Dipl.-Ing. Dr. Franz Graf
JOANNEUM RESEARCH Forschungsgesellschaft mbH
Steyrergasse 17, 8010 Graz, AUSTRIA
franz.graf@joanneum.at

Ing. Günter Rattei
ASFINAG Autobahn Service GmbH Ost
Modecenterstrasse 16, 1030 Wien, AUSTRIA
guenter.rattei@asfinag.at

Dipl.-Ing. Gerhard Ruhdorfer
ASFINAG Baumanagement GmbH
Fuchsenfeldweg 71, 8074 Graz-Raaba, AUSTRIA
gerhard.ruhdorfer@asfinag.at

Fire, incident and hazard detection and localisation

Giving tunnels ears – installation of the first acoustic monitoring system for road tunnels worldwide

Franz Graf, JOANNEUM RESEARCH Forschungsgesellschaft mbH

Günter Rattei, ASFINAG Autobahn Service GmbH Ost

Gerhard Ruhdorfer, ASFINAG Baumanagement GmbH

The length of time between occurrence of an incident and alerting of the tunnel manager is essential in critical incidents. The innovative safety system "Acoustic Tunnel Monitoring" aims to minimise this time. The operating noise of a tunnel is characterised by a typical mix of engine, rolling and airflow noise from vehicles passing through. Any acoustic anomalies, such as a vehicle crashing into the tunnel wall, two vehicles colliding, squealing tyres, load spills etc., as well as anomalies in the sounds from individual vehicles can be detected by microphones placed in the tunnel.

Special detection algorithms allow these sounds to be automatically identified and assigned to specific alarm classes. One big advantage of acoustic detection methods is that accidents or critical incidents in tunnels are virtually always accompanied by a characteristic sound, which occurs right at the time of the incident and can thus be immediately detected.

In May 2010, the first fully integrated system for acoustic tunnel monitoring went live in the Kirchdorf tunnel, which is a twin-tube tunnel with a total length of 2,700 m. A total of 49 microphones were installed in both tubes next to the video cameras at a maximum distance of 125 m from each other. The software of the acoustic monitoring system detects abnormal sound events in real time and classifies them into 4 sound classes. The tunnel manager receives the alarm only 0.25 s after the occurrence of the incident in the tunnel.

1 Introduction

As of the end of May 2010, the ASFINAG road network extends to 2,180 km and includes a total of 427 junctions. Austria's mountainous landscape represents topographic challenges for road construction and requires a large number of tunnels. ASFINAG currently operates and maintains more than 140 tunnel facilities with a total length of approx. 330 km, roughly corresponding to the distance between Vienna and Salzburg.

In 2001, ASFINAG launched a tunnel campaign involving the implementation of modern safety concepts. This includes the addition of second tubes and substantial upgrading work on existing tunnels. All Austrian motorway tunnels feature a modern and comprehensive safety concept tailored to the particular tunnel and the prevailing traffic conditions. The different systems closely interact to ensure safe operation as well as quick and efficient response in the event of incidents.

Austrian road tunnels are equipped with the following safety systems:

- Emergency phones in tunnels and portal areas
- Fire points for emergency services
- Escape and rescue routes
- Traffic control and surveillance systems
- Lighting installations at tunnel entrances and exits
- Ventilation
- Air quality monitoring systems
- Information systems (public address system, in-tunnel radio, seamless traffic radio reception with the option of transmitting messages via the tunnel control centre)
- Automatic fire alarm
- Lay bys
- Video surveillance

The targeted implementation of these safety systems has substantially enhanced the safety level of ASFINAG tunnel facilities by international comparison, which is demonstrated by excellent ratings awarded by several traffic organisations in international tunnel tests.

AKUT – rapid incident detection through acoustic tunnel monitoring

The AKUT system developed in Austria is designed to detect critical incidents in tunnels. The automatic detection of unusual sounds enables the system to recognise potentially dangerous situations or incidents such as collisions, tyre bursts etc. The location of the incident is immediately reported to the tunnel control centre with an accuracy of 100 to 150 m. This will help to substantially reduce response time in emergencies and enable the tunnel operator to take immediate traffic control, safeguarding and rescue measures. The AKUT system was developed by JOANNEUM RESEARCH in Graz in cooperation with ASFINAG.

In 2006, the AKUT research project won the Austrian State Prize for Telematics and in 2009 the "Fast Forward Award". The hardware and software components of the system were developed in two research projects funded by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) under the I2 – Intelligent Infrastructure programme and the Future Fund of the Province of Styria.

On completion of the research, the first pilot facility was installed in the new 2.8 km Kirchdorf tunnel on the S35 motorway and went into operation in May 2010. The new acoustic tunnel monitoring system (AKUT) is designed to complement the existing safety facilities in the tunnel. ASFINAG expects the system to further reduce the response time for emergency services in the event of an accident and thus make an important contribution to enhancing tunnel safety for road users.

2 Principle of acoustic tunnel monitoring

The operating noise of a tunnel is characterised by a typical mix of engine, rolling and airflow noise produced by vehicles passing through. Microphones installed in the tunnel can detect any acoustic anomalies both in the tunnel, such as a vehicle crashing against the tunnel wall, two vehicles colliding, load spills, tyre bursts etc., as well as in individual vehicles. Special detection algorithms make it possible to automatically identify these sounds and assign them to specific alarm classes.

One big advantage of acoustic detection methods is that accidents or critical incidents in tunnels are virtually always accompanied by a characteristic sound. These sounds occur right at the time of the incident and can thus be immediately detected. Conversely, the sudden absence of normal operating noise also indicates an anomaly in traffic flow. The detection of an incident in a specific tunnel section allows various immediate measures to be automatically activated. For example, the system may, depending on the alarm or accident class, trigger an acoustic alarm in the tunnel control room and display the video camera image of the respective section on a central screen. The tunnel operator thus obtains a real-time overview of the situation and can immediately take appropriate measures. This saves valuable time in providing first aid to people involved in the accident and in alerting drivers approaching the scene of the accident.

The system is equipped with all elements required for smooth and efficient operation under regular tunnel conditions.

Features

- Differentiation between normal ambient noise and alarming sounds (e.g. car crash, etc.)
- Differentiation between sounds in terms of different danger categories (event classes)
- Sound localisation by assignment to nearest microphones
- Distance between microphones 100 – 150m (depending on camera positions)
- Alarm in the tunnel control room through alerts (category, event) and display of camera image
- Live streaming of sounds and voices from the tunnel via microphones
- Tunnel operator obtains information about what is going on in the tunnel even when visibility is poor

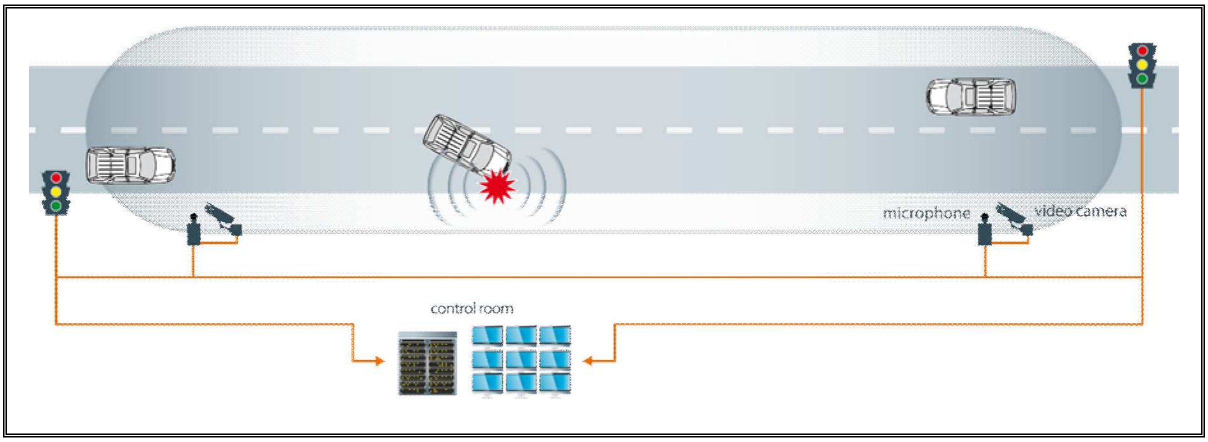

Figure 1: Principle of acoustic tunnel monitoring

3 System setup

The acoustic tunnel monitoring system consists of the following four main components:

- Microphone
- Connection box
- Optical signal transmitters
- Analysis computers including ring buffer and event log

The microphones recording the sound waves emitted in the tunnel constitute a key element of the system. They must be able to withstand the prevailing climatic conditions in tunnels (see next Section) and provide high quality signals. The higher the quality of the microphone signals the more robust the analysis algorithms. The microphones can be mounted on a separate fixture on the side wall of the tunnel or directly on the connection box. The connection boxes provide the power supply to the microphones and are responsible for the amplification and A/D conversion of the electrical microphone signals into optical audio signals. As in video systems, the audio signals are transmitted as optical digital signals via optical fibre. Audio technology offers a wide range of standards and possibilities for the optical transmission of audio data, most of which are limited to short distances (several meters). In tunnels, however, audio signals must be transmitted over longer distances of several kilometres, which in this case required the development of new optical transmission systems. The analysis computer constitutes the heart of the system. It analyses and classifies the microphone signals in real time. The first classification step is aimed at reliably differentiating the acoustic signals into the classes “normal” (sounds occurring under normal conditions) and “alarm” (abnormal sounds). In a second step, the alarm sounds are then automatically classified in more detail and assigned to individual event classes (crash, tyre burst, load spills etc.).

The analysis computer is also connected to a ring buffer, which currently stores the audio data of all microphone channels for a period of 24 hours, continuously overwriting older data. The event log also stores all incidents detected, including the start and end time of the incident, the classification results, the microphone channels involved, the detection parameters and the audio data.

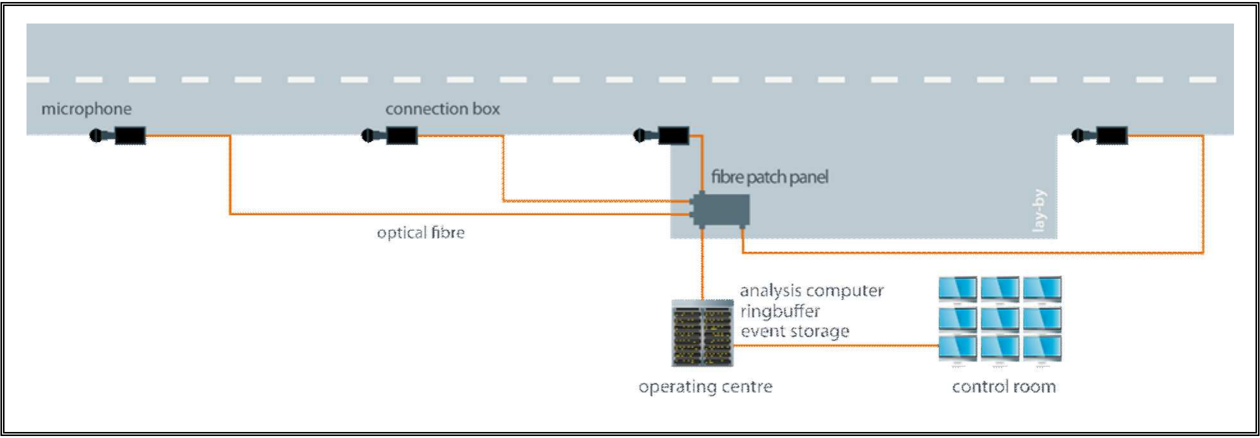

Figure 2: System structure

4 Tunnel microphones

The microphones, which constitute the first link in the signal chain, usually react sensitively to environmental conditions such as temperature, humidity and air pollution. The range of sensor damage may extend from slight changes in transmission characteristics to complete failure of the microphone. While conventional microphones can in principle be applied in tunnel environments, they are not protected from humidity and dust. As tunnels are periodically cleaned using high-pressure water to wash the side walls and ceiling, it was necessary to develop a microphone able to withstand these conditions. The microphones must meet specific functional criteria in order to provide high-quality signals under the harsh operating conditions found in tunnels.

Requirements for tunnel microphones

- Linear frequency response
- Temperature resistance
- Resistance to dirt and corrosion
- Fatigue strength and stability of components
- Easy maintenance and cleaning
- Simple and secure mounting
- Protection against splashing water and water jets in accordance with relevant IP ratings

The tunnel microphones developed were subjected to comprehensive splashing water and ageing tests, the results of which were validated by acoustic measurements. A series of wind noise measurements was carried out to analyse and reduce interference from airflow noise in the tunnel or air turbulence as a result of vehicle drag.

The tunnel microphones were mounted on the connection box using a specially designed clamping device. Hydrophobic dust-proof membranes provide additional protection against ingress of water and dust. Despite these protective characteristics, the membrane is acoustically transparent across the entire frequency range with a linear attenuation of only about 0.5 dB. The membranes are fitted in threaded protective caps and can be easily replaced during periodic maintenance.

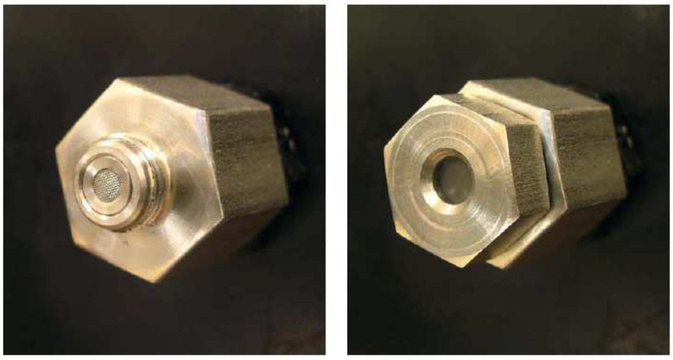

Figure 3: Tunnel microphone installed in clamping fixture (left), hydrophobic dust-proof protection cap for the tunnel microphones (right)

5 Sound database

A key feature of the acoustic tunnel monitoring system is the sound database, i.e. a “collection” of all sounds that can occur in a tunnel.

The sound database was set up in 2004 and was continuously extended over several years to obtain a sufficient number of data for algorithm training. Both “normal” and “alarm” data were recorded in the tunnel. The aim was to capture as many examples as possible for each sound class (e.g. tyre burst, crash etc.) to be able to account for the different qualities of the individual sounds in the development of the classification algorithms.

The “normal” data (normal tunnel sounds) are primarily characterised by engine, rolling and airflow noise generated by vehicles passing through the tunnel as well as ventilation noise. Other noise sources include loose lorry tarpaulins or tie-down straps. Normal tunnel sounds can be recorded relatively easily during regular tunnel operation by installing a suitable recording system.

The recording of alarming sounds such as car crashes or load spills, however, is far more difficult. The majority of the “alarm” data was recorded during tunnel closures. Several microphones were temporarily installed in the tunnel and different alarming sounds were played back over loudspeakers and simultaneously recorded. The interference of these sounds with the reverberation of the tunnel was analysed to obtain a sound basis for subsequent reliable identification. A crash test was specifically carried out to record a wide range of crash sounds for use in algorithm development. Months of work went into the manual annotation of several thousand signal segments, which involved the creation of machine-readable descriptions for each individual segment.

The sound database is only required for algorithm development and is not necessary for system operation.

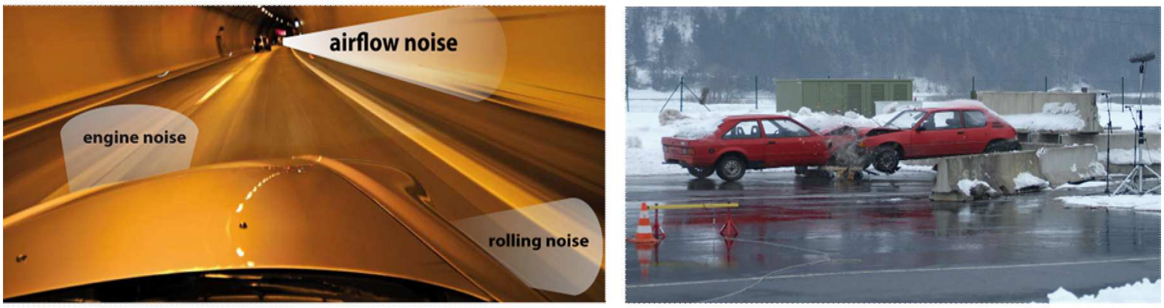

Figure 4: "Normal" sounds in a tunnel are characterised by the noise generated by vehicles passing through (left); a crash test was specifically carried out to record crash sounds (right)

6 Analysis software

The analysis software, without any doubt the heart of the system, is designed to process and classify the individual microphone signals in real time. The classification is aimed at reliably assigning the acoustic signals to their respective incident classes (e.g. crash, load spill etc.) and distinguishing them from the sounds occurring under normal conditions (engine, rolling, airflow and ventilation noise). This requires algorithms that can extract acoustic features from the recorded signals stored in the sound database. Feature extraction serves to convert the class-specific information contained in the acoustic signals into a parametric form suitable for further processing. The distribution of these features provides an indication of how similar or different the individual signals are and to which class they belong.

In the subsequent "training" step, the classification algorithm is trained on datasets whose class is known. A learning rule and additional model parameters are employed to train the system to derive the class from the given training features.

The result of this step is a statistical model containing the entire "knowledge" gained during the training phase. Once the training is completed, the system is able to correctly assign an unknown sound to one of the previously trained classes based on its features. This assignment is based on a comparison with the "knowledge" gained in the training phase. In real-time operation the system extracts the features from the sounds recorded in the tunnel and compares them with the statistical model in order to classify them. This classification involves two steps:

In the first classification step, abnormal tunnel sounds are distinguished from "normal" sounds based on the background model and classified as "alarm". The second step involves classification into detailed incident classes such as "collision", "load spill", "tyre burst" etc.

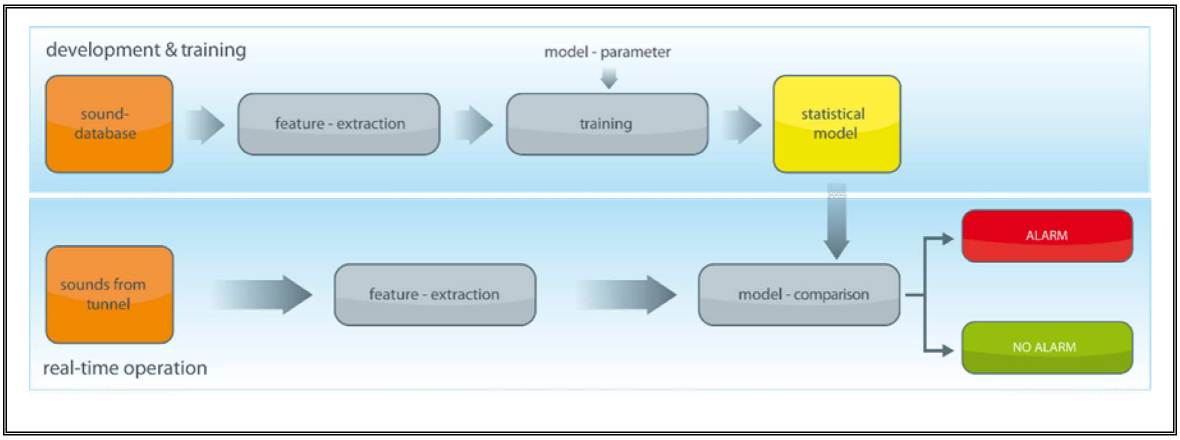

Figure 5: Processing steps during development and in real-time operation

7 Installation of first system worldwide

The Kirchdorf tunnel (Styria, Austria) was constructed to close the gap in the S35 motorway between the Zlatten reservoir and Mautstatt. The primary aim of the building project was to increase road safety and traffic flow and to provide relief from through traffic for the local population. The Kirchdorf tunnel is a round-profile twin-tube tunnel of some 2,700 m length with two lanes in each bore.

The Kirchdorf tunnel was chosen for installation of the first fully integrated pilot system for acoustic tunnel monitoring. Fully integrated in this context means that the AKUT system is connected to the traffic management system and any incidents detected are directly reported to the tunnel control centre in Bruck/Mur and displayed on the tunnel operator’s screen.

As the system was the first of its kind to be installed worldwide, it had to be approved by the Austrian Data Protection Commission prior to the commencement of planning. While video recordings in road tunnels are clearly subject to data protection legislation, there are as yet no statutory provisions regarding acoustic recordings.

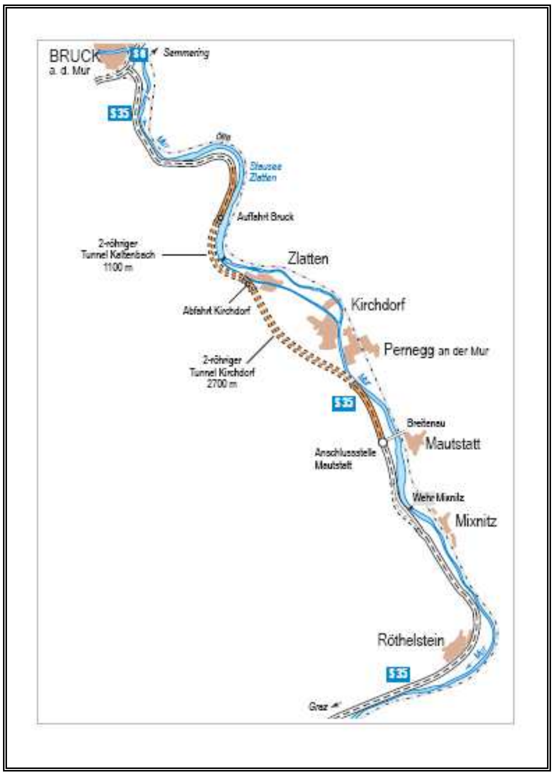

Figure 6: Section of S35 motorway between Graz and Bruck/Mur (Styria, Austria) [source: ASFINAG]

8 System overview

The AKUT system was installed in both tubes of the Kirchdorf tunnel. A total of 49 microphones were installed with 26 microphones in the southbound bore and 23 in the northbound bore. The locations of the microphones were determined based on the video camera positions. The Austrian Guidelines and Regulations for Road Design (RVS) specify a maximum distance of 125 m between video cameras in road tunnels. This guideline was also used for the microphones, with one microphone for each video camera. Exceptions are on curved sections where video cameras must be installed at shorter intervals as they require a direct line of sight. Curves, however, do not impede the propagation of acoustic waves so that the tunnel has 9% fewer microphones than video cameras.

In the connection box the microphone signals are amplified, digitised and converted into an optical signal. The optical network was implemented in a passive star topology and transmits the microphone signals via optical fibre to the nearest operating centre where the signals are converted back into electrical signals and discretised by an analogue/digital converter. The digital audio signals are forwarded to the audio router, which acts as a central hub for distributing the audio data to the analysis computers and the player. The two analysis computers process the audio signals in real time to detect incidents in the tunnel tubes.

The player operates the event log and ring buffer for the audio data and is also responsible for communication with the traffic management system via IEC protocols. It also provides an audio interface for playing back recordings of any incidents detected as well as live streams of tunnel sounds.

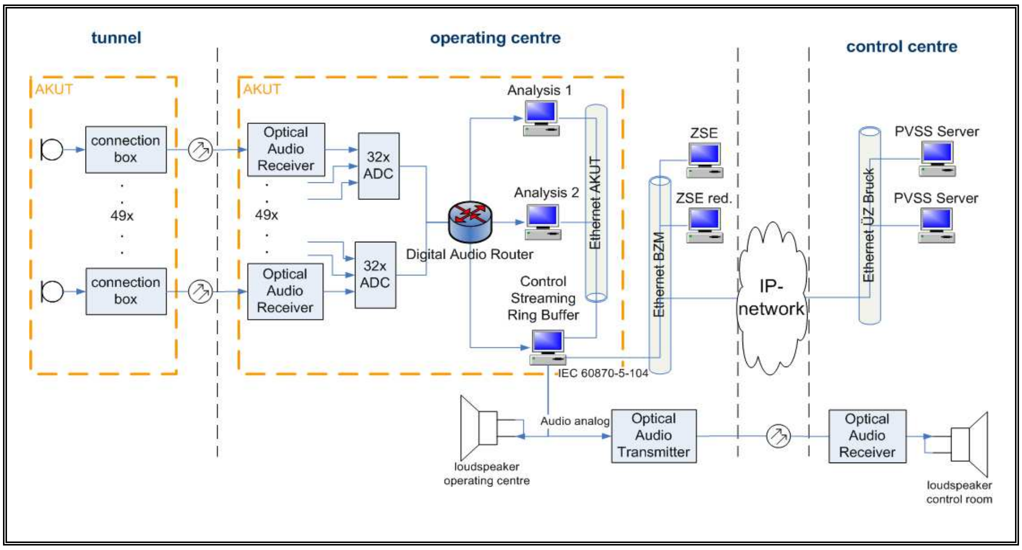

Figure 7: Block diagram of AKUT system installed in the Kirchdorf tunnel

9 Connection box

The connection box includes the microphone for recording the sounds in the tunnel as well as components for processing and amplifying the microphone signals. The amplified electrical microphone signal is converted into an optical signal by the integrated optical audio transmitter and processed for transmission to the operating centre via optical fibre.

As the planning work for the video system had already been completed at the start of the project, separate connection boxes had to be provided for the AKUT system. For future systems, however, it is planned to integrate all video and audio hardware components in a single connection box. The AKUT connection boxes were mounted above the corresponding video connection boxes at a sufficient distance from the camera housing in order to avoid interference with sound reflections from the casing. As shown in Figure 8, the AKUT casing is larger than that for the video camera. The reason for this is that adequate optical audio transmission systems are not commercially available in smaller sizes. Each housing was additionally fitted with a heating element to ensure smooth operation of the components in the specified temperature range in the winter. The tunnel microphones were directly integrated into the connection box, thus eliminating the need for additional wiring between the connection box and the sensor. The microphones were mounted with the microphone membrane facing in the direction of traffic flow, thereby substantially reducing contamination by exhaust gases and dirt.

Figure 8: AKUT and video connection boxes mounted in the tunnel

10 AKUT software

The AKUT software is designed as a distributed system whose individual components run on several computers. This enables efficient use of computing capacity, while also providing a high degree of scalability. The components communicate with each other via network connections. Communication with the control system takes place via the IEC 60870-5-104 protocol. The system is controlled by a central communications and control unit, which manages the entire communication with the control system and configures, controls and monitors all other components. The digital audio signals are recorded by capture units and provided with an NTP synchronised time stamp. The audio data is transmitted to the ring buffer, the analysis computers and, if necessary, to the player. The ring buffer stores audio data from all microphone channels over a period of 24 hours, permanently overwriting older data. The analysis computers constitute the brain of the system, implementing the signal processing and pattern recognition algorithms for each microphone channel. The detection results of the analysis computers are forwarded to the event modeller, where the detected incidents from different microphone channels are grouped into "events". An event is always assigned to one specific microphone and one specific camera. These events are then transmitted to the control system and stored in the alarm/event log. Each event is stored with the audio data that were relevant for its detection. The event log contains the start and end time of the event, the classification results, the microphone channels involved, the detection parameters and the audio data. The playback of audio data is controlled by the player. Live audio streams and recordings of any incidents detected are played over the loudspeakers in the control centre. The control system alone determines which data source sends audio data to the player.

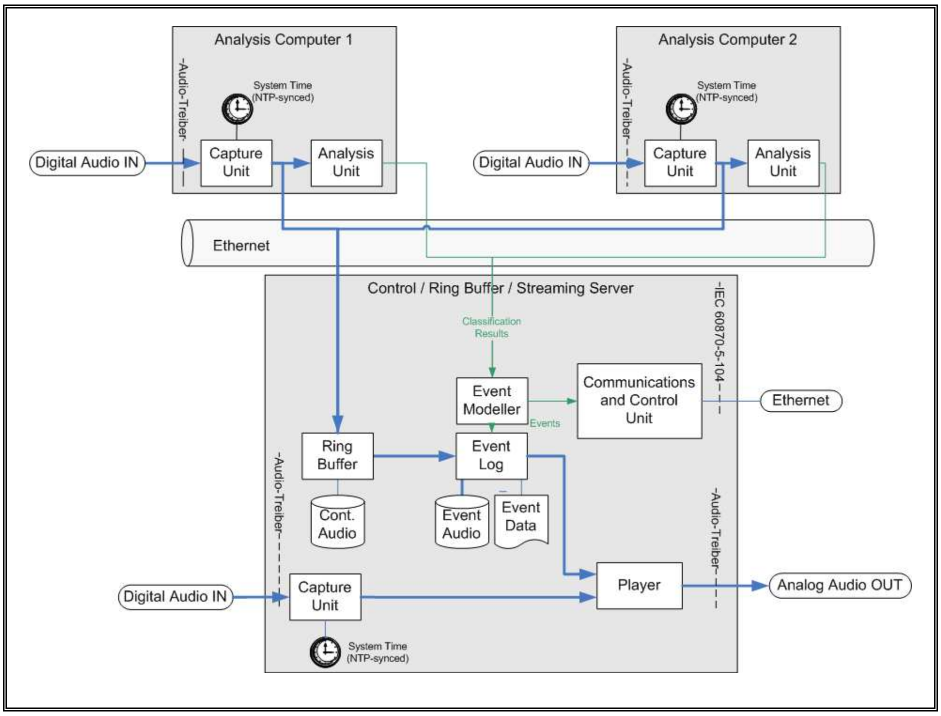

Figure 9: Components of the AKUT software

11 Event detection

The detection of alarming sounds involves several steps. First, abnormal sounds are distinguished from normal tunnel sounds for each microphone channel. The pattern recognition method used models the normal condition and detects any deviation from that condition. This enables the system to detect abnormal and unknown sounds.

The detector was tested for the following abnormal sounds:

- crash
- tyre burst
- load spill
- shouts
- door banging
- car horn
- tyre squealing

The abnormal sounds detected were then further classified into

- crash/tyre burst
- door banging/load spill
- car horn/tyre squealing
- other sounds.

The results of the first two steps are calculated separately for each microphone channel. The event modeller then groups the results of several channels into “events” and determines the location of the sound event detected. This location is assigned to the position of the nearest microphone and the position of the camera with the best view of the scene. The camera position must also be determined because certain events trigger an additional signal to the control system to display the scene covered by the corresponding camera on the operator's monitor. The action matrix of the AKUT system determines whether and which camera is activated to feed images to the tunnel control centre.

	ALARM	SIGNAL	EVENT LOG
crash or tyre burst, microphone X	camera Y activated	yes	yes
door banging or load spill, microphone X	camera Y activated	yes	yes
car horn or tyre squealing, microphone X	--	yes	yes
others, microphone X	--	yes	yes

Table 1: Action matrix of AKUT system

Figure 10 shows which camera is activated in the case of a sound event in the vicinity of microphone/camera Y. In case 1, the event takes place between microphones Y and X in the direction of traffic flow. The AKUT system localises the event between microphones X and Y. As camera Y covers the area between these microphones, the system sends a signal to activate that camera. In case 2, the event takes place before the vehicle passes microphone Y, so camera Z is activated. In cases 3 and 4, the event is detected by only one microphone and thus cannot be localised. As there is no possibility to determine whether the incident has taken place before or after microphone Y, camera Z will be activated.

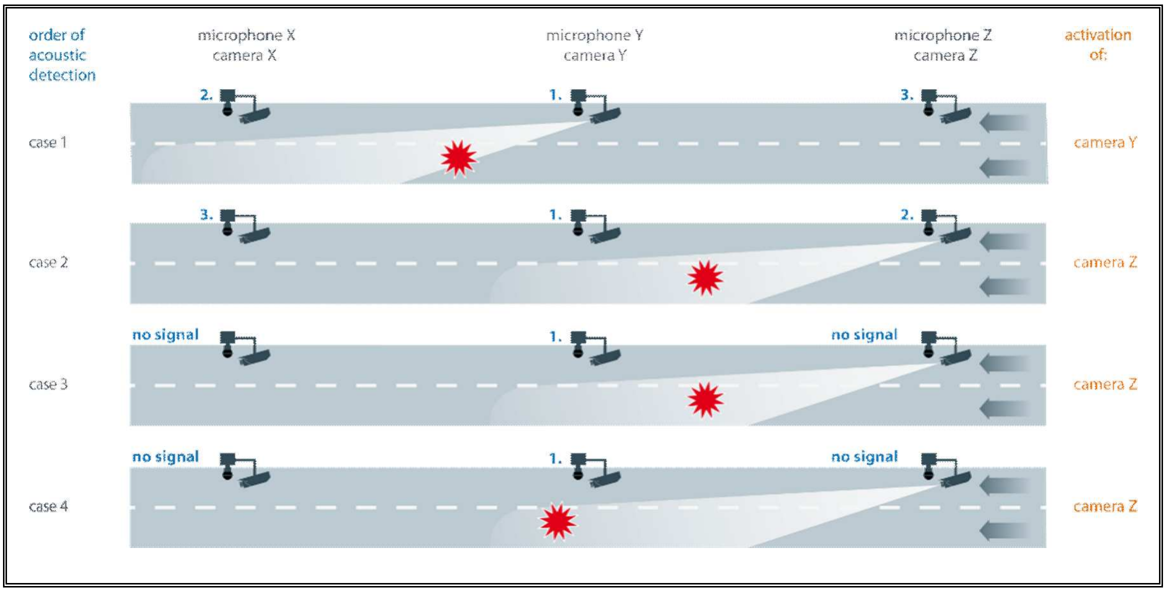

Figure 10: Camera activation strategy

12 Connection to the traffic management system

The AKUT system is connected to the tunnel control centre using the IEC 60870-5-104 telecontrol protocol. All of the monitored information is transmitted to the control centre located in Bruck/Mur, which is also responsible for system control. New symbols were designed for visualising the detected events and were then integrated into the graphical user interface of the tunnel control centre by adding a microphone symbol to each of the existing camera symbols. During maintenance, individual microphones or tunnel tubes or even the entire system can be set to maintenance mode. Failures are marked by a yellow frame. If an alarm is triggered by one of the microphones, the respective microphone is marked by a red frame and the corresponding activated camera is shown in green.

The user can also open a dialog box for extended event administration. The most recent events detected by the microphones are stored in an event list with a unique ID, the microphone number, the alarm category and the time of occurrence. A search mask allows the user to search for specific "older" events with the option of varying the search period and limiting the alarm category. The event can then be selected for playback. The respective audio signal is retrieved from the event log and played back over the loudspeaker in the control centre. The dialog box also allows the user to start live audio streams from a specific microphone to provide the tunnel operator with a real-time overview of the current situation in the tunnel.

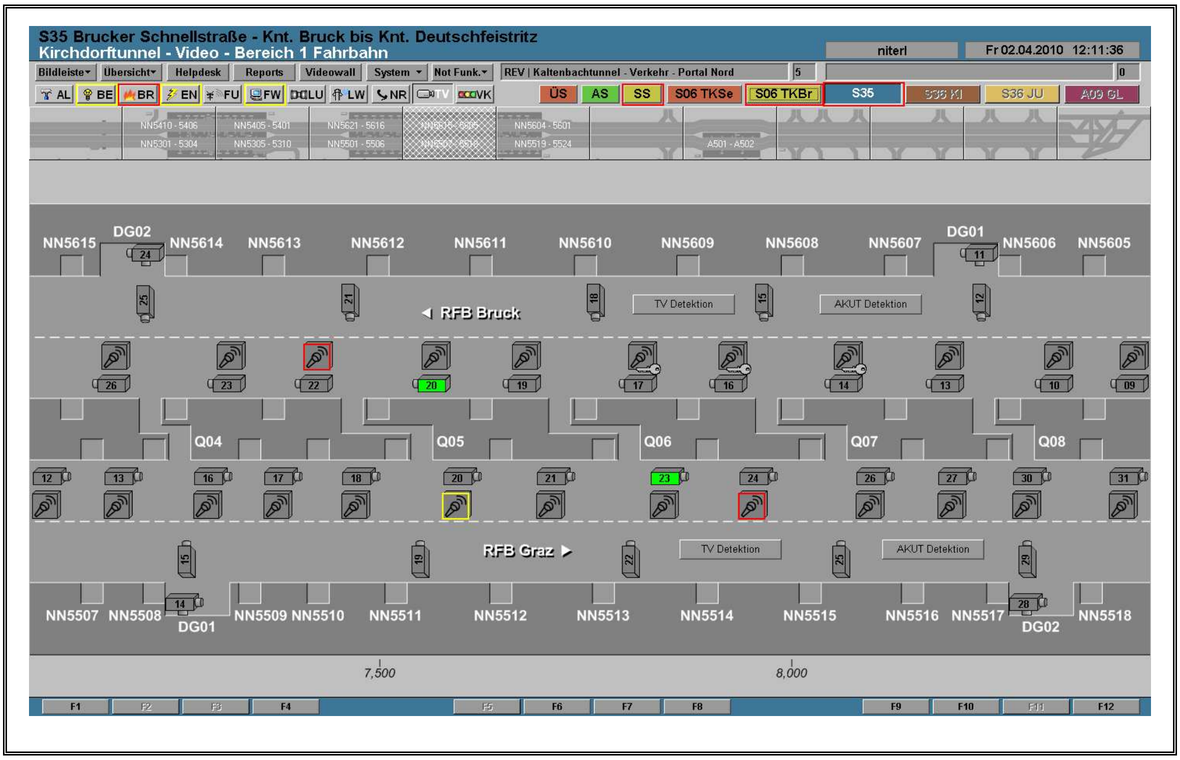

Figure 11: Section from the graphical user interface in the Bruck/Mur control centre with newly integrated symbols for the AKUT system

13 Notable incidents & alarms to date

The Kirchdorf tunnel was opened to traffic at the end of May 2010. The modern tunnel features (e.g. lighting, bright walls) have fortunately helped to keep critical incidents to a minimum.

The four incidents that occurred in the period from May 2010 to February 2011 are described in more detail below:

13.1 Vehicle fire, 24 October 2010

The vehicle fire took place in the northbound tube of the Kirchdorf tunnel. A burning passenger car entered the tunnel and came to a standstill after several hundred meters. After the driver had left the vehicle it burst into flames.

Figure 12 shows the alarm chain for the vehicle fire. It can be clearly seen that the AKUT acoustic tunnel monitoring system triggered an alarm 2 minutes and 21 seconds before the video surveillance system was activated, although the car was already on fire when it entered the tunnel. This time gain can be significant if not life saving in a car fire, given that, according to firefighting experts, it takes about 2 minutes for flames to engulf an entire vehicle.

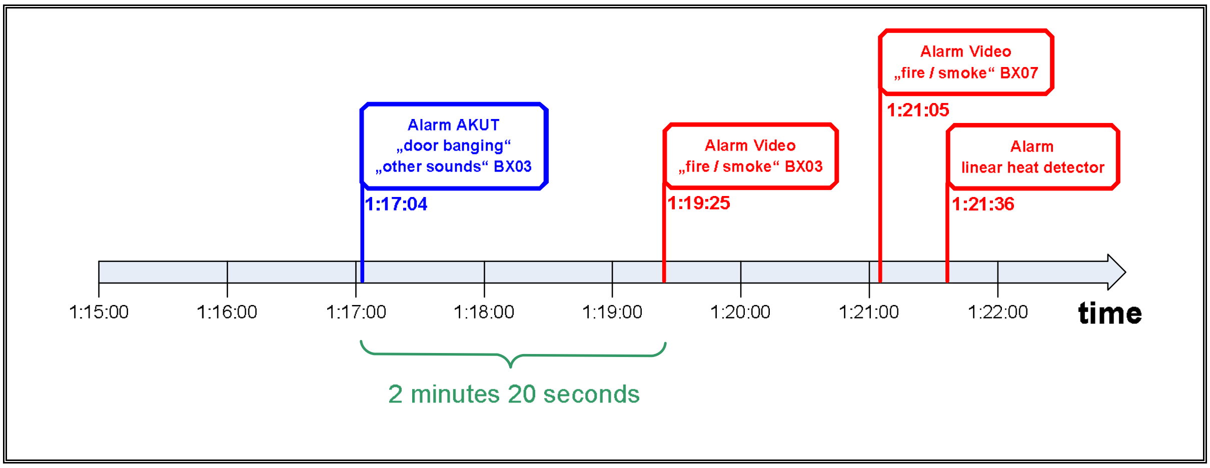

Figure 12: Alarm chain vehicle fire, 24/10/2010

13.2 Vehicle fire, 13 December 2010

A large fire engine broke down in the tunnel as a result of a drive shaft and transmission failure and immediately caught fire. Fortunately, the truck was followed by a small firefighting vehicle whose team used the extinguisher mounted in the tunnel to put out the flames. Despite the quick response of the trained firefighters the AKUT system detected the incident 43 seconds before the control centre received the signal that the fire extinguisher had been removed from its wall mounting. The alarm chain is shown in Figure 13.

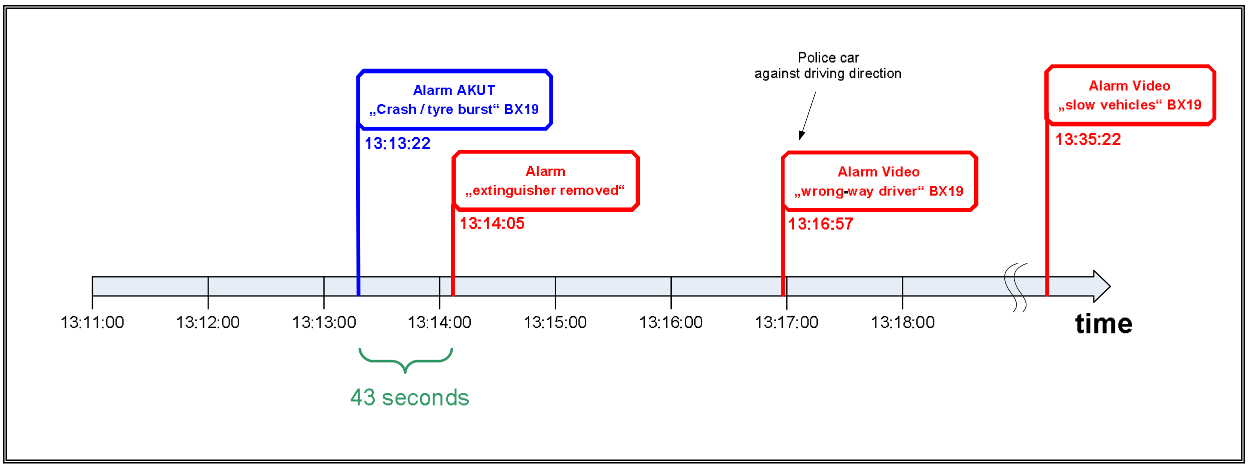

Figure 13: Alarm chain vehicle fire, 13/12/2010

13.3 Accident, 10 February 2011

The first accident in the Kirchdorf tunnel occurred on 10 February 2001 and was the first opportunity for the acoustic monitoring system to prove its worth in the event of an accident. As shown in Figure 14, the acoustic system triggered the alarm “crash/tyre burst” exactly at the time of the accident. The video surveillance system triggered the alarm “standstill” a full 2 minutes and 5 seconds later, after having detected that the vehicles approaching the scene had stopped due to the accident. This case clearly shows how the two systems work. The acoustic tunnel monitoring system detects the incident immediately (based on the crash sound), whereas the video system can detect the accident only indirectly based on the effects of the accident, i.e. that vehicles approaching the accident have come to a standstill.

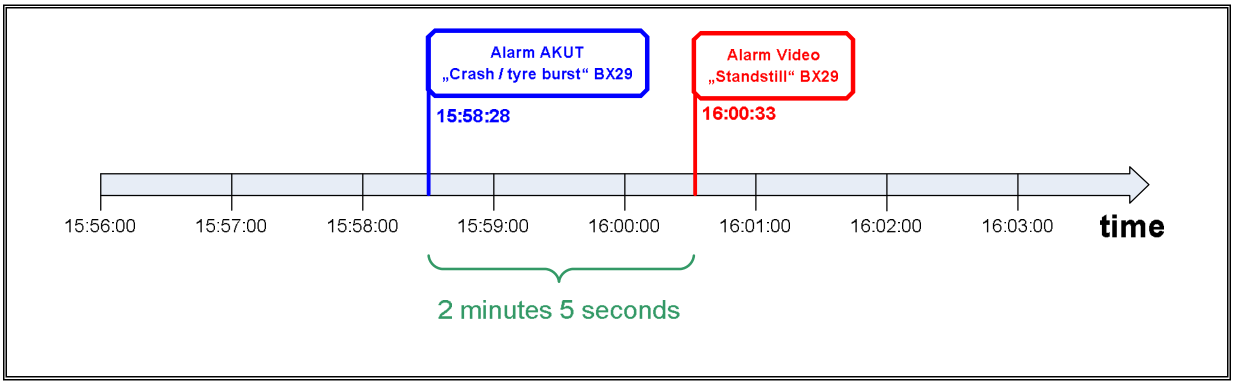

Figure 14: Alarm chain accident, 13/12/2011

13.4 Accident, 15 February 2011

Another accident occurred in about the same spot of the northbound tube only five days later. The acoustic system again detected the accident 35 seconds faster than the video system. This accident caused heavy smoke, which was detected relatively quickly by the video system and caused it to trigger the alarm “fire/smoke”. The acoustic system, however, triggered the alarm immediately upon capturing the crash sound, thus substantially reducing the response time of the emergency services. The alarm chain for the accident is shown in Figure 15.

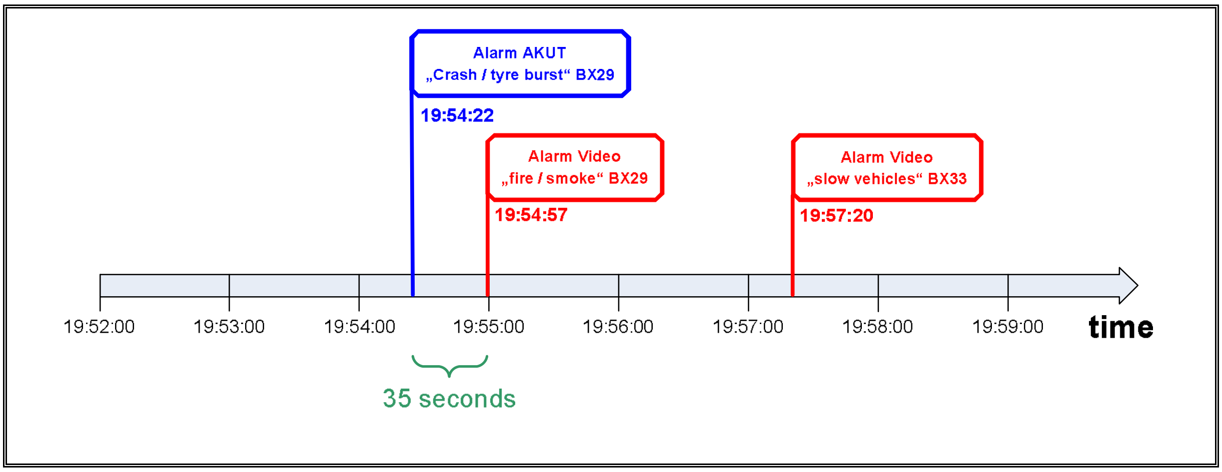

Figure 15: Alarm chain traffic accident, 15/02/2011

14 Summary

The acoustic tunnel monitoring system uses a new approach aimed at increasing tunnel safety. The great advantage of using acoustic methods in event detection is that the specific sounds associated with an incident are generated exactly at the time of occurrence and can thus be immediately (after approx. 0.25 sec) detected and reported by the AKUT system. As soon as an incident has been detected, the system provides the tunnel operator with all information required to assess the situation within seconds, enabling him or her to take appropriate measures within the shortest possible time.

A further advantage is that the microphones installed in the tunnel enable communication with the persons involved in an incident. The audio signals also allow the tunnel operator to detect the presence of people in the tunnel and monitor the progress of the emergency services even in thick smoke, in conditions which render video cameras "blind".

The AKUT system is the first acoustic tunnel monitoring system to be installed worldwide. It is in operation in the Kirchdorf tunnel on the S35 motorway and is fully integrated in the traffic management system of the tunnel control centre (Bruck/Mur). AKUT is equipped with all elements required for smooth and efficient operation under regular tunnel conditions. A total of 49 microphones have been installed providing an "acoustic image" of the tunnel in real time.

The first accidents and vehicle fires in the Kirchdorf tunnel have shown that the acoustic tunnel monitoring system detected all incidents, without exception, faster than the regular safety systems. The maximum time gain so far has been 2 minutes and 21 seconds, which in the event of a fire or an accident can mean the difference between life and death.

In future, it is planned to synchronise video and acoustic monitoring and combine the detection results of both systems to further enhance detection stability, thus making a valuable contribution to increasing safety in Austrian road tunnels.

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