Economic feasibility study for the use of fire protection boards in road tunnels

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Abstract
Fires in a tunnel can cause considerable damage to the structure, resulting in the tunnel being closed for refurbishment works, at times for many months. Such closures always have an additional and sometimes a very negative effect, because tunnels generally have a special role in the surrounding transport infrastructure (bottleneck). As a result, diversion routes are overloaded with unplanned traffic and the accessibility of locations or whole regions is restricted. In order to reduce the consequences of fire incidents, fire protection boards are actually being fitted to the inner shells in order to protect the shells from high temperatures. The study presented here, not only demonstrates the investment and consequential costs of fire protection boards, it also outlines the benefits achieved as a result of their use. For an exemplary tunnel it is shown that the use of fire protection boards could be an economically advantageous alternative.

Task and objective of the study

Fire incidents in tunnels cannot be completely prevented. For this reason, various approaches for structural and equipment-related fire protection are pursued in practice. One possible structural protection measure for the inner shell of a tunnel is the placement of fire protection boards on the surface of the concrete to protect it against high temperatures. However, the use of such fire protection boards is often not considered because the initial and follow-up costs are considered too high. In addition, the probability of a major fire in road tunnels is estimated to be very low and therefore a high degree of damage is accepted.
In an economic evaluation of fire protection boards, conventional calculations primarily consider the initial and consequential costs, but not the downtimes as well as the costs that can be avoided by fire protection boards, which would arise from a fire. The aim of the investigation presented here is to also take these parameters into account in the calculation.

Tunnel Fires

In recent years, vehicle fires have repeatedly occurred in tunnels in German-speaking countries. Examples are fires in the Gleinalm tunnel (Austria, 2016 and 2018), in the Königshainer Berge tunnel (Germany, 2013) and in the Elbe tunnel (Germany, 2018). In addition to the actual costs of repairing the damage, tunnel operators also incur losses due to lost toll revenues, which can be a multiple of the cost of repair. For example, the costs of the structural renovation of the fire in the Gleinalm Tunnel in August 2016 amounted to € 0.5 million, while the lost toll revenues amounted to € 3.5 million [1]. In addition, tunnel closures for the renovation work will cause considerable economic costs due to the extension of the route and travel times caused by diversions. The closure of the Königshainer Berge tunnel, for example, caused damage amounting to approximately €6 million [2] on alternative routes not designed for heavy goods traffic; the total cost of repairing the tunnel amounted to only approximately €2.2 million [3].
The tunnel fire statistics 2006 to 2012 published by the Austrian highway operator ASFINAG show that there are 6.5 fires in Austrian highway and expressway tunnels on average for every 1 billion vehicle kilometres travelled in tunnels. The probability of truck fires (≥ 3.5 t) with 25 fires per 1

billion tunnel kilometres travelled is significantly higher than for passenger cars (4.2). Statistically speaking, every 40 million kilometres travelled in a tunnel is therefore subject to a truck fire [4].

Application and Properties of Fire Protection Boards

Fire protection boards are primarily used in tunnels to protect the structural concrete from the effects of heat. This is because when the concrete is exposed to strong heat - especially when the temperature rises very rapidly to over 1,000 °C - drainage and evaporation processes take place in it, which usually results in high vapor pressure a few centimetres below the surface of the concrete, causing concrete spalling. As a result, the reinforcement is exposed to elevated temperatures and successively loses strength (above 300 °C).

Fire protection boards ensure that the temperature of the concrete surface as well as the temperature of the reinforcing steel in the concrete is kept below critical values in case of fire. The board materials can withstand the high temperatures (usually at least up to 1,350 °C) and significantly reduce the rapid heat transfer into the concrete and thus prevent its damage. Therefore, after a fire, only the affected fire protection boards need to be replaced, whereas the concrete does not need to be repaired.

Regarding the service life of fire protection boards, the European Technical Approval ETA-17/0170, for example, specifies a value of at least 25 years for a marketable fire protection board [5]. However, it can be assumed that, as is usual for (light) concrete, much longer useful lives are probable. In this respect, the service life of 30 years specified by the manufacturer seems realistic.

Calculation Model for Life Cycle Cost Analysis

Decisions on possible variants in construction projects should in principle not only be made on the basis of construction costs, but also the costs incurred during the – normally very long – service life of a tunnel should be taken into account. According to a recommendation of the DAUB (German Tunnelling Committee), an investment decision should therefore be based on a life cycle cost analysis [6]. Such an analysis considers not only the initial costs (construction), but also the follow-up costs (operation, maintenance and repair). The calculation takes into account both, the useful life of individual components and their replacement, as well as the calculation interest rate with which the amounts are discounted up or down.

As the current key interest rate (mid-2019) has been kept at a record low of 0.0 % by the European Central Bank since March 2016 and future developments are difficult to estimate, three calculation interest rates are assumed: 0.0 %, 1.7 % and 3.0 % p.a. The interest rate of 1.7 % is mentioned in the Federal Transport Infrastructure Plan 2030 [7] as the assumed real interest rate for calculations of life cycle costs. The interest rates 0.0 % and 3.0 % show how a change in this average interest rate affects the result.

In long observation periods, such as 100 years in the present case, the inflation rate also has an influence on the price development. However, it does not have to be taken into account if all the prices considered change at the same rate, since a uniform price level change occurs for all payment variables. In addition, the uncertainties resulting from an estimation of the inflation rate are greater than the expected gain in accuracy [8]. Therefore, the "actual value approach" is used in the present study and inflation is not taken into account.

The different useful lives (or re-investment intervals) of different components are taken into account in the calculation of life cycle costs via the annuity factor a_f. The interest rate i and the useful life n are considered as follows:

$$a_f = \frac{(1+i)^n * i}{(1+i)^n - 1} \quad (1)$$

With the calculation interest rate (i = 1.7 %) and the useful life of the fire protection boards (n = 30 years), for example, the annuity factor for the production and installation of fire protection boards is calculated at a_f = 0.043. The additional expenditure for maintenance, which is based on a

shorter interval of six years, results in an annuity factor of a_f = 0.177. The investment costs of the various components are multiplied by the respective annuity factor to determine the annual construction costs.
From the (total) annual building costs, the present value of all costs to be added in this period can then be calculated by multiplying them by the present value factor $b_f = 1/a_f$ for any useful life n. Using the calculation interest rate i = 1.7 % and a useful life of 100 years, the present value factor is calculated, for example, at b_f = 47.923.
This article focuses exclusively on the profitability of fire protection boards. Therefore, in a direct comparison between a tunnel with and a tunnel without fire protection boards, the other production costs of the tunnel are of secondary importance and are not considered in the following analysis. The follow-up costs for tunnel maintenance also differ only marginally between the two variants. Only the additional expenditure resulting from maintenance and repair work on the fire protection boards must be taken into account in monetary terms, as the boards may have to be removed for the structural inspection and then reinstalled.

Damage Scenario and Calculation Parameters

As an example for the economic efficiency calculation, a two-way tunnel with a circular cross-section RQ 10.5 T and a length of 1,000 m is considered. Depending on the design of the tunnel (e.g. circular or rectangular, with or without smoke extraction), the circumference to be protected in the cross-section is between approx. 12 and 19 m. In the calculation example, 16.5 m are assumed. The calculation parameters required for the calculation are summarised in Table 1.

Table 1. Summary of the input parameters for the calculation of the costs of the example tunnel

Tunnel		
Length of the tunnel	1.000	m
Diameter of the tunnel	10,50	m
Tunnel surface to be protected	16.500	m²
Maintenance interval	6	years
Fire protection boards		
Production and disposal	72	€/m²
Costs (installation)	70	€/m²
Additional maintenance costs	1,5	€/m²
Fixed costs (construction site equipment)	5.000	€
Useful life	30	years
Calculation interest rate		
Interest rate	1,7	%
Average daily traffic		
Total vehicles	24.900	Vehicles/d
Vehicles ≤ 3,5 t	21.200	Vehicles/d
Vehicles ≥ 3,5 t	3.700	Vehicles/d
Structural damage caused by fire		
Damaged length	80	m
Percentage damage to the surface	70	%
Damage level	4	
Traffic safety costs		

Fixed costs	103.000	€
Maintenance per month	6.500	€
Motor vehicles ≤ 3,5 t (cars)		
Hourly rate for additional travel time	8,84	€/h
Travel expenses	0,30	€/km
Average speed without traffic jam	80	km/h
Motor vehicles ≥ 3,5 t (trucks)		
Hourly rate for additional travel time	20,00	€/h
Travel expenses	0,65	€/km
Average speed without traffic jam	50	km/h
Diversion and loss of time		
Diversion	28	km
Time lost in traffic jams (for 50% of road users)	30	min
Missed toll		
Vehicles ≤ 3,5 t	9,00	€/Kfz
Vehicles ≥ 3,5 t	9,00	€/Kfz
Correction coefficient	0,50	

Damage Scenario
The average daily traffic was assumed to be 24,900 vehicles/d, as in the case of the Gleinalm tunnel [9]. Of these, 3,700 had a permissible total mass of over 3.5 t. This means that 3,700 km are travelled by trucks per day in the 1 km long example tunnel; in one year, a total of 1,350,500 km is covered. Based on the tunnel fire statistics of ASFINAG, which indicate an average of 25 fires per 1 billion truck kilometres (cf. Chapter 2), a truck fire should have to occur statistically every 30 years in the example tunnel under consideration. It was therefore assumed that there is at least one fire in the lifetime of the tunnel and that it occurs in the first year of the study. It was also assumed that the fire is caused by two burning trucks standing directly behind each other. As a result, over a length of 80 m, 70% of the surface of the reinforced concrete inner shell is damaged to category 4 (see Chapter 5.3).

Installation Costs for Fire Protection Boards
The life cycle costs of the fire protection boards are simplified here to a tunnel service life of 100 years. In this example, 72 €/m^2 are assumed for the procurement and disposal of the fire protection boards and 70 €/m^2 for the installation of the boards. Based on expert interviews, the additional cost for the maintenance of the tunnel is assessed in monetary terms at 1.5 €/m^2 per maintenance interval, since the boards have to be removed randomly during a main inspection of the tunnel according to DIN 1076 (every six years) in order to inspect the tunnel inner shell close to the hand.

Repair Costs
The main benefit of fire protection boards is the prevention of structural damage caused by fire. It is therefore necessary to consider the potential restoration costs of a damaged inner surface with and without the use of fire protection boards. For the calculations carried out here, data were used that were compiled in the project "Protection of critical bridges and tunnels in the course of roads" (SKRIBT [10]) funded by the Federal Ministry of Education and Research (BMBF, Germany). Five

damage levels were defined there for the assessment of fire damage. The damage levels 1 to 3 comprise isolated to large-area spalling with depths of 5 to 50 mm. Damage level 4 is defined as large-area spalling with exposed reinforcement and damage level 5 results in large-area spalling beyond the centre of the cross-section.
Table 2 summarizes the essential repair work and the associated costs for the different damage levels. According to the damage scenario, damage level 4 is assumed for a tunnel without fire protection boards. For a tunnel with fire protection boards the costs mentioned in chapter 5.2 are used.

Table 2. Calculatory cost estimates for recovery costs

Damage level	Main items of the repair work	Area-dependent costs €/m²	Fixed costs €
1	Cleaning, filling	20	5.000
2	Cleaning, high-pressure blasting, filling	70	20.000
3	Cleaning, high-pressure blasting, chiselling, shotcrete repair	120	25.000
4	Cleaning, high-pressure blasting, chiselling, reinforcement, shotcrete repair, joint repair	230	70.000
5	Demolition, reinforcement, formwork, concreting	360	80.000

Time needed to Repair the Damage

The repair of damage to a tunnel inner lining as a result of fire normally requires the closure of the tunnel (or tunnel tube). As an indication for the duration of the closure of a tunnel without fire protection boards, the values given in the SKRIBT project are reduced by one third, because it has been shown that the duration of the refurbishment was often shorter for past tunnel fires, despite a high level of damage. At the assumed damage level 4, the tunnel without fire protection boards remains closed for rehabilitation for about 7.3 months. The duration of the closure after a fire incident in tunnels with fire protection boards was set at 1.5 months based on the experience of manufacturers and operators and includes the removal of the damaged boards and the installation of the new ones. Depending on the degree of damage, this work can possibly also be carried out (in several stages) at night or during off-peak hours, thus reducing the impact on traffic.
The total closure time between fire and reopening is normally reduced even further in tunnels with compared to tunnels without fire protection boards, as the times for planning and tendering are shorter.

Traffic Safety and Diversion Costs

The closure of the tunnel, necessary for the repair of fire damage, requires local traffic control in the immediate vicinity of the tunnel. The cost estimates chosen on the basis of the SKRIBT project are listed in Table 1.
To estimate the diversion costs, the additional expenditure of the road users resulting from the diversion (increased time expenditure, longer driving distance) is included in the calculation. A

distinction is made between the number of vehicles under/above 3.5 t and the additional travel time resulting from the average speed on the diversion route plus a possible traffic jam duration is taken into account. Table 1 lists the car availability and operating costs for business and private trips as well as the costs for trucks, based on the method manual for the Federal Transport Infrastructure Plan 2030 [8]. The average speed without traffic jams, also shown in Table 1, was set relatively high, which has a positive effect on the time required to cover the diversionary route and thus leads to lower costs.
The method manual [8] gives values for the time-dependent costs which were determined on the basis of a willingness to pay analysis and which depend on the distance to be covered and the vehicle occupancy rate. For simplification, it was assumed in the study that cars are occupied by only one person and that the statutory minimum wage (2018) of € 8.84 per hour is to be calculated for this person. For trucks (over 3.5 t) that are generally used for commercial purposes, the hourly rate for the driver was set at € 20.
The length of the diversion is based on the diversion route for the Gleinalm tunnel and was set at 28 km. Due to the traffic volume shifted from a motorway to federal/state roads, traffic jams can occur, especially at peak times. It is therefore assumed that 50 % of road users are stuck in traffic jams for 30 minutes.

Missed Tolls

As in the case of the Gleinalm tunnel, a special toll of €9 per vehicle was assumed for this example [11]. Since tunnels are often used by vehicles from the immediate vicinity of the tunnel, vehicle owners usually have annual season tickets, which are considerably cheaper than a single trip. For this reason, only 50 % of the lost toll is charged over the duration of the closure. For comparison: in Germany, for example, the passage through the Warnow Tunnel in Rostock costs € 3.80 for a car and € 16.50 for a truck.

Influencing parameters not considered in the calculation

In addition to the parameters listed above, there are other cost factors whose monetary value cannot be determined or can only be determined with considerable effort. For this reason, the following influences on the diversion routes were not considered in the present study:

- Additional noise exposure and exhaust emissions,
- Additional CO_2 emissions,
- Damage to the roads,
- Higher accident costs due to increased traffic volume,
- Other costs incurred by neighbouring companies and companies dependent on the line due to the tunnel closure.

Material-specific influences are also not considered. For example, structural concrete that has been repaired, often does not achieve the same quality as the concrete produced in one piece during the concreting of an inner tunnel shell. Furthermore, positive effects of fire protection boards, which have an influence on the durability of the concrete, are not considered: For example, fire protection boards can protect the inner shell concrete from chloride ingress, either per se or through special coatings, which improves the durability of the concrete.

Results

The initial costs for the installation of the fire protection boards will amount to about € 2.34 million in total. Taking into account the additional expenditure for the building inspection (maintenance), the annual construction costs are calculated at the chosen calculation interest rate of 1.7 % at about 105,000 €. This results in life cycle costs over 100 years of about € 5.0 million. With a calculation interest rate of 0.0 % and 3.0 %, these costs are calculated at about € 8.2 million and € 3.9 million respectively (Fig. 1).

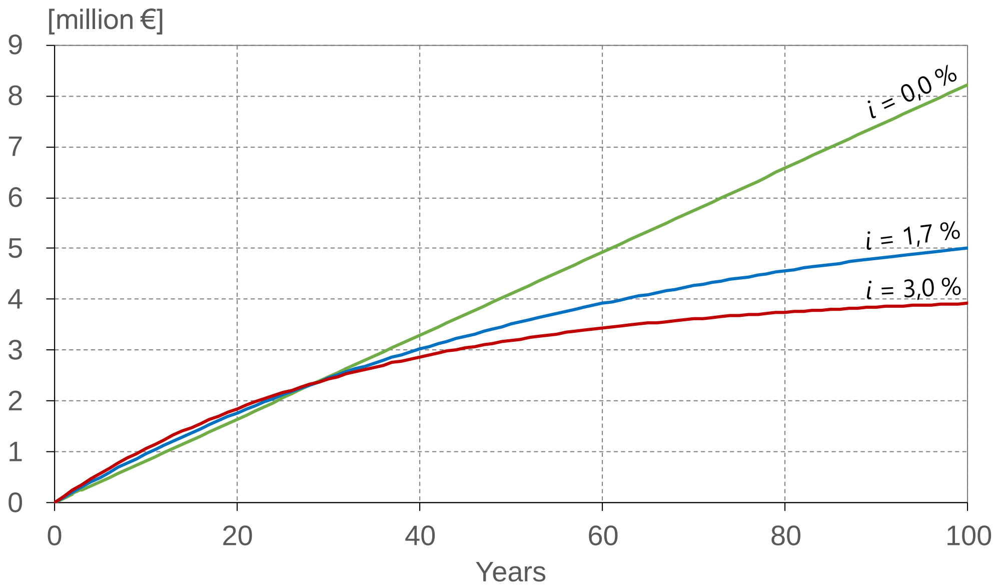

Figure 1. Life cycle costs (initial and maintenance costs) of fire protection boars for different interest rates *i*

A comparison of the calculated costs for the tunnel variants, without and with fire protection boards as a result of only one fire at the beginning of the useful life is shown in Table 3. The total costs avoided by the fire protection boards amount to about € 88 million, which is about 17 times the life cycle costs of the fire protection boards. In both cases, the repair costs after the fire and the traffic safety costs are relatively low. The diversion costs and the loss due to the lost toll, on the other hand, account for the majority of the additional costs.

For the tunnel operator, the loss of tolls after only one fire incident in the tunnel (€ 19.6 million) more than compensates the life cycle costs of the fire protection boards (approx. €5 million) due to the faster reopening. From an economic point of view – and thus from the perspective of the tunnel users – the savings resulting from the fact that no diversion costs are incurred when fire protection boards are installed – with only one fire incident – are even greater, amounting to around € 73 million. The cost difference for additional kilometres travelled is around € 31 million for cars and € 12 million for trucks, while the cost difference for additional travel time is around € 20 million for cars and € 10 million for trucks.

Table 3. Comparison of costs resulting from a fire in a tunnel with and without fire protection boards

Costs [€]	***without*** **fire protection boards**	***with*** **fire protection boards**
Life cycle costs	–	5.016.600
Repair costs	282.400	136.200
Traffic safety costs	150.700	112.800
Total diversion costs	91.917.000	18.801.200
thereof:		
Travel expenses, cars	39.177.600	8.013.600
Travel expenses, trucks	14.814.800	3.030.300
Time for diversion, cars	14.430.400	2.951.700
Time for diversion, trucks	9.116.800	1.864.800
Traffic jam time, cars	10.307.400	2.108.300
Traffic jam time, trucks	4.070.000	832.500
Missed tolls	24.651.000	5.042.300
Total	**117.001.100**	**29.109.100**

Summary

The results for the example tunnel show that the costs resulting from the non-arrangement of fire protection boards are several times higher than the installation costs. For example, in the toll tunnel assumed in the example – with only one major fire incident in 100 years – the losses due to the lost toll are already four times as high as the life cycle costs of the fire protection boards in the same period. And the costs for the additional distance travelled by the cars to be diverted during the closure for refurbishment are around six times the life cycle costs of the fire protection boards. All relevant costs taken together result in 15 to 20 times higher damage compared to the life cycle costs of the fire protection boards.
Although this result is not fully transferable to all tunnels, in general the costs of installing fire protection boards are expected to be recovered over the lifetime of the tunnel if there is (at least) one major fire during this period. Whether this will actually happen cannot be predicted. However, the tunnel fire statistics of ASFINAG evaluated for this purpose show this to be very likely.
A risk analysis will indicate whether an increased probability of fire in the tunnel is to be expected. The location and length of the tunnel, the proportion of heavy goods traffic and the gradient in front of and inside the tunnel have a particular influence in this respect. For tunnels with a high fire probability of vehicles, fire protection boards are recommended from an economic point of view. The same applies to tunnels whose closure would entail high economic costs.

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