OPTIMAL DESIGN OF TUNNELS
EXPERIENCE FROM AND FOR PRACTICE

Steen Rostam, Niels Peter Høj, Carola Edvardsen

ABSTRACT

This paper contains a discussion of the design process for tunnels. The design for safe tunnels is presented in the perspective of an overall performance of the tunnel system during the lifetime of the structure. The paper gives reference to the recent developments in European research projects as well as the application of the methods in practice.

1 INTRODUCTION

Tunnels are increasingly important parts of the infrastructure. In the mountainous regions, the tunnels create short-cuts for railways and roads, so that a higher traffic capacity is achieved and the car and train users can enjoy a shorter and more comfortable travel. Tunnels are also used as alternatives to bridges for connections across waterway: straits, rivers, canals etc. with the advantage that the tunnels do not influence the ship traffic and that the traffic is protected from weather impact. More and more, tunnels are used directly or indirectly for environmental reasons: In built-up areas underground transport facilities relieve the pressure on the surface infrastructure or the surface infrastructure can be replaced by underground arteries. This creates an improved urban environment. In densely populated areas underground transport facilities can be the only way to establish the necessary mobility. In the countryside there is an increasing resistance towards new roads and railways. The natural landscape is treasured, and the only way to create new traffic connections without changing the landscape is to establish underground traffic links.

The efficient construction of tunnels and the development of the modern construction methods also contribute to the feasibility of tunnels.

So with the already significant part of the road rail and metro transport taking place under ground and the prospect of a further increase in the future, one of the demands for tunnel professionals from traffic users and society in general is to create high quality underground facilities. This includes not least underground facilities with a sufficient high safety level. If we should fail to have acceptable underground traffic solutions it may be difficult to reach the aims of mobility and environment.

The theme of this Symposium is Safe and Reliable Tunnels and the Symposium is part of the inauguration of the Committee of Safety in Underground Facilities, so we can show the society that we take the challenge of creating safe tunnels and underground structures very seriously. In the following the design methods which can be used as part of our endeavours to create optimal safe and reliable tunnels are discussed.

2 DESIGN FOR SAFETY

Traffic accidents are the most significant cause of accidental fatalities. About half of all accidental fatalities (corresponding to 2% of all fatalities) are caused by traffic accidents (all types of traffic). This is for road traffic adding up to about 150000 fatalities per year in Europe and makes traffic safety an important societal problem. In spite of these frightening numbers it must be added that traffic safety is an unparalleled success story. For road traffic the fatalities per billion vehicle-km has halved every 15 years since the start of motorisation. Since the traffic is increasing, the total number of fatalities is not reducing with the same pace and we will also in the foreseeable future have many thousand fatalities in traffic.

In fact, fatalities in tunnels are only a rather marginal part of these fatalities, so the contribution from the improved standards in the tunnels for the traffic safety in general will be quite modest. Furthermore, if the general safety level of a tunnel (measured in fatalities per vehicle-km) is compared to a similar open section, it appears often that the safety is better in the tunnel than outside.

So why do we actually care about the safety in tunnels?

One side of the answer may be that this is what society and the tunnel users expect from us: it is clear that repeated accidents like the ones in Mont Blanc, Gotthard, EuroTunnel etc will not be tolerated by the society and will seriously damage the reputation and acceptance of tunnels and thereby influence the possibilities for development of mobility and economy in Europe.

Another side of the answer is that tunnels are engineering structures where we, the professionals, are expected to take responsibility for a design which gives the users a reasonable safety. If we compare with the structural design, it is also a fact that the number of people killed by structural collapse is quite modest; still an entire profession of structural engineers is occupied with creating sufficient safety in the structures. Compared to the structural safety, the determination of operational safety in tunnels has not reached the same level of maturity. The profession still need to reach consensus on methods to determine safety and acceptance criteria.

Safety in tunnels is here mainly understood as safety for the users against various accidents. Also consequences to the structure and to the surroundings are taken into account. Some accidents in tunnels are similar in frequency and consequences to a similar section of the infrastructure in the open; however for some events the consequences can be much more severe in tunnels. These events are particularly connected with the hazards of fire, explosion and flooding.

Different approaches for safety design are discussed in the following.

2.1 Prescriptive approach

Traditionally fire safety standards for tunnels and other structures have been prescriptive; they have contained minimum requirements, which must be fulfilled. These requirements have been established during years based on experience, tradition, and engineering/expert judgement. The standards can be prescriptive on different levels from specifying directly certain measures to specifying goals and methods

The advantage of a prescriptive standard is that it is not complicated to use and it ensures a minimum level of equipment which it ensures in the tunnels. On the other hand prescriptive standards may not be applicable to unusual situations and may in some cases not be able to take into account the interaction between different parts of the tunnel structure, installations and the local conditions.

For some parts of the underground facility it is beneficial that the standards give direct requirements for the measures. The users of the tunnel will have little chance to get acquainted with the safety equipment and it will be impossible for them to realise the difference in design in the various tunnels. Therefore the equipment with user interface should be as far as possible standardised. This is at present not the case: various tunnels have – depending on national regulation, local tradition, location, type of structure, etc. – different safety concepts and safety equipment which expect and require different actions from the users in case of an emergency. This makes also a general education of the users difficult.

It may be a point of concern that prescriptive guidelines with a high safety standard may specify expensive equipment in tunnels where there is very little use for it, or where the cost benefit ratio is very unfavourable. For this reason most guidelines distinguish between different tunnel types and classes depending on the traffic, length etc. The result of this is then, that tunnels do not have the same equipment, and the tunnel user may not know what kind of equipment is available or what the safety concept is.

In fact the prescriptive guidelines have apparently been developed in order to create a compromise between a standardised level of equipment and a homogeneous safety level (within the jurisdiction of each guideline). This has now for road tunnels been supplemented with the EU directive for minimum requirements.

2.2 Performance-based approach

In recent years, the performance based approach has found application for design for safety and for other design issues. By application of performance concepts, safety is achieved based on a scientific appreciation of the phenomena of the unwanted events, of the effects of the events and of the reaction, behaviour of people etc. Emphasis is often given to the safety of life, and the structural safety but also other objective can be pursued with performance based design.

By a performance-based approach, the regulatory requirements are given on a more general level specifying the safety of the users, economic values, etc. The objectives and the associated acceptance criteria used in a performance based approach need to be clearly defined and established to the particular design under consideration.

2.3 Risk analyses

In the design for safety the risk analysis is an essential part. Risk analyses can be carried out with different purposes and with different methods. However, with the analogy of the structural design, which was introduced above, the risk analyses can be compared to the static analysis of a structure. Without risk analyses one has to base the decisions entirely on experience and judgement. If we again make reference to the structural design, risk analyses compare so to say to the static analyses, i.e. the basis for an engineering approach to safety.

Risk analyses of road, rail and metro tunnels have become a widespread practise in the recent years and progress in establishment of methods and associated data has been achieved. The results of the European research projects like DARTS, FIT; UPTUN and SAFE-T as well as the European Directive have further contributed to this development.

3 DESIGN FOR FUNCTIONALITY

Design for safety is of course not the one and only design requirement. The purpose of the road, rail or metro tunnels and other underground facilities is to meet the functional requirements. Improvement for the creation of high capacity of tunnels, little disruption due to maintenance, easy operation etc, is of main concern for all types of tunnels. Some safety measures are influencing these objectives. For example low speed limits, long distances between the vehicles or even controlled access to the tunnels may benefit the safety but it also significantly reduces the capacity. Hereby the main purpose of the tunnel is in conflict with the objective of safety. Also other safety measures may cause problems for the basic functionality of the tunnel and for its operation and it is clear that a well-balanced compromise will have to be found between the functionality and safety of tunnels.

For metro systems and railway tunnels, the availability of the tunnels and the regularity of the traffic are particularly important. The safety in these tunnels is ensured by a high standard of preventive measures and a communication and control system, which mitigates accidents. In the future a similar system could be possible in road tunnels, so that a communication system between the vehicles and the control room can prevent accidents and by communication from vehicle to vehicle cab prevent the development of accidents into large consequences.

Cooperation between industries (tunnel industry, car technology, railway industry, control systems etc) will be necessary to reach higher goals in safety and functionality of the tunnels. The European research projects, SAFE TUNNEL has developed systems in this direction. The system enables onboard prognostics for detection of existing or imminent faults and it sends this information to a Control Centre, which can take the necessary action. Furthermore, with the newly developed system emergency messages are disseminated from the Control Centre directly to the onboard human machine interface on the dash board in the vehicle.

4 DESIGN FOR ECONOMY

It is also clear that the design has also to do with finding reasonable solutions with regards to costs. We might have the chance to design tunnels with an extremely high standard of equipment, ample dimensions, control of all vehicles etc. But by doing so the costs of the tunnels would be high and this might result in fewer tunnels to be built, and hereby the benefits with respect to environment and mobility would not be achieved.

On the contrary, it is required to use innovation and engineering skill to find better and more cost-efficient solutions for establishing and operating tunnels.

As we have seen tunnel safety is a problem which we as professionals have to take very serious, on the other hand we must also search for solutions which are reasonably cost efficient. In order to determine which measure are cost efficient, it is necessary to use a holistic approach which is taking into account all desired and undesired sides of the design and operation of tunnels. In the holistic approach, safety and economy are of course two very important aspects. Since some cost occurs at the construction and installation phase and other costs and consequences occur during operation, it is necessary to use a life cycle cost approach in order to find the overall best solutions for design and for other decisions.

5 DESIGN FOR DURABILITY

As part of the life cycle approach the durability and the maintenance costs will have to be considered. Few years ago design for durability was a largely experienced based science and it was difficult to document whether the 80 to 100 year required lifetime stated in many codes actually were achieved. In recent years a more engineering approach has developed. The research DURACRETE and DARTS developed the probability based models and particularly extended the models for tunnel structures and the effects of maintenance and repair. The tunnel specific conditions (environment, chloride and CO_2-loading, moisture, temperature) have been quantified, and it is now possible to design the tunnels and the durability measures for the specific purpose. Hereby the durability design can be achieved on a performance-based approach.

The term of durability is linked to the extent of deterioration and its effects over service life. Therefore the prediction of deterioration progresses over service life plays a key role, when optimising a structure with regard to durability. Deterioration mechanisms to be considered are for example chloride and carbonation induced corrosion, frost attack, acid attack and a number of other effects.

One of the major objectives of the reliability based service life design are the prevention of reinforcement corrosion, with focus on corrosion due to chloride ingress and carbonation, and the design for watertightness (avoidance of leakage) of the cracked and uncracked concrete. The risk of accumulation of chlorides by evaporative effects on the air-exposed face of tunnels, which are exposed to salt containing water (for example from the inside from de-icing salt, salt contained in the air and from the outside from seawater) is of major importance for the durability and an understanding of the mechanisms and quantification of the influence of different measures are now available. The model of chloride accumulation was until few years ago controversial and discussed by leading concrete and durability experts; this aspect has now largely been clarified.

This process of finding the optimal set of measures requires that the undesired event must be compared with costs and other aspects of the decision. Also aesthetic can be part of the durability consideration since some deterioration or aging processes may influence the structural capacity less than the appearance. Hereby the selection of the measures also includes an evaluation of appearance, costs, structural capacity etc. The aim is to find an economic optimum linked to the relevant limit state taking investment, prevention and intervention measures into account. The design of the overall best solution takes into account the durability aspects together with the safety aspects, functional requirements etc.

6 DESIGN FOR ENVIROMENT

As mentioned in the introduction tunnels can be regarded as environment measures in themselves: by means of tunnels the urban and natural environment can be preserved or improved. In spite of this also tunnels need to be designed and operated with environment in mind, and for larger projects evaluation of the environmental impact has become common and is in most cases legally required.

In order to assess the environmental effects of tunnel structures and to optimise designs, it is necessary to compare the different design solutions and aspects. Environmental aspects of tunnels, related to the impact on nature and health, are numerous, for example: pollution of air, soil, ground- and surface water; ecotoxicological effects; wildlife; noise; vibrations; consumption of resources (land, energy, water, materials etc).

These impacts will have a range of effects on the environment. Some are reversible and some are irreversible. Some are local and some are regional or global. Furthermore, they will occur at different stages of the life of the tunnel such as during production of building materials, tunnel construction, exploitation, maintenance and demolition, etc.

Traditionally, environmental studies have tended to be very much descriptive. However, in order to in integral part of the process the different impacts and effects will have to be quantified, prioritised and weighed in a lifetime perspective. For some environmental impacts (e.g. air pollution, CO_2 emissions and ground pollutions) model are available for quantification and weighting, for other impacts models will have to be developed. The aim is to have a quantifiable environmental impact, which facilitates an integration of environmental issues and gives an adequate weight to these problems.

7 OPTIMAL DESIGN

The basic formula for integrated design takes into account all disadvantages and benefits. Disadvantages may be related to for example construction and installation costs and unwanted events resulting in personal damage (safety aspects) costs related to repair and maintenance and environmental damage as described above. For each design option all relevant aspects must be accounted for. The optimal design is this respect not only performance based it is performance based in many dimensions and for processes and occurrences which take place at different points of time.

The concepts, which are used in the DARTS and also in UPTUN to facilitate rational decision making and optimisation, are:

1. Life cycle approach, and
2. Transformation of all effects into comparable measures

The life cycle approach will have to project all future events and scale them into present values. Apart from the technical values this requires the important decision of a discounting rate.

The transformation of the effects into comparable measures will require an evaluation of the effects relative to each other. This can conveniently be done by transformation into a cost scale, but this transformation may be controversial for some effects.

With the two above mentioned transformations the disadvantages/costs and benefits can be compared and with an identification of all relevant design or decision options the optimum solution can be found.

Due to legal requirements etc. it might be possible that the range of allowed decisions is limited and the optimum may be located in the illegal area. The legal requirements should of course be respected, but in this case it should be discussed why the optimum can not be achieved. It might be a question of different approaches and preferences of the decision maker and of the law-makes, - or it may indicate that the legal requirements are over-conservative. For more explanation and discussion of the methodologies reference see [7] and [8].

8 INNOVATIVE SOLUTIONS

In order to achieve progress in the tunnel industry, also with respect to the design objectives discussed above, we professionals will have to be innovative. We will not only have to compare all available solutions and design options and find the best solution among those, we will have to invent new solutions which better live up to the existing or new demands.

The innovations can include both hardware and software: new materials, new equipment, new approaches for design and operation, etc.

Whereas in the thematic network FIT the existing solutions have been identified and evaluated UPTUN, DARTS and SAFE T and SAFE TUNNEL has developed and evaluated innovative solutions. With the framework discussed above the innovative solutions can be assessed in terms of overall performance and optimality.

Examples of innovative solutions could be:

- Prevention of accidents and fire and mitigation of the consequences by electronic communication between vehicle and operation centre
- Prevention of development and spread of fires by means of water mist systems and other measures
- Improved reaction to critical situation by the control centre by more extensive and semi automatic monitoring
- Improved reaction of the users / passengers by better communication between control centre / train crew and users
- Prevention of structural damage to the tunnels by new concrete materials
- Improved understanding of the actual critical structural behaviour during fire

8.1 Example

An example may be mentioned for the explanation of the value of innovation:

For construction of a TBM bored tunnel with segmental lining it is necessary to have reinforcement due to the high forces on the segments during construction. Many codes and standards require a certain maximum temperature of the reinforcement during a fire, which makes a large cover or even fire protection necessary.

For durability it is of benefit to have a very dense concrete, which on the other hand does not have favourable characteristics during fire and may be difficult in production. Vice versa a porous concrete with less spalling problems would have significant disadvantages for corrosion of the reinforcement and for durability in general.

One solution could be to design the segment against corrosion by using stainless steel, coated steel and/or reinforcement with cathotic protected, and then design the concrete material consequently against the fire damage. This solution may, however, be complicated and costly. Furthermore there might be remaining durability problems and the protection of the reinforcement from the high temperatures will still be required.

Another solution, which has been applied for a bored tunnel in Copenhagen recently, could be to design the concrete segments without reinforcement. The segments can be designed against the loads of the construction phase and the loads in the permanent situation by replacing the reinforcement by steel fibres. The problems with spalling during fire can be mitigated by admixture of polypropylene fibres. An optimised design with this approach can give a solution, which at the same time is durable, fire safe and cost efficient.

9 CONCLUSION

An overall optimum tunnel design will have to respect a number of criteria. Not only will the tunnel have to fulfil demanding requirements for the use, the operation, and function in general, it is also required that the tunnels are respecting environmental requirements, are durable with little maintenance, can be built and operated with reasonable costs. Furthermore, the tunnels and underground structures will have to be designed for safety so that:

- Users can continue to travel safer per kilometre in tunnels compared to sections on the outside network
- Tunnels can gain the reputation of a safe part of the transportation network
- Underground facilities can be publicly accepted.

In order to achieve the best possible solutions in the creation and operation of tunnels the decisions related to the design and operation shall be based on a well-structured and transparent methodology. With the results of the recent European research projects the tools are now available for this optimisation of the process. These methods are now being used in the practical design of tunnels and underground facilities. A consequent use of such methods will result in tunnels, which are well balanced with respect to costs, environmental impact, safety, durability and other specified aims.

10 REFERENCES

Selected European Research projects and thematic networks, supported by the European Commission:

[1] DARTS, Durable And Reliable Tunnel Structures (www.dartsproject.net). Research project, Fifth Framework.
[2] FIT, Fire In Tunnels (www.etnfit.net) Thematic network, Fifth Framework.
[3] DURACRETE, Probabilistic Performance based Durability Design of Concrete, Research project, Forth Framework, Brite-EuRam.
[4] UPTUN, Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels (www.uptun.net) Research project, Fifth Framework
[5] SAFE TUNNELS, Innovative systems and frameworks for enhancing of traffic safety in road tunnels. (www.crfproject-eu.org) Research project, Fifth Framework
[6] SAFE-T, "Safety in Tunnels" (www.safetunnel.net) Thematic Network on development of European guidelines for upgrading tunnel safety.) Thematic network, Fifth Framework

Papers

[7] Steen Rostam & Niels Peter Høj: "Integrated tunnel design from cradle-to-grave enhancing structural performance and owner confidence". Proceedings of 1st International Symposium "Safe & Reliable Tunnels, Innovative European Achievements" Prague, Czech Republic, 4 - 6 February 2004.
[8] Niels Peter Høj, Steen Rostam & Carola Edvardsen: "Optimisation of decisions in the process of creating and operating tunnels" Proceedings of the ITA World Tunnelling Congress (Re)claiming the Underground Space, Amsterdam, the Netherlands, 12 - 17 April 2003.