INFLUENCE OF ACOUSTIC TUNNEL MONITORING AKUT ON TUNNEL SAFETY

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ABSTRACT

The acoustic tunnel monitoring system AKUT is used in Austrian motorway tunnels since 2015 to detect critical events during tunnel operation. Through the automatic acoustic detection of unusual noises, the system detects potentially dangerous conditions or abnormal noises. By increasing detection possibilities, detection times can be reduced and subsequent traffic control as well as safety and rescue measures can be implemented faster. This can reduce the risk potential in case of an accident.

Since the first installation of AKUT the detection times have been recorded in an event database, which is continuously updated. On this basis the detection times with and without AKUT can be objectively evaluated and the safety benefit of the system can be determined:

- Faster event detection allows for faster activation of safety equipment.
- Faster activation of traffic lights at the portal prevents people to enter hazardous zones.
- Faster activation of warning systems can reduce the subsequent accident rate after vehicle breakdowns and accidents.

Based on the event data, an approach for the tunnel risk model TuRisMo has been developed. This has included establishing statistical fatalities numbers for the model tunnels selected through detailed fire simulations. Subsequently, reduction factors for application in the standard risk analysis model have been extracted. In this paper, the influence and changes to the event tree of the Austrian instruction RVS 09.03.11 will be presented.

The result of the study allows a data-based quantitative consideration of AKUT as an additional safety measure in road tunnels.

Keywords: acoustic monitoring system, detection system, detection time, accelerated event response, risk assessment approach

1. INTRODUCTION

Fast detection of critical incidents in tunnels is essential for triggering emergency measures and evacuating people who have been involved in an accident in the tunnel. This enables operators in the traffic management centre to take immediate action and leads to a reduction of dangerous situations and consequently reduces related consequences corresponding to tunnel users and to infrastructure. Acoustic monitoring in tunnels has shown to significantly reduce detection times [3]. AI-based detectors recognise the abnormal noises in real time and assign them to predefined noise classes.

The advantage of acoustic detection is that AKUT can react directly to the critical incident (e.g. accident noises after a collision). This means that AKUT can trigger an alarm in the traffic management centre in less than 1 second after the occurrence of an incident. Other safety systems usually recognise the consequences of an accident indirectly (e.g. slow drivers, traffic jam, etc.) and therefore require a longer time to trigger an alarm.

The following sound classes are currently recognised: (i) accident/tyre blowout, (ii) tyre squeal, (iii) door slam, (iv) horn honking, (v) voices/shouting.

After the development of the system, the first pilot system was installed in the network of the Austrian highway operator ASFINAG in 2010. Following clearly positive evaluation results in 2014, ASFINAG started to gradually equip all tunnels of hazard classes 3 and 4 with AKUT. Currently, the acoustic monitoring system is installed in 35 tunnels with approx. 2.100 microphones. Around 177 km of tunnels in the ASFINAG network are currently acoustically monitored. Over the next few years, another 21 tunnels in Austria will be equipped with the system. In recent years, it has become apparent that many critical events in the tunnels were recognised very quickly by AKUT.

However, there has not been a comprehensive analysis and no approach has been recognised as to how the rapid incident detection of AKUT effects the risk assessment of a tunnel and what advantages can result from it.
Consequently, the highway operator ASFINAG initiated a study to develop an approach for the evaluation of acoustic monitoring in risk analysis based on the evaluation of a large number of real incidents in tunnels.
Focus points for the study have been potential benefits in risk assessment, such as for instance a reduction in the fire risk through faster activation of safety equipment (e.g. activation of red lights at the portal, ventilation, loudspeakers, lighting, water mist system) or a reduction in subsequent accident rates (following breakdowns and accidents).

2. DATA ANALYSIS

In order to obtain a basis for assessing the performance of acoustic monitoring, incidents in a one year period have been evaluated as part of this analysis. The ASFINAG incident database [1] and the alarm lists of the individual tunnel control servers [2] have been used as the data basis for the analysis.

2.1. ASFINAG Incident Database (IDB)

The analysis is based on the entries in the ASFINAG incident database (IDB). The IDB has been operated by ASFINAG for many years. In case of an incident, the operators enter the incident data into the IDB. This basis thus represents an optimal starting point for the evaluation.

The following data is entered into the IDB for each incident in a tunnel: tunnel name and route number, date and time of the incident, exact location of the incident, tunnel area (entrance, inner area, exit), vehicles involved, verbal description of the incident, etc.

2.2. Tunnel alarm lists

In addition to the IDB, the alarm lists of the individual tunnel control servers were used to analyse the individual incidents. The alarm lists were exported from the respective tunnel control servers and made available by ASFINAG in the form of MS Excel files. These alarm lists contain the following data:

- Date and time stamp of the alarm that occurred or the action performed by the operator (e.g. switching traffic lights to red)
- Text of the message (alarm)
- Description of the alarm
- Time stamp of the acknowledgement by the operator

In agreement with ASFINAG, the events of an entire year were analysed, namely 1 September 2021 to 31 August 2022.

2.3. Procedure for analysing the incidents

Based on the alarm lists and the entries in the IDB, the following procedure has been pursued. For each individual incident in the IDB, based on the timestamp, the matching incident in the alarm lists has been identified. As soon as corresponding alarms were found in the alarm lists, these were extracted and (i) the date of the incident, (ii) the timestamp of the alarm and (iii) the description of the alarm were saved.
Because the exact timestamp of the alarms is particularly relevant for the analysis, the time stamps of the first, second and third alarms have been extracted for each incident.

2.4. Analysed tunnels

The analyses has been carried out for 28 tunnels in the ASFINAG road network encompassing a total distance of 156.7 kilometres.

2.5. Incident distribution across the tunnels selected

A total of 168 events were analysed over a period of one year. Of these 168 events, 126 events could be analysed beyond any doubt. This corresponds to 75 % of the total number of events. For the remaining 42 events, a clear allocation was not possible. These cases reflected situations with a traffic jam, resulting in a relatively high number of alarm messages making it (often) not possible to clearly assign them to a specific incident. These events were therefore not further analysed.

2.6. Data analysis of first alarms in case of incidents

One of the most important aspects with critical incidents in tunnels is the time of detection and resulting alert in the tunnel control centre. For each incident, the sequence in the alarm chain was analysed and it was determined which safety system in the tunnel provided the first, second and third alarm according to that incident.

Figure 1 shows the distribution of which system sent the first alarm to the tunnel control centre. In 68% of the incidents AKUT sent the first alarm to the tunnel control centre, 29.7% of the incidents were first reported by the video detection system and the remaining 2.3% were first reported by induction loops.

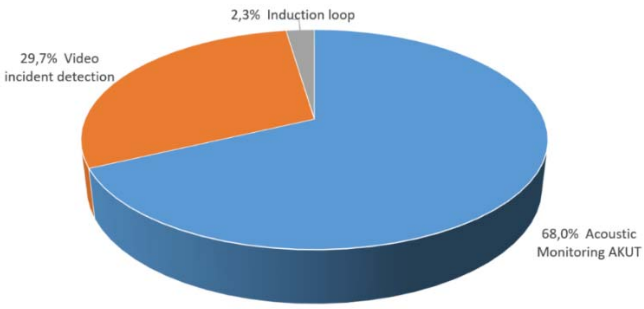

Figure 1 Overview of which safety system sent the first alarm to the tunnel control centre

2.7. Time advantage of AKUT alarms

Time differences between the first and the second alarms triggered have been analysed. The second alarms triggered in all 87 events in which AKUT detected first have been categorised in six time categories. Figure 2 shows the time advance of AKUT against other detection systems.

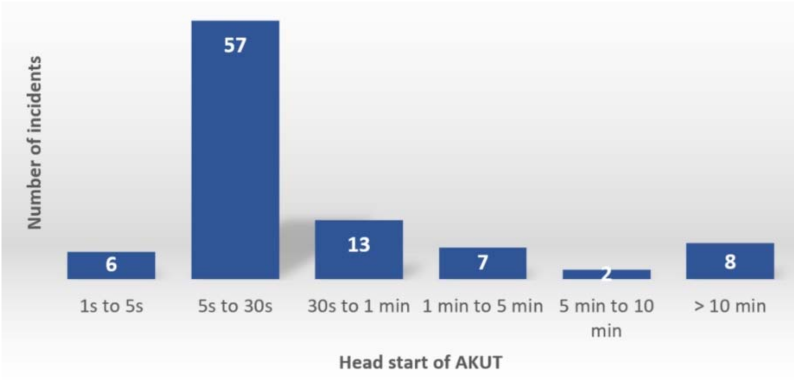

Figure 2 Time advance provided by AKUT compared to other tunnel safety systems

All time differences between first and second alarms triggered have been determined, ordered by size and their Median value calculated. According to this data set analysis, the time advantage of AKUT could be identified to amount to 23 seconds.

2.8. Data analysis in case of secondary incidents

The analysis has shown that the database unfortunately contains too few events to be able to make a well-founded statement regarding the influence of AKUT on the accident rate following initial incidents (so-called secondary incidents). Therefore, other data bases and valuation methods were used (see chapter 3.1).

3. DEVELOPMENT OF AN ASSESSMENT APPROACH

3.1. Valuation approaches for the risk model

Faster detection time (extent of damage model)

The Austrian tunnel risk model consist of both an event tree based probability analysis and a consequence model to determine statistical number of fatalities. The consequence model is further differentiated into a detailed smoke propagation simulation and an agent-based evacuation simulation. The advantages of AKUT are relevant for both of these simulation parts, as faster detection times lead to faster activation of safety equipment (ventilation, tunnel closure) and faster start of the evacuation (play-back tunnel-user information).

To be able to quantify this logic, two different simulation approaches have been used for the individual model tunnels selected:

1. Without AKUT: Absolute detection time of 37 seconds is applied according to the previous data basis (simulation approach adopted in accordance with RVS 09.03.11).
2. With AKUT: Values adapted for an absolute detection time of 14 seconds (37 seconds – 23 seconds faster detection due to AKUT = 14 seconds detection time for tunnels with installed AKUT system).

The detection times of 37 and 14 seconds represent solely the event being detected. In both cases, additional time periods must be added for which the following has been considered: 15 seconds for response time of operating personnel, 8 seconds for the system reaction time, 30 seconds for the time until the red light signal is respected (in accordance with RVS 09.03.011). Further reaction times of critical safety systems, such as activation of the ventilation and start of the evacuation process have been considered as detailed in table 1:

Table 1: Time line for key parameters

	Tunnel without AKUT	Tunnel with AKUT
Absolute detection time	37 seconds	37 – 23 = 14 seconds
Tunnel closure	90 seconds	90 – 23 = 67 seconds
Activation of fire ventilation	120 seconds	120 – 23 = 97 seconds
Alert time	150 seconds	150 – 23 = 127 seconds

Reduction factors have been determined based on comparison of the fatalities or consequence numbers for both simulations of each of the tunnel studied. These factors are subsequent applied to the precalculated consequence values of the standard risk analysis to account for an installed AKUT system.

Accelerated closure time (event tree – frequency of incidents)
Faster detections lead to faster activation of safety devices; this also influences tunnel closure time (traffic light). As a result, fewer vehicles enter the tunnel and consequently the number of vehicles stopping after a traffic disruption is reduced, which also reduces the number of vehicles that can cause a rear-end collision.
This effect can be considered in the frequency analysis by adjusting the percentage of subsequent accidents after accidents and breakdowns and is determined as follows (value C2 of event tree, in accordance with RVS 09.03.11):

$$C2 = A1 \cdot B1 \cdot \boldsymbol{\bar{N}} \cdot p_{A,P} + A1 \cdot B2 \cdot \boldsymbol{\bar{N}} \cdot p_{A,U}$$

Where $p_{A,P}$ and $p_{A,U}$ are the probability for one vehicle to be involved in a rear-end collision after a breakdown or after an accident respectively. $\bar{N}$ defines the average number of vehicles queuing up behind the incident vehicle and is determined as follows:

$$\bar{N} = \left(\frac{t_{SP}}{3600} + \frac{L_{TA}}{2 \cdot v_{max}}\right) \cdot \frac{JDTV}{24}$$

With values A1, B1 and B2 of event tree, in accordance with RVS 09.03.11; in addition the tunnel length without additions L_{TA}, maximum permitted speed v_{max} and AADT (annual average daily traffic), the closure time t_{Sp} is also included here.

This assessment approach influences all secondary events in the tunnel – occurring after accidents and breakdowns, thus influencing the fire risk and the mechanical risk.

Reduced probability for rear-end collisions after break downs or accidents
Faster detection leads to faster activation of safety devices; consequently, the warning facilities in the tunnel are also activated more quickly. This increases the attention of tunnel users and reduces the probability of a vehicle being involved in a rear-end collision. That effect can be considered in the frequency analysis by adjusting the value C2 in the event tree. The value C2 represents the subsequent accidents after accidents and breakdowns and is determined as follows (in accordance with RVS 09.03.11):

$$C2 = A1 \cdot B1 \cdot \bar{N} \cdot \boldsymbol{p_{A,P}} + A1 \cdot B2 \cdot \bar{N} \cdot \boldsymbol{p_{A,U}}$$

The Austrian RVS specifies values for both probabilities, $\boldsymbol{p_{A,P}}$ and $\boldsymbol{p_{A,U}}$. This values have been determined on the basis of the ASFINAG event database. However, as mentioned before, it is not possible to derive adapted subsequent accident probabilities (after breakdowns or accidents) when using AKUT in tunnels on the basis of the current ASFINAG event database due to the low number of incidents.
Nevertheless, in order to account for the positive effect, it would be possible to define

reduction factors for the two probabilities mentioned above on the basis of expert judgement. A general reduction factor f_{AKUT} or two specific reduction factors for breakdowns $f_{AKUT,P}$ and for accidents $f_{AKUT,U}$ could be incorporated into the formula for C2 as follows

$$C2' = A1 \cdot B1 \cdot \bar{N} \cdot p_{A,P} \cdot f_{AKUT,P} + A1 \cdot B2 \cdot \bar{N} \cdot p_{A,U} \cdot f_{AKUT,U}$$

This assessment approach influences all secondary events in the tunnel – occurring after accidents and breakdowns, thus influencing the fire risk and the mechanical risk.

3.2. Representative model tunnels

Determining the influence of AKUT for all possible tunnel types for which consequence numbers are available in RVS 09.03.11 would have considerably exceeded the scope of the research project. For this reason, several representative motorway tunnels have been selected for the analysis. Among other things, the focus was on tunnel types with AKUT in the ASFINAG network for which a risk assessment with the standard risk model could be relevant:

Table 2: Selection of representative model tunnels

Operation	Tunnel length	Ventilation type	Longitudinal inclination	Distance of emergency exits
Uni-directional (no traffic congestion)	0.7 km	Natural ventilation	-3.0%	233m
				350m
			+3.0%	250m
				350m
	1.5 km	Longitudinal ventilation	-3.0%	250m
				500m
			+3.0%	250m
				500m
	4.0 km	Longitudinal ventilation	-3.0%	250m
				500m
			+3.0%	250m
				500m

The detailed risk analysis has been carried out for three model fires (5 MW, 30 MW and 100 MW) and for two fire scenarios, primary events and secondary events. Events involving congested traffic (tertiary events) have not been considered.
Tunnels with bi-directional traffic, special structural properties or traffic characteristics (e.g. congestion) were not considered, as in these cases the standard model is often not applicable.

3.3. Detailed risk analysis for model tunnels selected

Methodological framework
The TuRisMo risk model [4] is a system-based quantitative risk analysis model. It allows a systematic and quantitative risk assessment and takes into account all relevant incident scenarios in a road tunnel.
The risk model considers the personal risk of tunnel users and results in an expected risk value for the group of tunnel users. Therefore, all data used in the risk model refers to accidents with personal injury. The method consists of the following two basic elements:

1. Quantitative frequency analysis (event tree analysis)

2. Quantitative consequence analysis which consists of two simulation parts – the smoke propagation simulation and the evacuation simulation

Results

The model tunnels selected are all uni-directional tunnels and are equipped in accordance with the guidelines. Therefore, small fires (5 MW) result in negligible consequences, both for primary and secondary events. This can, for the most part, be explained by the relatively low fire load. Accordingly, the difference in the resulting consequence numbers is too small to be able to determine a factor related to the effectiveness of AKUT.

For the large fire scenarios, 30 MW and 100 MW, differences in the consequence numbers for the primary scenarios are too small to determine an improvement factor for AKUT. This is mainly caused by the favorable spread of smoke in traffic direction for uni-directional tunnels, protecting the tunnel users in the traffic jam behind the fire location. Factors for the effectiveness of AKUT can only be defined for both of these fire sizes in case of secondary scenarios. These scenarios represent a fire related accident in the traffic jam combined with the spread of smoke in traffic direction. Under these circumstances, tunnel users in front of the fire location could be effected by smoke. The improved detection time by AKUT causes a reduction in the consequence numbers.

Reduction factor for standard risk model

In order to establish an improvement factor for the consequence numbers used in the standard risk analysis, the absolute difference of the respective consequence numbers has been calculated. The aim was to obtain as few representative factors as possible in order to ensure simple applicability. In the following, the resulting reduction factors according to the three model tunnels selected and only for secondary events will be presented and discussed:

- Tunnel without mechanical ventilation

The resulting reduction factors differ roughly in terms of fire load and longitudinal inclination. For this reason, no further simplification is possible and individual factors are required in each case.

Table 3: Reduction factor for unidirectional tunnels without mechanical ventilation for secondary events

	30 MW -3%	30 MW +3%	100 MW -3%	100 MW +3%
Reduction factor AKUT	0.7	0.8	0.4	0.6

- Tunnel with longitudinal ventilation

Contrary to the model tunnels with natural ventilation, it is possible to further reduce the number of reduction factors for the tunnels with longitudinal ventilation systems.
This is firstly due to the relative small differences between model tunnels with a positive or negative gradient, reflecting that the ventilation system is designed for the respective longitudinal inclination and the fires can therefore be controlled. Secondly, the factors for different fire sizes can be summarized, as the differences become negligible due to the positive influence of the installed ventilation system. In addition, the damage extent values of the model tunnels with 1.5 km and 4.0 km show only minor differences. This means that the tunnel length factor can be neglected in case of longitudinal ventilation.

Hence, it was possible to limit the number of reduction factors and to define only one generally valid factor for unidirectional traffic with longitudinal ventilation, namely **0.5**.

4. SUMMARY AND CONCLUSIONS

It is undisputed that AKUT - as a safety measure - provides an advantage for the safety level in road tunnels. However, until now there has been no measurable and therefore quantifiable factor in the tunnel risk assessment. This means that the benefit for the tunnel operator cannot be taking into account during the risk analysis.

To develop such an approach, an extensive data analysis of the event database and the recordings of the tunnel control servers was carried out. It was found that AKUT is often the first system to detect an event, highlighted by a first detection in almost 70% of the tunnel incidents recorded. Moreover, analysis has shown that AKUT can accelerate the detection time in these case by around 23 seconds.

The faster detection time can be taken into account in the risk model in both the event tree based frequency analysis and in the fatalities or consequence analysis:

- For the evaluation in the frequency analysis, individual adjustments must be made in the event tree with regard to the subsequent accident rate (secondary events). These relate firstly to a reduced number of vehicles entering the tunnel due to faster activation of tunnel closure and secondly to a reduced probability of collision after breakdowns and accidents due to faster activation of warning devices in the tunnel.
- In the Austrian guideline RVS 09.03.11 two different risk models are available for analyzing the fire consequences: A standard risk analysis model, for which the RVS specifies the consequence numbers, and a detailed risk model, for which individual simulation calculations are required for each tunnel. For the evaluation of AKUT, an approach was provided for both risk models:
    - When evaluating AKUT with a detailed risk analysis and only when the tunnel is similar to the model tunnel parameters, the reduction factors can be applied to the individually determined consequences. In most cases, however, the individual time parameters have to be adjusted in the risk analysis. For tunnels with installed AKUT, a doubling of the simulation effort has to be taken into account. A set of simulations representing 70% of cases with the detection time, time for tunnel closure, activation time of ventilation or loudspeaker announcements reduced by 23 seconds. The second set of simulations represent the remaining 30%, using the standard time parameters.
    - In order to evaluate AKUT with the standard risk model, the defined reduction factors can be applied to the precalculated consequence numbers (RVS 09.03.11). Depending on the specific tunnel under investigation, the installation of AKUT reduces the secondary fire consequences by 20% to 60%.

5. REFERENCES

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