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INFLUENCE OF THE REDUNDANCY OF TUNNEL VENTILATION SYSTEMS ON THE AVAILABILITY OF ROAD TUNNELS

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ABSTRACT

Tunnel ventilation plays a significant role in road tunnel availability. Especially in single-tube, but also in twin-tube road tunnels with transverse ventilation, the failure of an exhaust fan often leads to complete tunnel closure – at least in Austria.

Comparison of international guidelines shows that different countries have different specifications regarding exhaust fan redundancy for transverse ventilation systems in tunnels. Almost all stipulate the need for redundancy in the design and operation of transverse ventilation systems. The Austrian guidelines and regulations are the only ones of those investigated not containing information on the requirement for a redundant ventilation system.

Increasing the availability of road tunnels through a redundant ventilation concept is always associated with increased investment costs. However, these are justified when considering the loss of revenue as a result of tunnel closure. Redundancy can be achieved through various approaches. On the one hand, redundancy can be achieved by setting up additional fans in parallel; on the other hand, a redundant ventilation system can be achieved by using structural solutions.

In future there will be an increasing need to ensure the availability of major road networks. It is therefore necessary to update the Austrian guidelines and regulations to make them state of the art.

Keywords: Tunnel, Ventilation, Redundancy, Availability

1. INTRODUCTION

Tunnel ventilation plays a significant role in road tunnel availability. Especially in single-tube, but also in twin-tube road tunnels with transverse ventilation, the failure of an exhaust fan often leads to complete tunnel closure. The Austrian Guidelines and Regulations for the Planning, Construction and Maintenance of Roads (RVS 09.02.31) do not stipulate that redundancy is a requisite for exhaust fans in transverse-ventilated tunnels.

Since complete tunnel closure is associated with massive financial losses and also has economic consequences, the position that other countries take with regard to the issue of failure safety has been examined. In addition, the different specifications for the dimensioning of transverse-ventilated tunnels in different countries are shown, as well as the requirements for exhaust fans.

As there are no specifications related to redundancy in RVS 09.02.31, the possibilities for counteracting failure of one of the exhaust fans are discussed, as exhaust fans are essential for tunnel operation. Due to the fact that setting up redundant systems involves additional costs that should not be underestimated, the costs incurred and the effect on the availability of the individual systems are also evaluated and compared.

2. REDUNDANCY: GUIDELINES, REGULATIONS AND POSSIBILITIES

2.1. Comparison of guidelines and regulations with regard to the requirement for a smoke extraction system

The specifications of the country-specific guidelines and regulations for road tunnel smoke extraction systems in Austria, Germany, Switzerland and the USA are outlined in the following. An overview of all of the specifications is given in Table 1: Overview of Design Criteria for Exhaust Fans.

RVS 09.02.31 (Guidelines and Regulations for the Planning, Construction and Maintenance of Roads – Austria)

RVS 09.02.31 stipulates a heat release rate (HRR) of 5 MW for car traffic only and 30 MW for mixed car and heavy goods vehicle (HGV) traffic. When the share of HGVs is more than 15%, the HRR is to be increased depending on the result of the respective tunnel risk analysis. [1]

The exhaust fans must be designed in such a way that their functionality at a smoke gas temperature of 400°C is guaranteed for a period of minimum 120 min. [1] This corresponds to fire class F400 in accordance with the European standard (EN 12101-3). [2] RVS 09.02.31 does not stipulate that redundancy is a requisite for exhaust fans. [1]

EABT-80/100 (Recommendations for Equipping and Operating Road Tunnels with a Design Speed of 80 km/h or 100 km/h – Germany)

The HRR stipulated in EABT-80/100 depends on the HGV kilometres travelled per day and tube. A HRR of 30 MW applies when up to 4,000 HGV-km are travelled per day and tube. If the number of HGV-km travelled per day and tube is between 4,000 and 6,000, the HRR must be increased to 50 MW. If the number of HGV-km travelled per day and tube exceeds 6,000, a HRR of 50 to 100 MW must be assumed for the design of the ventilation systems, depending on the result of the respective tunnel risk analysis. [3]

In the case of smoke extraction via an exhaust duct with a length greater than 50 m, the functionality of the exhaust fans, at a temperature of up to 250°C, must be guaranteed for 90 min. In the case of point extraction, or smoke extraction via a shorter exhaust duct, with a length less than 50 m, the functionality of the exhaust fans, at a temperature of up to 400°C, must also be guaranteed for 90 min. [3] As this information is not classified in EN 12101-3, fire class F400 must be used. [2]

The redundancy requirement for the exhaust fans in EABT-80/100 stipulates that it should be possible to extract at least 70% of the total design flow rate in the event that an exhaust fan fails. [3]

ASTRA 13001 (Swiss Federal Roads Office – Switzerland)

The HRR stipulated by the Swiss ASTRA is 30 MW, independent of the traffic load. [4]

In the case of smoke extraction via an exhaust duct with a length greater than 50 m, the functionality of the exhaust fans, at a temperature of up to 250°C, must be guaranteed for 120 min. In the case that the distance between the first exhaust damper and the exhaust fan is less than 50 m, the functionality of the exhaust fans, at a temperature of up to 400°C, must be guaranteed for 120 min. [4] To ensure this, fire class F400 must be used for the exhaust fans in accordance with EN 12101-3. [2]

Swiss ASTRA's redundancy requirement for the exhaust fans stipulates that it should be possible to extract at least 65% of the extraction flow rate from the tunnel traffic area in the event that an exhaust fan fails. This requirement applies to each tube individually, even if other structural measures, such as ventilation cross passages, are in place to increase the extraction flow rate. [4]

NFPA 502 (National Fire Protection Association - USA)

NFPA 502 stipulates a HRR of 15 to 300 MW. The HRR used for the design depends on the type of vehicles that are to be expected. In addition, in tunnels with life-saving safety systems, such as fixed fire-fighting systems, NFPA 502 allows for mitigation of the design fire scenario. [5]

The exhaust fans must be designed in such a way that operation, at a smoke gas temperature of up to 250°C, must be guaranteed for 60 min. [5] When considering EN 12101-3, this specification does not correspond to any fire class. For reasons of comparison, fire class F300 is used. [2]

The redundancy requirement in NFPA 502 stipulates 100% redundancy in the event that an exhaust fan fails. This means that the ventilation system must be designed in such a way that it is still possible to extract 100% of the flow rate in the event that an exhaust fan fails. [5]

Table 1: Overview of Design Criteria for Exhaust Fans

Guideline	Exhaust fan redundancy	Heat Release Rate (HRR)	Exhaust fan fire class
RVS 09.02.31 [1] (Austria)	not required	5 MW for car traffic only 30 MW for mixed car and HGV traffic >30 MW for >15% share of HGVs; risk analysis required	120 min at 400°C → Fire class F400
EABT-80/100 [3] (Germany)	70% of design flow rate if one exhaust fan fails	30 MW for up to 4,000 HGV-km/day and tube 50 MW for up to 4,000 HGV-km/day and tube 50–100 MW for > 6,000 HGV-km/day and tube; risk analysis required	90 min at 250°C 90 min at 400°C → Fire class F400
ASTRA 13001 [4] (Switzerland)	65% of design flow rate per tube if one exhaust fan fails	30 MW	120 min at 250°C 120 min at 400°C → Fire class F400
NFPA 502 [5] (USA)	100% of design flow rate if one exhaust fan fails	15–300 MW, depending on type of vehicles expected and installed fire protection measures	60 min at 250°C → Fire class F300

2.2. Possibilities for increasing availability and achieving redundancy

In a tunnel with transverse ventilation or point extraction, the exhaust fans in the ventilation buildings are the most important components. Due to their size and the requirements, these fans are in most cases individually manufactured. As a result, long waiting times must be expected, in most cases, for replacements in the event of damage.

There are several possible ways to achieve redundancy in tunnel ventilation systems. However, the goal remains the same: to increase the availability of road tunnels and subsequently maintain operation of important main traffic routes.

Increasing availability by keeping replacement parts in stock:

The motor is the component of an exhaust fan which is most likely to be damaged. Therefore, procurement of a replacement motor is a possibility for reacting quickly in an emergency and for counteracting long tunnel closure. However, the necessary storage space must be available for this measure. If this is not the case, it is possible to store the replacement motor with the manufacturer for a storage fee. The respective manufacturer then also takes care of the necessary maintenance works, such as regularly moving the rotor. This solution is well suited to increasing availability in existing tunnels where the required storage space is not available, without the need for structural measures. Another possibility to increase availability is to keep a complete replacement fan in stock (n+1).

Increasing availability by means of redundant systems:

Fully redundant systems

For every individual exhaust fan, there is an additional parallel fan that can completely (100%) replace the failed exhaust fan (= fully redundant system: 1+1) in case of an incident. If the fans are all in operation during normal operation (part-load operation), this is referred to as hot redundancy. If the parallel exhaust fans are not in operation during normal operation, this is called cold redundancy. Fully redundant systems are very cost-intensive, but also offer the highest standard in terms of failure safety.

Transverse-ventilated tunnels with ventilation systems designed according to NFPA 502 always have a fully redundant system.

Partially redundant systems

As some guidelines and regulations do not require 100% redundancy, the system can be designed in such a way that all components have to be operated in part-load operation during normal operation, in order to achieve the design flow rate and reduce costs. In the event that an exhaust fan fails, the remaining exhaust fans are operated in full load mode. In total, depending on the design, only 70% of the design flow rate is achieved. As all exhaust fans are needed to achieve the design flow rate, partially redundant systems always comprise a hot redundancy. In a partially redundant system, the costs can be slightly reduced in comparison to a fully redundant system, as the individual exhaust fans will be smaller, depending on the redundancy requirement. The availability is not affected, provided the applicable guidelines and regulations permit a partially redundant system. It is to be noted that, in some cases, parallel operation of fans may lead to significant fluctuations in electricity demand. This problem particularly occurs at fans with asymmetrical inflow.

Tunnels for which the EABT-80/100 or the ASTRA specifications were used for the dimensioning of the ventilation system have at least one partially redundant system.

Structural redundancy:

In twin-tube tunnel systems, the exhaust air ducts of both tubes can be connected via ventilation cross passages. In the event that an exhaust fan fails, both of the exhaust fans in the second tube can replace the exhaust fan that has failed. However, this type of redundancy is not permitted by all guidelines and regulations.

Example: Karawanken tunnel, see Chapter 2.3

2.3. The Karawanken tunnel as a project-specific example of structural redundancy

The approx. 8 km long Karawanken road tunnel connects the A11 Karawanken motorway and the A2 motorway (which forms part of the Slovenian road network). Since March 2015, the first tube of the Karawanken tunnel has been operated as a bidirectional road tunnel with a ventilation system rehabilitated in accordance with the requirements of RVS 09.02.31. After completion of the second tube, the twin-tube tunnel will be operated as a unidirectional tunnel system with 2 lanes for each direction of traffic. The ventilation system is planned as a semi-transverse ventilation system that has jet fans in the lay-bys, as illustrated in Figure 1.

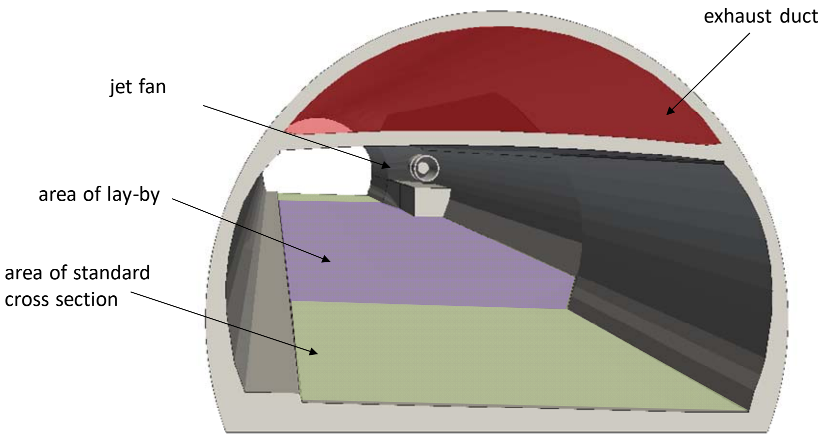

Figure 1: Lay-by niche [6]

A concept for a redundant tunnel ventilation system has been developed by ILF Consulting Engineers Austria GmbH in collaboration with ASFINAG for the construction of the second tube of the Karawanken tunnel. Although it is not stipulated in RVS 09.02.31 that redundancy is a requisite for exhaust fans, the interconnection of the ventilation systems in both tunnel tubes, via four ventilation cross passages, as shown in Figure 2, increases the tunnel's availability. The great advantage of this combined ventilation system is that if an exhaust fan fails, it can be replaced by one or both fans in the neighbouring tube. For this, only the dampers at the end of the cross passages have to be opened, see Figure 3.

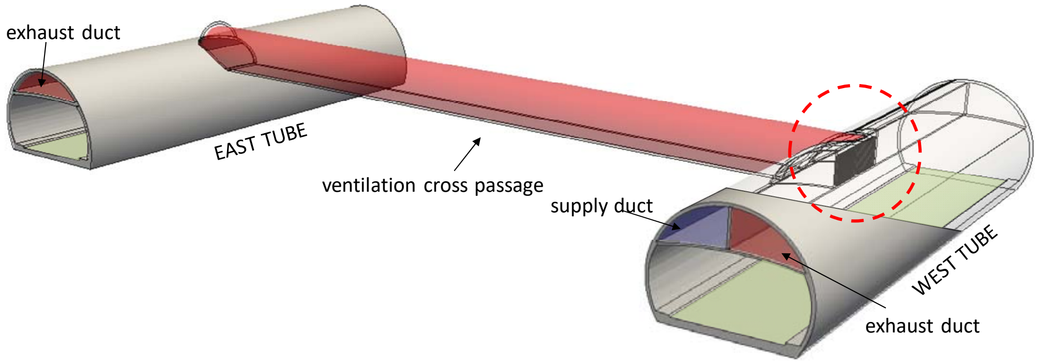

Figure 2: Ventilation cross passage [6]

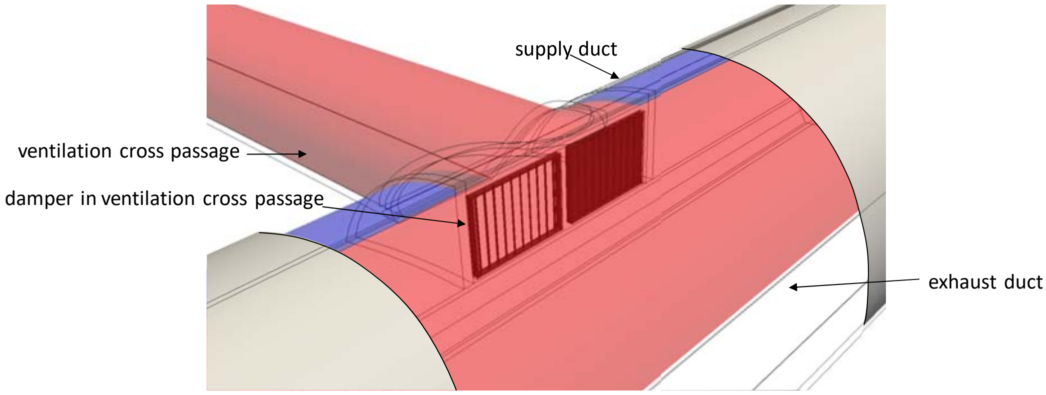

Figure 3: Detail: Connection of the ventilation cross passage [6]

This ventilation system ensures the availability and thus the continued operation of the tunnel in case of an incident or planned maintenance works. This makes it possible to achieve redundancy through a structural solution – in this case ventilation cross passages – without needing to change the number or size of exhaust fans. Consequently, there are no extra costs for additional ventilation equipment. As the ventilation cross passages are constructed as part of the construction of the second tube, the investment costs are kept within reasonable limits.

Estimated loss of revenue as a result of tunnel closure

To illustrate the costs arising in the event of tunnel closure, the loss of toll revenue has been calculated and is shown in Table 2. The cost estimate is based on the annual average daily traffic (ADT) volume (the ADT volume used for the dimensioning of the tunnel system) as well as the current toll costs of EUR 7.60.

Table 2: Loss of toll revenue as a result of tunnel closure

Toll costs	Loss of toll revenue
per hour	~ EUR 4,000
per day	~ EUR 100,000
per week	~ EUR 700,000
per month	~ EUR 3,000,000
per year	~ EUR 36,000,000 €

The economic consequences for other companies – due to delivery delays resulting from detours and traffic jams, additional costs as a consequence of longer delivery routes, etc. – have not yet been taken into account.

2.4. Comparison of different systems for achieving redundancy

For a better understanding of the different types of systems available for achieving redundancy, an evaluation matrix showing different alternatives is included below. A comparison of the additional costs and the increase in availability is made. The reference case is the case without redundancy, as it is described in the current version of RVS 09.02.31, where:

0 … the same, + … better, ++ … much better, - … worse, -- … much worse.

Table 3: Comparison of different solutions

Redundancy system	Availability	Costs
No redundancy	0	0
Fully redundant systems	++	--
Partially redundant systems	++	-
Keeping replacement parts in stock	+	-
Structural redundancy	++	--

3. SUMMARY AND CONCLUSION

The comparison of guidelines and regulations showed that the respective design specifications for the HRR in each of the respective countries differ greatly from each other. In almost all of the countries considered, the HRR used for the design depends on the expected transport mix. The exception is Switzerland, where a recommended value is specified. When allocating the fire classes given in EN 12101-3 to the requirements prescribed for the exhaust fans, it can be seen that there is consensus on this topic among European countries. Internationally, the requirements are somewhat less stringent. In all of the guidelines and regulations examined, with the exception of the Austrian RVS 09.02.31, redundancy for exhaust fans is required to varying degrees. It is mostly specified as a percentage availability and refers to exhaust fan failure. If permitted by the applicable guidelines and regulations, redundancy can be achieved through a structural solution without the need for keeping additional equipment in stock. In twin-tube tunnels, for example, redundancy can be achieved by connecting the ventilation systems of the two tubes by means of ventilation cross passages.

Increasing the availability through a redundant ventilation concept is always associated with increased investment costs. For redundant or partially redundant systems, the investment costs for the ventilation equipment increase noticeably. If the resulting additional costs are compared with those which are incurred in the event of complete tunnel closure, the investment already pays off within a few weeks. This is why the option of implementing a redundant system should be considered for greenfield tunnel projects in Austria, especially for important main traffic routes.

In order to effectively counteract the high loss of revenue and the economic consequences associated with tunnel closure due to defective ventilation equipment, the safety-relevant systems required for tunnel operation have to be constructed as redundant systems. Thus, the growing need for major road networks to have a higher availability can be met.

Evaluation of the country-specific guidelines and regulations showed that the Austrian RVS 09.02.31 constitute an exception, when compared internationally, as regards the non-existent requirement of redundancy. In order to keep pace with the state of the art, at least in Europe, it is necessary to revise and update the content of RVS 09.02.31.

4. REFERENCES

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