistics makes it obvious that there is already a frequency for tunnel fires and not only a probability. Furthermore the frequency shows us that also major tunnel fires must not be classified as “rare events”. On the other hand, events such as in the Mont Blanc and Tauern tunnel showed us the consequences could range up to fail of the whole system. In order to end up with an acceptable remaining risk in each case a tunnel must not be seen as a static building any more but as a living organism, a dynamic tunnel system. The result of this approach is to claim for a tunnel safety management system (SMS). Thereby the organizational and technical elements of the system must be able to manage all phases in the life cycle of a tunnel (from “cradle to grave”) in particular the phases of construction, normal operation, maintenance, re-construction, emergencies and shut down, as it is already common practise e.g. in the process industries.

2.4 Generic and Particular Elements of the Safety Management System

DMT holds the opinion that SMS may vary from tunnel to tunnel concerning their particular elements but is based on the same generic (or key) elements (cf. [17]). Based on the approach of Hagenkötter concerning the general management of working processes and the tactical scheme used by fire brigades, the preventive and emergency management of tunnel systems in general can be described with a control loop consisting of four generic elements (cf. [1]). These are:

- Policy
- Organization
- Instruments
- Controlling

For particular tunnel systems then the individual control loop consists of certain individual elements. Following the Periodical Systems of Elements, which is well known in Chemistry a Periodical System of Safety Elements (PSSE), can be set up in order to visualize generic and individual elements of a particular tunnel system (cf. [2]). Due to this transparency is given for all persons on duty with the safety of the tunnel system. Also an easy communication is possible whenever a certain element is replaced or added.

Furthermore the PSSE allows to assign elements intended to fulfil preventive safety requirements as well as those for incidents related to the availability of the tunnel and not related to safety as well as for the various scales of emergencies.

Policy

Management of a tunnel system must have a safety policy, which shows that safety belongs to the major goals. Furthermore this illustrates that the top management stands behind this goal
as well as safety belongs to all employees and is an integrated part of all activities of the operating company. In order to illustrate this issue the safety policy should be layed down in a written document, which is made available to all employees and third parties and is subscribed by the top management (cf. [14]).

Organization

The “normal organization (staff)” of a tunnel is intended to operate the tunnel sufficiently under normal conditions. Therefore a clear procedure is required to define the responsibility, the particular tasks and authorization of the line management. Usually extraordinary situations such as construction work, collisions, maintenance work etc. can be handled. Experience shows that if a certain point is reached, for example, when an initial fire (e.g. at a tire) in the tunnel gets out of control the pressure on the normal organization might get so high that it leads to collapse.

Therefore an adequate “emergency organization” has to be prepared including employees of the operating tunnel company and external emergency organisations such as municipal or voluntary fire brigade and rescue services. Besides an adequate equipment these persons must provide the necessary competence and in particular an adequate training level (cf. [9]).

Instruments

Tailor-made instruments (in terms of practices, procedures etc.) must be selected and implemented for the individual tunnel system. Examples are the emergency communication plan, permissions for hot working (e.g. tar work), basic safety behaviour training of employees and third parties in order to deal with smaller events (e.g. initial fire at a tire, spill of hazardous materials) and special training of emergency response forces (e.g. municipal/voluntary fire brigade, rescue services) in terms of occupational safety and health as well as for tactical optimisation. Realistic training is one of the very few possibilities to build up experiences which are necessary to deal with greater emergencies like rare huge tunnel fires.

Controlling

In order to ensure that a safety management system once works adequately concerning the defined demands and furthermore is adapted adequately in cases of significant changes within these demands control elements must be implemented and maintained. Therefore a well-known instrument in various industries is safety auditing (cf. [1], [2], [14]).

The role of the audit is to establish an instrument providing a top down and bottom up information flux between management and staff concerning current safety conditions. The audit may be carried out based on checklists. The results are documented in a written report. Frequent audits provide management with the necessary information about possible safety gaps. Management then can maintain those installations or measures. DMT proposes to carry out a very detailed audit the first time taking into account technical documentation and local inspection. After significant changes in the tunnel system e.g. a re-construction, changes at safety installations or a fire an audit is urgently recommended. In case where a tunnel system is operated under normal conditions a frequent repetition of the audit is recommended after two years.

3. TECHNICAL ASPECTS

One of the primary technical aspects is ventilation. Ventilation of traffic tunnels on one hand targets on the dilution and removal of emissions from vehicles. On the other hand ventilation should be capable to control heat and smoke in case of a fire. Due to the fact that
the specific emissions from vehicles decreased continuously during the past the required flux of air for a tunnel decreased also for its normal operation but for the case of a fire the requirements mentioned above are still valid. So far the case of a fire determines more and more the design of tunnel ventilation systems. Certain generic types of ventilation (systems) are available to operate the various traffic tunnels:

1. Natural ventilation
2. Longitudinal ventilation
3. Semi-transverse and transverse ventilation

DMT carried out a scientific examination based on certain fire tests (i.e. EUREKA-Project, Memorial-Tunnel-Project and Investigations at the German Test Mine Tremonia), interpretation of fire events (i.e. Caldecott-tunnel, Gotthard-tunnel, Pfänder-tunnel, Ekeberg-Tunnel, Nihonzaka-tunnel), 3 dimensional simulations (i.e. CFD-code) and the corresponding literature. Main results concerning the suitability of tunnel ventilation (systems) are:

- When deciding on a particular tunnel ventilation system it may be to think over a variety of some thousand versions due to the various parameters such as frequency of jam traffic, contra flow traffic, transportation of dangerous goods etc. Therefore DMT recommends using its decision-matrix.

- The DMT decision-matrix and a detailed discussion of the Pros and Cons of particular ventilation (systems) can be found elsewhere (cf. [11]).

- In case of natural ventilation there are no separate measures available for the fire mode. Therefore the use of natural ventilation should be restricted to tunnel lengths of up to 400 m.

- In case of longitudinal ventilation systems good conditions may result in front of the fire in terms of evacuation, rescue and fire fighting for one-directional traffic. Longitudinal ventilation systems shows significant restrictions in case of frequent jam traffic or contra flow traffic. Thereby the use of longitudinal ventilation should be restricted to tunnel lengths of up to 400 m in case of contra flow traffic and up to 800 m in case of one-directional traffic. Generally DMT recommends verifying the suitability for the fire mode of such complex ventilation systems due to fire tests and numerical simulations (cf. [8]).

- In case of semi-transverse and transverse ventilation systems good conditions may result in terms of evacuation, rescue and fire fighting for one-directional traffic and for contra flow traffic as well. Caused by a complete aspiration of smoke near by the fire the smoked zone is limited to a certain part of the tunnel near by the fire. These systems can be optimised taking into account the distance between ventilation openings in the ceiling, their size and the volume rate of airflow.

Beside this “fix-installed” ventilation systems “mobile” ventilation devices can be applied by the fire brigade in case of an emergency mode. Such mobile ventilation devices should be assessed in advance of a fire mode in order to prevent unintended interactions with fixed-installed ventilation systems and expansion of smoke, gases and heat of a fire.

4. FIRE FIGTHING

4.1 Basic Principles

In order to make the tactics more understandable, the common characteristics of the building aeration (necessary) are presented first. The basic physical principles are:

1. generation of an overpressure(and/or directed air flow)
2. creation of a ventilator application of artificial ventilation
3. locking of unwanted apertures.
For the generation of the overpressure several turbo ventilators are combined in series as well as in parallel in order to receive a sufficient service. It is very important that a sufficient distance is kept in front of the smoke filled area so that the cone-shaped air flows bulging themselves cover the entire cross-sectional area of the room. A second access point of the affected building is used as an exhaust if possible.

Tunnel plants (for example subway-system) however are far more detailed and locking of all unwanted apertures is hardly possible. Therefore the solution is a purposeful combination of several ventilators. The lock of the unwanted apertures there results from building an "overpressure-plug" which can be made in the tunnel tube at the neighbouring subway station. By this the smoke, toxic gases and heat are forced into the chosen direction.

The adaptation of these basic principles lead to the concepts for the tunnel fire fighting and aeration:

1 generation of a directed air flow (and/or regular overpressure); in this case list of the exhausts into sufficiently great distance opposite the fire 
2 selection of a ventilator (as at building aeration) 
3 "lock" of unwanted apertures through 
4 combination of the exhausts parallel or in line (as at building aeration).

4.2 Tactical Concept

An application of this is a mission concept for the fire fighting in subway-systems. This concept is based onto the so-called "combat patrol tactics" in combination with artificial ventilation. The task of the "combat patrol" is to fight the fire already in the origin stage and to extinguish the fire by a fast first extinguishing-attack. In parallel the aeration tactics shall provide a powerful and sufficient ejection of smoke in spite of the difficult structural circumstances. This bases on the known overpressure ventilation which allow desired combined aeration tactics similar to the building aeration.

From that a fire inside a standard subway station can be attacked in the following way:

The first unit for the extinguishing-attack is the "combat patrol" (1/4). they proceed through a subway access point, from which none or at least little smoke leaks. In parallel the aeration is initiated by additional fire-fighting forces. At the smoke boundary, the intermediate level in front of the access to the platform is struck, mobile tunnel ventilators are brought into position behind the combat patrol. The fresh air drives away the smoke form the access point the departure too or at least prevents a additional smoke distribution.

Because of the great spatial dimensions of the building at least four mobile ventilators have to be used at this place. Above the last entrance to the platform the air cone should expand to the entire sectional view and to generate a continuous overpressure in the platform tier. The opposite departure of the platform is used as exhaust. As heat, smoke and toxic gases will be spread over the whole floor the are must be searched for fleeing persons before the ventilation can start.

In order to direct the smoke for this purpose, to keep exactly within this area and to avoid to be pressed into the entire subterranean tunnel system, a back pressure is made at the two nearest entrances to the tunnel (neighbouring subway stations or emergency escape hatches) by bringing additional ventilators into the tunnel tube. Also here the ventilators are brought in position that the air cone can expand onto the entire tunnel sectional view.
4.3 Discussion

Practical experiments following the described basic principles - using cold smoke - showed, that the aeration effect in spite of the difficult architecture of the tunnel plants were predictable at a astonishingly high precision. From this, this aeration concept can be fitted to the actual situation without great problems based own judgement individually. Alternatively only partial elements can be applied in order to protect for example a neighbouring cross-breeding railway station against a dangerous heat and smoke distribution.

The intense noise of the ventilators as well as the additional requirement of fire fighting personnel are disadvantageous. On the other hand the described concept gives a more effective fire-fighting operation and an improvement of the safety for the fire-fighting forces. So the raised strength requirement might make itself paid for the aeration. Finally also the expenditure is manageable, from the view of the training as well as from the view of the technique expenditure, since only standard fire fighting devices are applied and since the building aeration tactics is only adapted.

CONCLUSIONS

Based on their specific experiences in auditing European tunnels, system analysing, contributing to safety concepts and training emergency response teams DMT and RISC RUHR conclude:

1) Each traffic tunnel must be seen as a living organism in other words as tunnel system with its individual system-environment.
2) Tunnel fires are no rare events (there is already a certain frequency and not only a probability) and may end up in huge disasters.
3) Within the operational company/institution a single person within the top management must take over the responsibility for safety.
4) The operational company/institution must not leave the responsibility to deal with huge disasters exclusively to the fire brigade.
5) In order to achieve best management of safety based on limited human and financial resources an integral approach is substantial.
6) Safety of tunnel systems may be marked individually but must in principle be managed systematically.
7) In order to end up with a small acceptable remaining risk the operational management of a tunnel system must implement and maintain a safety management system.
8) Prior safety goal is to protect people, i.e. users, employees, third parties and emergency response forces. Operational measures and technical measures thereby must be capable to manage escape and rescue. In this manner installations and/or mobile devices for smoke control are of primary importance.

LITERATURE

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Further information:
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