Ventilation concepts for the Northern Ring Road Zurich

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ABSTRACT

The Northern Ring Road Zurich, commissioned 1995, is one of the highway sections with the highest traffic volumes in Switzerland. This leads to extended daily congestion episodes. An important effort for increasing its traffic capacity is in progress. Particularly relevant in this effort are the existing cut-and cover tunnel Stelzen, the new cut-and-cover tunnel Katzensee and the Gubrist tunnel, with two existing tunnel tubes and the new 3rd tube. This paper summarizes the ongoing effort from the point of view of tunnel ventilation, as a representative and innovative example for the Swiss practice.

1 INTRODUCTION

The Northern Ring Road Zurich (NRRZ) is part of the A1 motorway, which follows Switzerland's main east-west axis. The motorway connects Switzerland's largest cities of St. Gallen, Zurich, Berne, Lausanne and Geneva. The Northern Ring Road plays therefore a key role for national and international mobility and good transportation and is one of the highway sections with the highest traffic volumes in Switzerland. About 120'000 vehicles transit through the NRRZ on workdays. About 80% of them are commuters between the agglomerations of Berne and Zurich, the dominant political and economic poles of Switzerland. This leads to extended daily congestion episodes (345 days in 2017), to increased travel times and higher levels of risk.

An important effort for increasing traffic capacity is in progress. From the point of view of tunnel ventilation, the key elements of this ongoing effort are:

- Modernization of the cut and cover tunnel Stelzen (380 m, natural ventilation)
- Construction of the new cut and cover tunnel Katzensee (580 m, longitudinal ventilation)
- Construction of the new 3rd Gubrist tube (3.4 km, longitudinal ventilation with concentrated smoke extraction in case of fire)
- Modernization of the existing 1st and 2nd Gubrist tubes (3.4 km, longitudinal ventilation with concentrated smoke extraction in case of fire).

All tunnels are generally operated with unidirectional traffic. Exceptions are allowed under very special conditions, in particular during refurbishment of the 1st and 2nd tunnel tubes. The overall requirement in terms of safety is that at no time the safety level of the NRRZ shall be lower than the one characterizing normal operation before works.

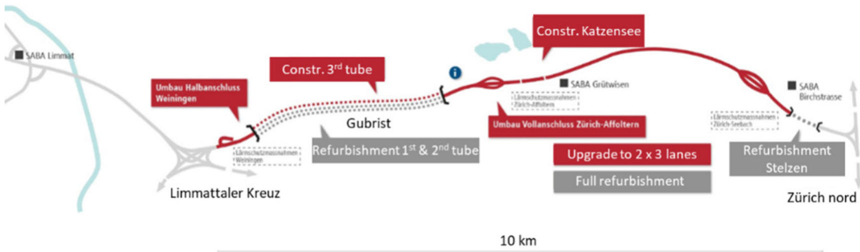

Figure 1: Overview of the ongoing works on the NRRZ (Source: FEDRO).

The general timeline of the NRRZ is as follows:

• Refurbishment of tunnel Stelzen:	2016 - 2019
• Construction of tunnel Katzensee:	2016 - 2020
• Construction of 3rd tube Gubrist:	2016 – 2023
• Refurbishment of 1st and 2nd tube Gubrist:	2023 – 2027

The total investment is in the range of 1.5 Mia. Euro (reference 2008).

The wide range of tunnel characteristics will be used for illustrating the general characteristics and peculiarities of tunnel ventilation in Switzerland. Related relevant topics, such as emergency exits, congestion and fire detection, shall be illustrated as well.

2 REGULATIONS

2.1 Ventilation system

The relevant Swiss national regulations for tunnel ventilation and fire detection issued by the Swiss Road Authority FEDRO ("ASTRA" in German) are:

- ASTRA 13001: Ventilation of road tunnels (1)
- ASTRA 13002: Ventilation of safety galleries (2)
- ASTRA 13005: Fire detection (3)
- ASTRA Technical manual on equipment (4)

The selection of a ventilation system according to ASTRA 13001 depends primarily on traffic characteristics and tunnel length. Secondary criteria are traffic volume, percentage of HGV and longitudinal slope. It is important noticing that the requirements for tunnels with high congestion frequency, such as the NRRZ, are similar to the ones relevant for bidirectional traffic. In both cases vehicles could be blocked on both sides of the fire. This represents a potentially critical situation in terms of smoke management, particularly in case of longitudinal ventilation. Compared with international regulations, the maximum allowable length, for which a longitudinal ventilation without smoke extraction can be applied in Switzerland, 2 to 3 km in case of low congestion frequency, is short. Both the selection of the ventilation system and its design are carried out accounting for unidirectional traffic, but ventilation control fully accounts for exceptional conditions with bidirectional traffic.

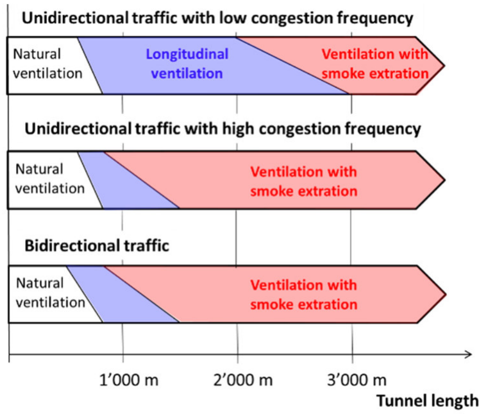

Figure 2: Selection of ventilation system according to ASTRA 13001.

A fundamental principle of ventilation design in Switzerland (1) is that ventilation design is carried out based on the usual operating mode, uni- or bidirectional traffic. Exceptional conditions, such as bidirectional traffic in double-tube tunnels or congestion in tunnels with low congestion frequency, are accounted for at the operational level. This generally implies that specific ventilation scenarios are defined and implemented in the ventilation-control software for all relevant conditions. Most scenarios run in a fully automated manner. Manual interventions by the operators are almost completely prevented.

In Switzerland, a dedicated mechanical ventilation of cross connections between two tunnel tubes is required only in very special cases (2). Cross connections are generally equipped with two fire-protection doors. In case of doors in the separating walls between two cut-and cover tubes, such as Katzensee, a single fire-protection door is used. The minimum fire-protection level is EI 30. Smoke penetration into the safe tunnel tube is prevented by means of an appropriate overpressure created using the ventilation system of the safe tube. Flow reversal is the safe tube is used for preventing portal smoke recirculation. Additionally, ASTRA 13001 (1) requires structural measures like separating walls, as shown in Figure 3.

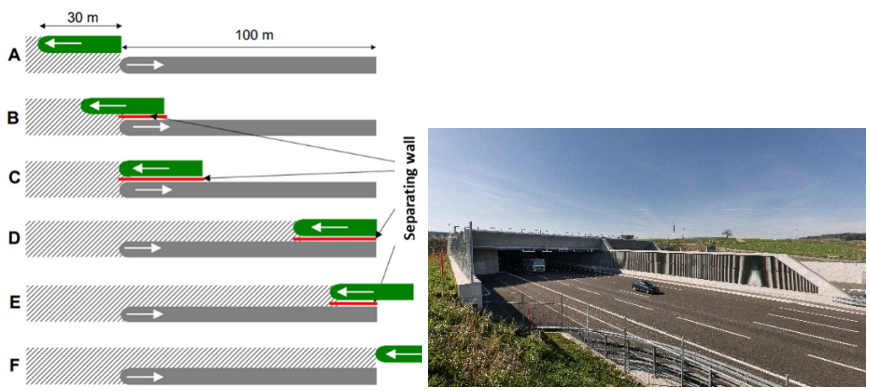

Figure 3: General principles of prevention of smoke recirculation at portals (1) and implementation in tunnel Katzensee (Source: FEDRO).

2.2 Ventilation sensors and fire detection

Sensors for air quality are limited to opacity. Additionally, CO should be monitored, if the analysis for normal operation shows, that this is necessary. NOx measurements are not required in Switzerland, since the composition of the national vehicle fleet ensures, that the thresholds for NOx are satisfied if the thresholds for opacity and CO are satisfied (1).

The measurement of air velocity is based on the concept of using at least two redundant, fully integrated velocity measurement locations, each of them consisting of three measurement points (either diagonal velocity measurements through the tunnel cross section or pairs of point sensors installed on each side of the tunnel) (4). The use of three measurements per station ensures that a full plausibility check and averaging can be carried out. The use of two measurement stations generally allows having at least one station outside the smoke-propagation range.

Fire detection in Switzerland is required for all tunnels equipped with a mechanical ventilation or other safety equipment for the fire case. Additionally, the need for a fire detection system shall be investigated for all tunnels longer than 300 m. Fire detection is based on the combined use linear thermal detection and smoke detection. This allows for rapid detection of all likely fire characteristics, including slowly developing fires generating substantial amounts of smoke but with low heat-release rates. CCTV provides supporting information but is not used for fire detection. Smoke detectors shall be installed at a typical distance of 100 m. In case of ventilation systems with smoke extraction, smoke detectors are installed close to each smoke-extraction damper. In case of longitudinal ventilation with low congestion frequency, the distance between smoke detectors can vary between 100 and 300 m. Two sensor rows are required in tunnels with 3 or more lanes. In case of fire detection through smoke detectors, it is essential distinguishing between stationary and moving sources, which call for different reactions of the ventilation system.

Traffic congestion has generally a significant impact on ventilation control, particularly in case of longitudinal ventilation. Congestion detection is an emerging field, for which there is no predefined standard solution in Switzerland.

2.3 Emergency exits

The overall specifications for road-tunnel design, including minimum requirements on emergency exits, are specified in the Swiss national Tunneling norm SIA 197/2 (5). For cut-and-cover tunnels the maximum allowable spacing is 300 m. For mined tunnels, the maximum distance between emergency exits depends primarily on longitudinal slope and varies between 500 and 300 m. Significantly shorter distances are generally used in case of longitudinal slopes in the range of 5% or higher. For comparison, the EU-directive 2004/54/EC (6) specifies a maximum distance between emergency exits of 500 m.

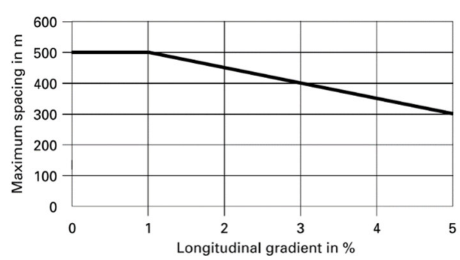

Figure 4: Maximum spacing of emergency escape routes for mined tunnels according to SIA 197/2.

3 TUNNEL STELZEN

The 380 m long cut-and-cover tunnel Stelzen was built between 1980 and 1982. It has two tubes with three traffic lanes each. The tunnel was completely renovated between 2016 and 2019.

The tunnel Stelzen is not equipped with a mechanical ventilation. This is in line with the requirements of ASTRA 13001 (Figure 2) and no modification was required. Important aspects of the renovation relevant for the purposes of the present paper are the extension of the antirecirculation walls at the portals and the integration of fire detection with smoke detectors. Because of the significant width of the tunnel tubes, point smoke detectors were installed in two rows, one over the right and one over the left lane. The staggered installation of the sensors, with a sensor distance of 100 m on each row, results in a smoke sensor every 50 m in longitudinal direction. This allows for a very rapid detection also in case of low-energy fires.

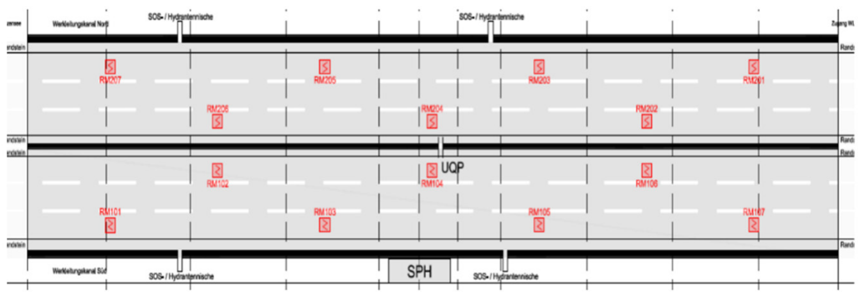

Figure 5: Location of smoke sensors in tunnel Stelzen.

4 TUNNEL KATZENSEE

4.1 Overview

The tunnel was created by covering the A1 motorway over a length of 580 m for reducing its environmental impact. This includes reducing noise emissions, better connecting both sides of the motorway and creating new green and leisure areas. Because of connections with the nearby rest area Büsisee, the northern tube has 4 lanes (including an emergency lane, total width 17.5 m), the south tube 5 lanes (including an emergency lane, total width 21.0 m). The longitudinal slope is small, 0.55%.

Because of its length and secondary evaluation criteria according to ASTRA 13001 (1) the tunnel Katzensee is located at the transition range between natural and longitudinal ventilation. Because of the high availability requirements, coupled with high congestion frequency, it was decided to realize a longitudinal ventilation. The tunnel was therefore equipped with ventilation sensors and fire detection.

4.2 Ventilation design

Ventilation design was carried out according to ASTRA 13001 (1). Normal operation results in virtually negligible requirements and shall be used only in very particular conditions characterized by long-lasting congestion episodes. Ventilation design was dictated by safety in case of fire.

Figure 6: Jet-fan battery in the Nord tube of the tunnel Katzensee (Source: FEDRO).

The jet fans are installed in two batteries installed in niches located roughly 80 m from each tunnel portal. According to the state-of-the-art, ventilation design is based on achieving the critical air velocity in the tunnels under all relevant conditions. This includes tunnel and vehicles drag, thermal effects (natural temperature differences between tunnel and environment and stack effect in case of fire) and pressure differences between the portals, resulting from (small) barometric pressure differences and wind effects. An additional key requirement results from the creation of an overpressure in the safe tunnel tube in case of fire, for preventing smoke circulation through temporarily open fire-protection doors during self-rescue and intervention.

A peculiarity of the Swiss 13001 is that a fixed value of 3.0 m/s is specified for the critical velocity. Since ventilation design is carried out based on a relatively low heat-release rate of 30 MW, this requirement ensures that adequate margins are provided with respect to the ventilation design velocity. Even in the case of very large fires, 30 MW are seldom exceeded during self-rescue. Redundancy requirements according to ASTRA 13001 were applied. In case of loss of one jet-fan battery due to fire, the remaining jet fans shall provide at least 90% of the total jet-fan thrust required. This results in this specific case in a particularly strong ventilation design. Since the jet fans are installed in two groups, accounting for the loss of one group leads to 100% redundancy.

The characteristics of the jet fans used are: wheel diameter 710 mm, min. static thrust 800 N, motor power 35 kW. The resulting number of jet fans is:

- Tube Nord: 6 jet fans at the inlet + 6 jet fans at the exit
- Tube South: 8 jet fans at the inlet + 6 jet fans at the exit

This ventilation design ensures full flexibility and robustness in both normal and emergency conditions.

Air-quality sensors are limited to 2 opacity measurements per tube, installed 80 m from each portal. Since air velocity measurements are not used for fire-ventilation control, the requirements according to ASTRA 13001 (1) (Section 2.2) could be relaxed. 3 diagonal ultrasonic sensors are installed about 200 m from each portal and in the centre of each tube.

4.3 Ventilation control

Ventilation in normal operating conditions is required only in case of prolonged congestion and bidirectional traffic. The ventilation-control procedures adopted are entirely conventional and do not call for specific remarks.

Ventilation in case of fire is complicated by an important requirement. In case of congestion downstream of the fire or bidirectional traffic, smoke stratification shall be preserved as much as possible throughout the self-rescue phase. For this reason, ventilation with the critical velocity and the activation of jet fans in zones with smoke are not allowable. This results in severe constraints on jet-fan activation in this short tunnel. A detailed analysis of all relevant scenarios was carried out based on 1D-simulation and CFD. This resulted in the identification of the fire locations for which the ventilation system cannot be activated without destroying the stratification of the hot smoke layer. These "forbidden" zones are illustrated in Figure 7. Tunnel sections around jet fan groups are marked red. Activation of jet fans for fire locations in the red sections will certainly lead to destratified smoke propagation, as smoke is conveyed through jet fans, or the turbulent jet impinges on the smoke layer. Yellow marked sections indicate fire locations from where smoke propagates into the influence areas of jet fans (red section), which will lead to destratified smoke propagation. The length of the yellow marked sections is dependent on time between start of fire and activation of jet fans. Figure 7 shows that the activation of jet fans would be problematic for about 85% of the fire locations in case of congested traffic. If activation of jet fans is delayed (2.5 minutes after start of fire), activation of jet fans will cause smoke destratification for all fire locations. For this reason, it was decided not to activate the jet fans in the fire tube in case of congestion downstream of the fire or bidirectional traffic. The analysis of the relevant fire scenarios with natural ventilation showed that smoke propagation due to natural ventilation is sufficiently slow and a good level of smoke stratification can be expected throughout the self-rescue phase under most relevant conditions. The situation was further improved by increasing the number of cross connections, as shown in Section 4.5. Congestion detection is discussed in Section 6.1.

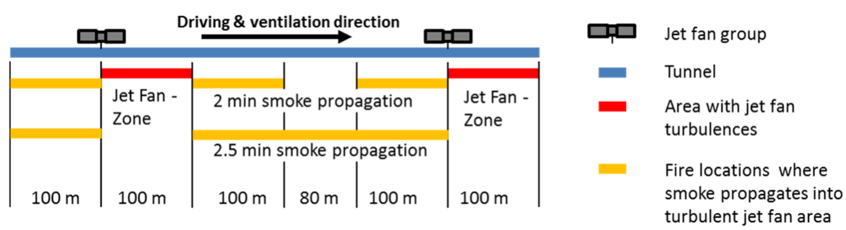

Figure 7: Illustration of fire locations where activation of jet fans would result in destratified smoke propagation for fan installation in the tunnel.

In case of fluid unidirectional traffic, the jet-fan battery located farther away from the fire is activated at full power in traffic direction. The ventilation of the parallel tunnel tube is carried out in a conventional manner. The objectives of generating a sufficient overpressure and reversing the airflow for preventing portal smoke recirculation are achieved by activating a variable number of jet fans in the appropriate direction, depending on fire location and traffic conditions. All ventilation strategies are programmed in the tunnel-ventilation control and are activated in a fully automated manner at fire detection.

4.4 Fire detection

The unusual aspect ratio of the tunnel Katzensee leads to extremely challenging conditions for thermal detection. For this reason, it was decided to deviate from ASTRA 13004 (3).

Thermal detection is not used, but a double row of smoke detectors is installed, with a maximum axial distance of 50 m between the sensors, analogously as for the tunnel Stelzen. This ensures a rapid detection of all relevant kinds of fires.

An important practical aspect is related to the characteristics of different smoke sensors. Because of different working principles and constructive details, smoke detectors from different manufacturers can perform in very different manners. In this specific case, the use of a more sensitive smoke detector model led initially to an excessive number of false alarms compared to the most widespread model. The calibration parameters were optimized during commissioning using smoke petards.

4.5 Emergency exits

In consideration of the large number of lanes, which can lead to an unusually large concentration of vehicles per unit tunnel length, it was decided to increase the number of cross connections from 1 to 3. This reduces the distance between emergency exits from 290 m (in line with the 300 m specified in the SIA 197/2 (5)) to 145 m. Detailed investigations of self-rescue coupled with smoke propagation could show that the resulting self-rescue times are in line with tenability times with natural ventilation.

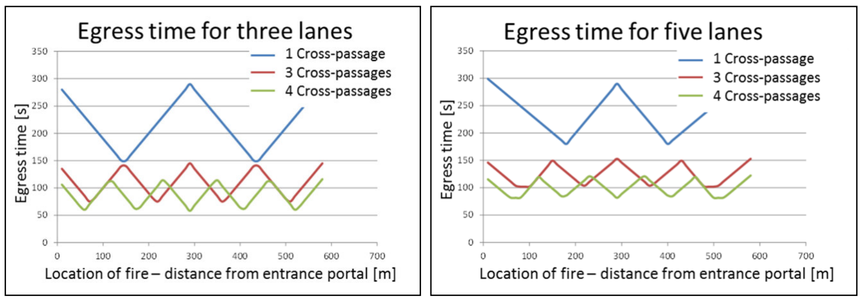

Figure 8: Total egress times as a function of fire location.

5 TUNNEL GUBRIST

5.1 Project overview

The Gubrist tunnel connects the NRRZ with the “Limmattalerkreuz”, where the A1 connects with the Western Ring Road Zurich and leads to the main north-south motorway A2. The two existing tunnel tubes, 3.3 km long, have two lanes per traffic direction. The construction of the 3rd tunnel tube represents the main element of the refurbishment project. In its final configuration the tunnel will provide 3 lanes in western direction and 2 + 2 lanes in eastern direction. With the construction of a new coverage at the western portal for environmental reasons, the three tunnel tubes will reach a length of 3.4 km.

5.2 Construction of the 3rd tunnel tube

5.2.1 Overview

The 3rd tunnel tube is in construction and shall be commissioned at the beginning of 2023. The tunnel has a total length of 3’405 m and a longitudinal slope of 1.3%. A technical duct is integrated in the lower part of the profile. The tunnel is generally used with unidirectional traffic in western direction. Bidirectional traffic is covered by the control system but allowed only exceptionally (e.g. refurbishment of the 1st and 2nd tunnel tubes) over short times.

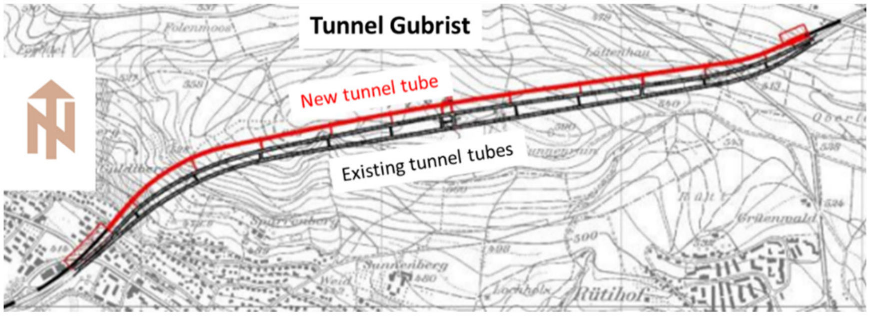

Figure 9: The 3 Gubrist tunnel tubes (3rd tube in red).

5.2.2 Ventilation design

According to ASTRA 13001 (1) (Figure 2), a ventilation system with concentrated smoke extraction is required. As a general rule, in Switzerland, the ventilation systems for each tunnel tube are independent from the other ones from both the mechanical and electrical point of view (1). The general layout of the ventilation system (Figure 10) is representative for the most recent ventilation standards used in Switzerland.

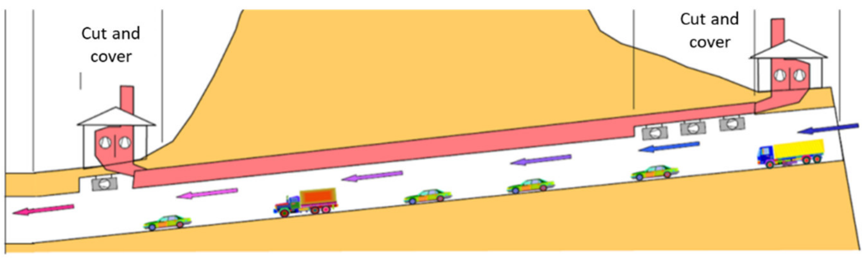

Figure 10: Layout of the 3rd Gubrist tunnel tube.

Ventilation stations are hosted at the two tunnel portals and can be accessed from the outside without disturbing the traffic in the tunnel. Each ventilation station hosts two exhaust fans in order to achieve a very high level of availability and redundancy. The exhaust duct has a cross section of 25.3 m^2, reduced to 12.7 m^2 close to the eastern portal for hosting the jet fans. The false ceiling and the exhaust duct are interrupted at the portal, over about 320 and 80 m. The jet fans are installed in the immediate proximity of the tunnel portals, smoke-extraction dampers are installed at regular distances of about 100 m. Special accesses located in the immediate vicinity of each damper provide access for quick maintenance during tunnel operation. Additional dampers are installed at both extremities of the smoke-extraction ducts. This allows for limiting the smoke-extraction length also in the vicinity of the portals. In normal operating conditions the tunnel is operated in a longitudinal mode. In case of fire, concentrated smoke extraction is activated through the nearest smoke-extraction dampers (generally 3).

The ventilation system is designed for a comparatively low heat-release rate of 30 MW according to ASTRA 13001 (1) but a high smoke-extraction rate of 4 m/s x tunnel cross section [m^2] is required. This results in a high smoke-extraction rate ranging from 302 m^3/s to 355 m³/s close to the easter portal. ASTRA 13001 also provides explicit specifications for accounting for leakages to the exhaust duct, developed based on extended experimental investigations:

$$q_{Leak\ dampers} = 3 \cdot 10^{-3}\sqrt{\Delta p} \quad in \;\; m^3/(s \cdot m^2)$$

$$q_{Leak\ structure} = 3 \cdot 10^{-4}\sqrt{\Delta p} \quad in \;\; m^3/(s \cdot m)$$

Additionally, the maximum underpressure in the smoke-extraction duct shall be limited to 2500 Pa, for reducing leakages.

A further important aspect of the Swiss ventilation design rules is represented by redundancy. The main redundancy requirements for ventilation systems with smoke extractions are:

- In case of loss of a smoke-extraction fan, the remaining units should achieve at least 65% of the nominal smoke-extraction rate
- If a damper does not open and smoke extraction is carried out through 2 instead of 3 dampers, at least 90% of the nominal smoke-extraction rate should be achieved
- In case of loss of a jet-fan battery due to fire, the remaining jet fans shall achieve at least 90% of the required thrust.

It is important noticing, that operation with reduced smoke-extraction capability is limited to 72 hours. This frequently leads to the installation of additional exhaust fans, or at least to the storage of spare units, which can be replaced in short time.

Because of the very high requirements on system availability and safety, in this specific case it was decided to increase the redundancy level. 100% of the required smoke-extraction capacity can be achieved also in case of loss of an exhaust fan. The main fan specifications are: flowrate 155 m³/s, static pressure 2.8 kPa, motor power 430 kW. All exhaust fans have variable pitch for optimum regulation of the start-up phase, but only two blade angles shall be used for steady fire operation, depending on fire location. This simplification increases the system's stability and robustness.

The longitudinal ventilation was designed for covering the requirements of normal operation and achieving an appropriate level of control of the longitudinal air motion in case of fire. It is important noticing that ASTRA 13001 provides explicit indications on the thrust due to natural temperature differences and fire "stack" effect, based on empirical data from Swiss tunnels and the fire test carried out in the Memorial tunnel. 4 groups with 3 jet fans are installed, with a motor power of 90 kW and an individual static thrust of 2290 N. The 6 jet fans installed in the groups closest to the portals are equipped with frequency converters, for achieving optimum thrust control.

5.2.3 Ventilation control

Ventilation control is fully automatic. Ventilation control in normal operating conditions is implemented in a conventional manner, with a regulation based on the measured visibility conditions. The principles of fire ventilation (fluid traffic) in case of fire with fluid unidirectional traffic are:

- Fire in the entrance zone without dampers: ventilation with 3 m/s and concentrated smoke extraction at the beginning of the false ceiling.
- Fire in the main range with smoke extraction: Concentrated smoke extraction using 3 dampers and air velocity of 3 m/s upstream of the fire.
- Fire in the exit zone without smoke extraction: Smoke expulsion through the portal with at least 2 m/s and no smoke extraction.

During congested traffic and in the exceptional case of bidirectional traffic, similar ventilation principles are used, but the airflow around the smoke-extraction zone is symmetric, with roughly 2 m/s. In case at the exit portal, smoke is expelled but the velocity is reduced to 1.5 m/s. Based on a specific test campaign (Section 6.1), it was decided detection congestion using CCTV.

Ventilation control is fully automated, based on traffic regime (uni- or exceptionally bidirectional), fluid or congested traffic, fire location and component availability. The resulting ventilation system for the three tunnel tubes is quite complex. For this reason, the control software will be extensively tested using a "digital twin". This is a full digital replica of the ventilation systems of the tunnel tubes and their control systems. All relevant ventilation scenarios will be simulated using appropriate inputs and the system's response verified in a systematic manner before implementation in the tunnel. This will allow for a more thorough testing procedure, which can be carried out in significantly shorter time. Particularly important is the significant reduction of testing time inside the tunnel and the drastically reduced risk of negative impact on the existing tunnel tubes, which will remain in operation throughout the testing and commissioning phase. Automatic test programs ensure that all components of the ventilation system can be periodically tested, and failures are detected immediately.

5.2.4 Fire detection and ventilation sensors
According to ASTRA 13001 (1), the tunnel is equipped with two separate systems for fire detection, linear thermal detection and smoke detection installed close to each smoke-extraction damper. Ventilation sensors include the measurement of air opacity at 6 axial locations, no CO monitoring and 3 redundant anemometer groups with 3 diagonal ultrasonic anemometers each. Congestion is detected through CCTV, see Section 6.1.

5.3 Refurbishment of the two existing tunnel tubes

5.3.1 Overview
The existing Gubrist tunnel was commissioned in the year 1985. Its ventilation system was refurbished 2010 for setting it in line with the current regulations. The next refurbishment of the 2nd tunnel tube will begin immediately after the 3rd tunnel tube is commissioned and the traffic will run through the 3rd and 1st tube. The refurbishment of the 1st tube will follow, with traffic running through the 3rd and 2nd tube. This allows maintaining the current traffic capacity in eastern direction during refurbishment. Selected safety-related issues during refurbishment are discussed in Section 6.2.

The existing tunnel tubes are conceived for unidirectional traffic but can also be operated with bidirectional traffic. This option was used so far in case of large incidents and maintenance. In the final situation both tunnel tubes will be operated in the eastern direction. The second tube will be conceived also for traffic in the western direction. Bidirectional traffic will be restricted to exceptional situations during refurbishment.

5.3.2 Ventilation design
Components and structure of the existing a new ventilation system are generally analogous as for the 3rd tunnel tube. An important difference is represented by the ventilation station located underground around the centre of the tunnel with a shaft and a ventilation stack on the surface. This solution allows reducing the number of smoke-extraction fans (two fans per tunnel tube, each designed for achieving at least 65% of the nominal flowrate in case of loss of the other one) at the cost of reduced accessibility from the outside. Jet fans are installed in the proximity of the two portals, for each tube 2 x 2 jet fans (wheel diameter 1250 mm, unit thrust 1630 N) at the western end and 1 x 6 jet fans (wheel diameter 710

mm, unit thrust 800 N) at the eastern portal. Otherwise ventilation design is generally in line with the 3rd tunnel tube.

An important question concerns the renovation option for the existing mechanical components, which are generally well within their useful life span, but which should be able reaching the next periodic refurbishment period. This is related to the general FEDRO maintenance philosophy "UPlaNS". Refurbishment of national motorways is carried out on sections with a length of about 5 km in such a way, that no further intervention shall be needed in the following 15 years. Accordingly, it was decided to carry out an extensive maintenance on the smoke-extraction fans and dampers. This shall be carried out at the contractor's workshop. All further components, in particular jet fans and sensors shall be replaced with new components. Power supply and the control system shall be completely renovated as well.

5.3.3 Ventilation control

Ventilation control for the 1st and 2nd tunnel tubes is carried out along similar lines, as for the 3rd tube. Self-rescue is carried out towards the nearest tunnel tube, in the case of the 2nd tube either the 1st or the 3rd tube. The uncommon combination of 3 tunnel tubes results in a significantly more complex interaction between the tunnel tubes in case of fire. The 3 tunnel tubes are immediately closed, and fire ventilation is activated. The ventilation of the safe tubes is always activated in order to achieve an overpressure with respect to the fire tube (2). An overpressure is established in all relevant cross connections and, in case of smoke exiting from a portal, the ventilation is directed towards this portal in all tunnel tubes. More complex interactions occur during the refurbishment of the different tunnel tubes, as discussed in Section 6.2.

6 SPECIAL TOPICS

6.1 Congestion detection

Traffic congestion has a significant impact on ventilation control for the three Gubrist tunnel tubes and in particular for the new tunnel Katzensee. As discussed in Section 4.3, the activation of jet fans in the tunnel Katzensee would almost certainly lead to smoke destratification during the self-rescue phase. This would endanger the escaping persons in an unacceptable manner. In the case of the Gubrist tunnel, the standard ventilation mode for fluid unidirectional traffic (with a longitudinal air velocity of 3 m/s upstream of the smoke-extraction range) provides an optimum level of protection for the users blocked upstream of the fire. Best-possible conditions for self-rescue and intervention in case of bidirectional traffic (exceptional situation) or congestion are achieved with symmetric flow towards the smoke-extraction dampers. The different ventilation-control principles are implemented in the ventilation-control system. The correct, automatic activation of the corresponding ventilations scenarios requires a reliable congestion detection.

Congestion in road tunnels is generally detected in a routinely manner for the purposes of traffic management. It can be monitored by means of CCTV, inductive loops or point detectors (e.g. optical, ultrasonic, or infrared). Recently, new radar-based technologies are becoming available on the market but have so far hardly been implemented for detecting traffic congestion in road tunnels. The requirements resulting from the activation of the most appropriate fire-ventilation scenarios are entirely different from the needs of traffic management, both in terms of time delay and detection parameters. Fire ventilation requires a very rapid detection of congestion and a good localization accuracy (only congestion downstream of the fire location is relevant for ventilation control). Furthermore, even a few vehicles at rest or moving at speeds lower than 10-20 km/h are relevant for self-rescue. An additional safety-relevant aspect is the availability of a ventilation-own system, less prone to errors e.g. during maintenance or refurbishment.

In the framework of ventilation design for the NRRZ, existing technologies were initially assessed in a qualitative manner. The open literature was investigated, and several experts were consulted. The findings pointed out many open issues with a high level of relevance for ventilation design and operation. For this reason, an experimental campaign for comparing and assessing three potentially viable technologies was carried out between June 2015 and February 2016 in the first tube of the Gubrist tunnel (direction St. Gallen) over a length of 1.4 km. The following systems were tested: traffic counting devices (multi-technology point traffic sensors), CCTV and newest-generation radar sensors (7).

The detailed investigation showed that the new radar technology provides very rapid, reliable and accurate congestion information. Its main advantage is its virtually complete independence of meteorologic and light conditions. The system performs in an excellent manner also in case of rain, fog or unfavourable light conditions at the portals. On the negative side, system setup, optimization and testing were significantly more work-intensive than in the case of CCTV. The extensive testing also allowed assessing the effective detection range in a tunnel, which showed a significant asymmetry, 400 m in traffic direction and 100 m against it. The radars installed in the tunnel Katzensee could be tested very extensively during the different construction and commissioning stages. The system proved very sensitive to small objects in the tunnel, such as cones for lane delimitation or closure in case of tunnel inspection and maintenance. Under such conditions, all temporary elements installed in the tunnel tend to generate spurious congestion signals, unless a new background “image” of the tunnel is generated.

CCTV provides, if properly calibrated with the correct parameters, a similar detection quality. Not surprisingly, detection quality significantly deteriorates in case of rain resulting in wet roadway and foggy conditions, as well at the portals. An additional difficulty is represented by the unusually large aspect ratio of the tunnel Katzensee. Points sensors proved to be much less reliable for this specific purpose, resulting in slow or missed detection of relevant congestion episodes and low spatial resolution. Their performance is not adequate for the purposes of ventilation control.

Based on the results of this test campaign, it was decided to implement a radar-based solution in the Katzensee tunnel and a CCTV-based solution in the Gubrist tunnel. The main reason is that adverse environmental conditions have a much larger impact on the short Katzensee tunnel, where congestion detection has a much more significant impact on ventilation control. The more conventional CCTV solution was deemed adequate for the Gubrist tunnel, which is significantly less demanding from these points of view. The radar solution installed in the tunnel Katzensee is now operated since 2020.

6.2 Ventilation control and self-rescue during works

The renovation of the tunnel Stelzen was carried out under traffic, since no traffic deviation was possible. The intense traffic volumes allowed for the closure of only one lane. Renovation started from the north tube, followed by the south tube. Lane by lane, first partition walls were erected, then the blocked lane was structurally renovated and finally the technical equipment was installed. Stringent prescriptions of the working site resulted in a safe operation throughout the renovation.

The conditions during the realization of the new tunnel Katzensee were very different. The cut-and-cover tunnel was built covering the existing highway and resulted in several intermediate stages in terms of traffic conditions and ventilation. The north tube in direction Bern was built fist, and traffic was led on two lanes per direction on the open air. During the construction of the south tube, the north tube was operated (after comprehensive testing and commissioning) with bidirectional traffic with two lanes per traffic direction. The 3 emergency exits were available throughout the construction stages. They led to the construction site of the south tube. Special safety measures were implemented for ensuring a safe self-rescue and intervention in case of relevant incidents in the tunnel or on the construction site. Specific acoustic and visual signals as well as alarm buttons were installed in the construction site. The ventilation of the north tube was fully available for normal operation but was not active in case of fire, as discussed in Section 4.3. The tunnel Katzensee was completed and commissioned at the beginning of 2020.

Several intermediate stages characterize the commissioning of the 3rd Gubrist tunnel tube and the subsequent refurbishment of the existing tunnel tubes. After commissioning of the 3rd tunnel tube, the traffic in eastern direction will run initially through the 1st tunnel tube while the 2nd one is renovated and vice versa, once the refurbishment of the 2nd tube is completed. This leads to a number of different situations, requiring different self-rescue, intervention and ventilation-control procedures. The discussion of this very complex topic shall be limited to a few selected aspects.

Prior to the renovation of the 2nd tube, the 1st tube must be closed for about 4 weeks for installing temporary cabling. During this period, the 2nd tube needs to be operated with traffic in the eastern direction. This operational mode is not implemented in ventilation control. Adaptation of ventilation control for this short time was ruled out mainly because of the additional risks arising from the modification and testing of an existing software during tunnel operation. A thorough analysis allowed identifying as the best option the operation of the 2nd tube using the ventilation routines established for bidirectional traffic. As a further optimization, fire detection is blocked in the vicinity of the western portal, for preventing smoke blowout against the temporarily reversed traffic direction. One-dimensional simulation was used for showing that this temporary operation mode allows to achieve a safety level, which is very close to standard operation for all relevant scenarios.

During the renovation of the 2nd tunnel tube, located between the 1st and 3rd tube, self-rescue and intervention result in a direct interaction with the construction site. Similarly, relevant incidents on the construction site could have a direct impact on the safety of the traffic tubes. This requires a careful planning at several levels. The interaction between tunnel operation and construction site in normal and emergency conditions is managed along similar lines as for the tunnel Katzensee and shall not be discussed here. From the point of view of ventilation, since the construction site acts as safe tube, a temporary pressurization system is required for preventing smoke penetration through the emergency exits. This is carried out using temporary walls closing the tunnel entrances and axial fans pressurizing the whole 2nd tube in case of emergency.

During the renovation of the 1st tunnel tube, located south of the 2nd and 3rd tube, self-rescue and intervention can use the opposite open traffic tube and can be carried out in a quite conventional manner. The construction site can be isolated in an effective manner and has a limited impact on the safety of the tunnel in operation.

6.3 Ventilation testing

The test of the complex ventilation routines is significantly complicated because of the complex interaction between the tunnel tubes in case of fire. All safety-relevant functionalities for each tunnel tube shall be systematically verified without impacting the safe operation of the other tunnel tubes and the whole system shall be able to react in case of a real emergency. Further complicating is the combination of new and old ventilation-control system, implemented on a different hardware by different contractors. For this reason, a thorough verification of all ventilation control routines is carried out in a fully digital manner before implementing them in the tunnel, using a digital twin. This reproduces in full detail the whole ventilation control system and runs the ventilation-control routines on an emulated hardware.

6.4 Redundancy concepts for high availability

Very high availability and safety are key requirements for this essential traffic artery. Traffic closures shall be strictly limited, and maintenance shall be carried out under traffic and without reducing the safety level. A thorough analysis was carried out for identifying all safety-relevant elements, all possible modes of failure, minimum conditions for safe operation and measures required for achieving a very high availability level. A selection of the steps undertaken shall be mentioned here.

- Fully independent ventilation systems for each tunnel tube.
- High level of fan redundancy for both smoke-extraction and jet fans. The redundancy level in case of loss of a smoke-extraction fan is 65% (spare fan and additional blades available) in the 1st and 2nd tube, 100% in the 3rd tube.
- High level of power supply redundancy.
- Direct accesses from the traffic room to each smoke-extraction damper, allowing for damper maintenance under traffic.
- Comprehensive analysis of possible compensating measures in case of partial or total loss of any relevant component of the ventilation system incl. e.g. smoke-extraction dampers, fans, jet fans, ventilation sensors, fire detection, congestion detection. These measures are implemented in the control software.
- Testing of ventilation control using a digital twin.

7 CONCLUSIONS AND OUTLOOK

The NRRZ is a key element of the Swiss national motorway system. The ongoing improvements will increase its overall capacity while reducing its environmental impact. The different construction stages result in complex and everchanging requirements on tunnel ventilation in order to provide a consistently high safety level throughout the whole renovation. From the point of view of tunnel ventilation, the different tunnels are representative for a wide spectrum of relevant characteristics, which was used for illustrating some key aspects of Swiss tunnel ventilation engineering.

REFERENCES

(1) ASTRA 13001, Richtlinie Lüftung der Strassentunnel – Swiss Directive on the Ventilation of road tunnels (in German).
(2) ASTRA 13002, Lüftung der Sicherheitsstollen von Strassentunneln - Swiss Directive on the Ventilation of safety galleries in road tunnels (in German and Frech).
(3) ASTRA 13004, Branddetektion in Strassentunneln – Swiss Directive on Fire detection in road tunnels (in German and French).
(4) ASTRA FHB BSA, Fachhandbuch Betriebs- und Sicherheitsausrüstungen – Technical handbook on equipment (in German, French and Italian).
(5) SIA 197/2:2004, SN 505 197/2, Design of Tunnels – Road Tunnels.
(6) Directive 2004/54/EC of the European Parliament & of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.
(7) M. Bettelini & S. Rigert, On the detection of traffic congestion and ventilation control, 9th International Conference 'Tunnel Safety and Ventilation' 2018, Graz.