KEY ELEMENTS IN FUTURE TUNNEL DESIGNS: HAZARDS AS A SPECIFIC DESIGN ISSUE

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ABSTRACT

This paper describes a specific element in future tunnel designs: hazards. If a vehicle transporting dangerous goods catches fire because of a defect or is involved in an accident, these goods may either lead to explosion, to fire or both. Examples of such goods are liquefied natural gas, poisonous gas like chlorine and ammonia and inflammable gas or liquids like petrol or kerosene. But also previously considered lower risk cargoes, like wood or food components, may lead to serious fires. The impact of such a catastrophe can be very large. It is not difficult to imagine scenarios with hundreds of victims and substantial damage to the tunnel structure. This paper describes how to deal with these small probability - large impact phenomena in the design phase. It includes a simple design example and ends with some thoughts about the future design process.

1. GENERAL DESIGN PHILOSOPHY OF THE DARTS PROJECT

The general design philosophy adopted in the DARTS project can be stated in one sentence: the design process should be an optimisation, leading to an optimum design, with safety constraints. The keywords in this phrase are optimisation and safety.
Optimisation, i.e. the process that leads to an optimum, should be performed in a broad sense, including all relevant aspects, e.g. durability and sustainability. The optimum the designer is looking for is defined by a product that is, overall, the product that will produce largest utility to society. In this case largest utility for society, because, in the end, society is the customer that uses the final product: the tunnel. Largest utility means that not only costs should be part of this optimisation, but also benefits.
The utility starting point brings about that the optimisation cannot be performed on a simple economic basis. Also aspects (usually benefits) that cannot easily be expressed in terms of money should be accounted for. Another major consequence is that possible future costs (and benefits) should be considered. As costs and benefits in future are never certain, probability comes into play: the *expected* costs and benefits should be part of the optimisation. On top of that: these costs and benefits should be discounted in some manner to make them comparable with current costs and benefits.

Another important consequence of the DARTS philosophy is that *all* costs and benefits are considered. This means a fully integrated design procedure. If a design adaptation has different effects, all effects should be incorporated. If, for instance, application of a certain thermal insulation not only reduces the probability of tunnel collapse in case of a tunnel fire, but also reduces the possible access of carbon dioxide into the structural concrete (carbonation affects tunnel durability) and reduces noise, all three aspects should be part of the weighing process. This is the major challenge of the DARTS project.

The solution chosen by DARTS for the weighing and accounting process in order to reach the optimum is yet to allocate money in some standard manner to aspects that usually are not expressed in money terms. Noise reduction, poisonous gas emission reduction, water pollution, safety, security, beauty, cleanliness and so on are expressed in terms of money. This, of course, involves subjectivity. It is believed, though, that the amount of subjectivity tends to be less than in, for instance, a multi criteria analysis, especially when the process of allocating money is related to comparable, political decisions. And by expressing all aspects into one common "valuator", a true integrated design process becomes feasible.

One special aspect is safety. The loss of human life, or becoming seriously injured, should also be valued in the over-all optimisation process. But on top of that, due to ethical reasons, society may pose a minimum level of safety in absolute terms. Or, in other words, may pose a maximum to the probability of people getting injured or killed. If so, the optimisation process is limited in such a way that this minimum amount of safety is always present.

Note, by the way, that the value of human life must take part in the optimisation process. If not, specific measures that reduce the probability of getting hurt or killed will always be dropped because they cost money (investment) but have no benefits (saving human lives). This surely is not a desirable situation. Not valuing a human life is not ethic, in this approach.

2. HAZARDS: A DESIGN ISSUE?

Hazards are defined, at least in this paper, as catastrophes with a small probability of occurrence and large consequences. Usually the consequences extend to loss of life. Tunnels may endure different types of hazard (fire, explosion, earth quake, collapse due to overload) and the question arises whether we are able to deal with these kinds of hazards within the DARTS design framework.

The first step is to investigate what type of measures exists to reduce the probability of occurrence of a hazard (prevention) or even prevent it altogether (pro-action). Also measures that mitigate the consequences should be investigated (preparedness, repression). Both types of measures are design options. If these measures can be found and specified, the answer of the question in the title of this paragraph is yes: hazards are a design issue.

Costs, in this respect, are the investments that have to be made to effectuate the measures. These costs may extend into the exploitation phase: maintenance costs. As stated, the benefits are either the reduction of probability of occurrence or the reduction of loss of life and damage given the specific hazard has occurred.

The costs, as described, can usually be calculated quite straightforward. Future maintenance costs must be discounted. The benefits are more difficult to obtain. Just looking at damage means that we are dealing with *expected damage*, i.e. damage given the hazard has occurred multiplied by the probability of occurrence. As we look at the total benefit, the real benefit of a measure is the expected damage without the measure minus the expected damage with the proposed design measure. The optimisation rule now dictates that if the resulting benefit is larger than the investment, the design measure should be implemented.

If loss of human life plays a role (it usually does, in case of severe hazards), also the net saving of human lives should be added to the benefit side of the balance. This means allocating money to a human life, as argued before. On top of this, society may demand a minimum safety level, regardless of the added extra costs.

3. EXAMPLE: THERMAL INSULATION

As an example we look at a tunnel fire. In concrete tunnels large fires may lead to:
1. Fatal and non-fatal casualties
2. Collapse of the tunnel

Immersed tunnels are especially sensitive to reduction of strength of reinforcement. The middle section of the tunnel roof is heavily reinforced and the tunnel roof collapses if the steel is not able to perform its function properly. Flooding of the tunnel will be the final result if the tunnel crosses a waterway.
Bored tunnels are sensitive to severe, propagated spalling of the concrete. Especially when high strength concrete is used, the concrete section could be reduced dramatically and will collapse.
There are a few design options to reduce the probability of collapse (or serious damage) in case of a substantial fire in a concrete tunnel structure. They are, in short:
1. Application of thermal insulation
2. Cooling by means of sprinklers
3. Construction of a double ceiling
4. Addition of polypropylene fibres to the concrete mix
5. Application of steel fibre concrete.

The first three options work for immersed tunnels: it reduces the reinforcing steel temperature. Option 4 and 5 work for bored tunnels: they reduce the amount of spalling.
In order to decide whether or not a specific design option should be implemented, costs and possible benefits are investigated. We choose just one option as an example: the application of thermal insulation in a tunnel to be built in the Netherlands: the Roer tunnel in a new part of the A73 motorway. The example is gathered from Wolsink and Hoeksma[1].
The application of thermal insulation is a rather expensive measure and it does not prevent a disaster, but it will save the (immersed) tunnel if a large fire occurs. So the benefit consists of a reduction of (severe) damage, but it has no effect on (the probability of) casualties, at least, if we assume that the tunnel is evacuated before it collapses.
In case of a less severe fire the damage with or without insulation is comparable and in case of a very severe fire the insulation will not work: the tunnel will collapse, with or without insulation. Note that we only have to model the costs, the benefits and probabilities that are influenced by the design option: the probabilities of loss of life, of a small fire or an extreme large fire do not enter the marginal optimisation process and do not influence our design decision in this simple case.
The Roer tunnel will consist of four parts: three parts in an urban area with regular soil on top and one part crossing the river Roer. This last part is especially vulnerable because of the consequences of collapse. If the tunnel roof collapses, the tunnel will flood and will be closed for at least one year. The length of this part of the tunnel is around 900 m.
The tunnel will consist of a triple box cross-section. The traffic flow is separated in each direction and will go through the outer tubes. A much smaller escape carriage way is situated in between.

One tunnel tube is approx. 10.00 m wide and an additional 1.00 m wall covering will be applied (see Fig. 1). So the total tunnel roof to be insulated amounts to 2 * 900 * 12.00 = 21600 m^2. Total costs of fire protection are about € 100 per square meter, giving a total investment of M€ 2.2 (*Mega euro*).

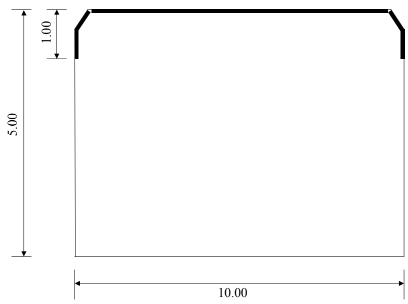

Figure 1 Cross section of tunnel tube with insulation

The probability of having a large fire is estimated from statistics. These statistics stem from data from the Netherlands on all motorways, tunnels and bridges included. The probability of having a large fire ranges from 2.10^{-9} to 10^{-8} per transported kilometre of heavy goods, with an estimated best guess of 5.10^{-9}. The expected number of heavy goods trucks will be around 6500 both ways each day, or 365 * 6500 = 2.4 10^6 each year. The probability of a large fire anywhere in the 0.9 km long tunnel will thus be: $\lambda = 2.4\ 10^6 * 5.10^{-9} * 0.9 = 0.01$ per year.
Note that this probability should be an estimate for just those fires where insulation helps. As argued before, the small and the extreme large fire frequencies are not relevant.
This part of the new Roer tunnel is rated at around M€ 60. Collapse of the tunnel will have two cost components: the rebuilding of the collapsed part, estimated M€ 15 and an estimated year of traffic hindrance: all traffic must be rerouted. The economic effects of the expected traffic hindrance are estimated at another M€ 25. So the total costs of the Roer tunnel collapse will be M€ 40. These estimates are low, more elaborate studies will probably yield higher values. On top of that the decreased safety as a consequence of rerouting is not taken into account in this simple example.
Damage to the tunnel, given insulation and a large fire, will result in repair costs of estimated M€ 1, included two weeks of two-way traffic in one tube.
The annual expected damage must yet to be discounted for the 100 years planned lifetime:

$$C_{cap} = C_d \sum_{i=1}^{100} \frac{1}{(1+r)^i} \approx C_d \sum_{i=1}^{\infty} \frac{1}{(1+r)^i} = \frac{C_d}{r}$$

where C_d equals damage costs, given a fire has occurred and r the net discount rate.

With a net discount rate of 4% the expected costs without insulation become:

$$C_{without} = \lambda \cdot \frac{C_{collapse}}{r} = 0.01 \times \frac{40}{0.04} = 10\ M€$$

The expected costs with insulation become:

$$C_{with} = \lambda \cdot \frac{C_{damage}}{r} = 0.01 \times \frac{1}{0.04} = 0.3\ M€$$

The (expected) benefit of thermal insulation thus amounts to M€ 10 – M€ 0.3 = M€ 9.7. As the total costs of applying the insulation amounted to M€ 2.2, the design decision is clear: thermal insulation should be applied.

Another way is looking at total costs, as specified in the table.

Alternative	Investment (Initial costs, M€)	Expected damage, discounted (M€)	Total costs (M€)
No thermal insulation applied	0	10	10
Thermal insulation applied	2.2	0.3	2.5

If we take the uncertainty in the probability into account, using the range specified before ($2.10^{-9} < \lambda < 1.10^{-8}$) we find the following total costs:

Alternative	Low extreme for λ (Total costs, M€)	High extreme for λ (Total costs, M€)
No thermal insulation applied	4.3	22
Thermal insulation applied	2.3	2.7

Indicating that in any case fire insulation should be applied.

Note that in this simple example we did not look at the other ways of preventing collapse by fire. In the DARTS philosophy all options should be looked at and the option with the lowest total costs is preferred.

4. FUTURE DESIGN PROCESS

The example clearly shows that hazards certainly are a design issue and also shows the shift in focus of the design process. Two ingredients, now only existing rudimentary, will become much more important: costs and probabilities.

The designer will be very much more cost aware. Costs, future expected costs, will be at hand and used in every design phase. At present, structural design and cost rating are different trades, performed by different persons at different times. Cost effective choices are made intuitively, usually by the structural expert. Feedback with cost experts is an exception. And only initial execution costs are looked at.

In future it will be possible to calculate effects of all design options in a fairly standardized way. This means that the amount of traffic hindrance, safety, pollution, et cetera given a design option, is known, or can be estimated in a standardized manner. The translation of the non-monetary aspects to a common valuator will be generally accepted. Of course, these translations change in time and politicians will have a large influence, but not as much random as now seems to be the case in many instances.

To be able to predict future costs (maintenance, exploitation, renewal, accidents, hazards) the designer has easy access to probabilistic data: e.g. he knows the probability of a large fire. He will have traffic intensity predictions, predictions of the amount of heavy goods vehicles, the type of dangerous goods that will be transported and so on. These predictions will be presented to him in a statistical sense and one of his skills will be to deal with this information.

Certainly, the physical description of tunnel behaviour will improve as well. Important areas of research currently are computational fluid dynamics to model fires and explosions, micro behaviour of concrete and steel to model deterioration processes and geotechnical behaviour to model external loads on the tunnel.

But we will get answers only in a probabilistic sense and the future designer knows how to incorporate these random variables into his decision making process. He will be a true probabilistic designer.

5. LITERATURE

1. G. Wolsink, J. Hoeksma: Bescherming tegen brand in tunnels A73 (Fire Protection in Tunnels of the A73 Motorway, in Dutch). Bouwdienst Rijkswaterstaat, February 2001.
2. A. Gudum, N. Buus Kristensen, S. Rostam and N.P. Høj: Comprehensive Decision Tool. *DARTS WP5*, September 2003