ASPECTS OF LONGITUDINAL AIRFLOW CONTROL IN ROAD TUNNELS

Simon Frey, Matthias Lempp, Christina Zimmermann
HBI Haerter AG, Zurich, Switzerland

ABSTRACT

Whether a tunnel is equipped with a pure longitudinal ventilation system or a semi transverse ventilation system, the control of the airflow is crucial for the safety in case of a fire incident. The article focusses on all relevant aspects regarding the implementation of a fully functional airflow control system including target airspeed and upper/lower threshold, tunnel specific system design (fan / drive combination), airflow measurement including plausibility test and the corresponding control-system algorithms. The analysis is performed for a tunnel with congested traffic prior to the occurrence of the incident / with bidirectional traffic, both having a pure longitudinal ventilation system. The findings are also valid for semi-transverse ventilation systems.

First, the target airspeed as well as the maximum threshold (upper and lower control limit) are determined considering different design codes and best practices. With respect to this range, the impact of tunnel geometry (length, cross section, roughness) and traffic scenario (filling level, heavy goods portion) on airspeed increase / decrease for an individual jet fan is assessed. The temporal evolution of airspeed inside the tunnel is compared for different set-ups (i.e. variable speed drive versus direct-online technology). This allows for a good project specific choice of fan and drive technology regarding airflow control.

Besides the actuators (jet fans), an appropriate airspeed measurement is vital for a fully functional airflow control. Regardless of the effective measurement technology (i.e. transversal measurement, pointwise measurement), a plausible value must be available to initiate the control process and to achieve/maintain the target airspeed. A novel plausibility test is presented as well as some general advice for its practical implementation. The article also presents a summary of the state-of-the-art control algorithms and some pitfalls typically encountered in practice.

Keywords: Tunnel safety, jet fan, variable speed drive, DOL, star-delta starting, air velocity measurement, plausibility test, ventilation control

1. INTRODUCTION

Smoke management is one of the key points to maximise the safety of the tunnel users involved in a fire incident. When discussing the smoke propagation in presence of a longitudinal airflow, keywords are critical velocity, back-layering and stratification.

In tunnels with unidirectional traffic without regular traffic congestion, smoke management is rather straightforward, as the primary goal is to keep the upstream portion of the tunnel smoke free. Thus, the longitudinal ventilation system must be able to generate airflow velocities larger than the critical velocity. Whilst the airspeed remains moderate (i.e. up to 5 m/s), no particular airflow control system is needed.

Otherwise, if tunnel users are expected to be on both sides of the fire (e.g. bidirectional traffic, congested situations), this kind of ventilation would be disastrous. In such a tunnel, the smoke management must account for the back-layering upstream of the incident position as well as for the airflow downstream of the fire. Hence, the desired airspeed must be significantly lower than the critical velocity. As, in general, deviations from the chosen target airspeed should be avoided and as some governing aspects (ambient conditions, buoyancy effects etc.) may vary over time, an effective yet robust control system is required. This not only includes the control system itself but also suitable ventilation equipment (fans and airflow measurements).

As many interactions and side effect must be taken into account, holistic considerations are required to obtain a fully functional system. The article focusses only on pure longitudinal ventilation systems for tunnels needing airflow control (i.e. bidirectional traffic / congested traffic). Nevertheless, the ideas and findings can be translated to semi-transverse ventilation systems or systems with pointwise smoke extraction and longitudinal flow control.

2. TARGET AIRSPEED AND THRESHOLD

When defining the target velocity for longitudinal smoke management in tunnels with bidirectional traffic or tunnels prone to congested traffic, multiple aspects must be considered: limitation of back-layering upstream of the incident, possible destruction of stratification (downstream of the fire), smoke-propagation speed in conjunction with egress speed and dilution of toxic substances / hot gases.

The different design codes are in quite good agreement regarding the target airspeed. It can be deducted that the ideal airspeed for longitudinal smoke management for bidirectional / congested traffic situations shall be 1.2 m/s. According to the Austrian RVS [1] and German EABT [2] the longitudinal air velocity must be in between 1.0 m/s and 1.5 m/s. According to the French Dossier Pilote [3], the airspeed must be limited in between 1 m/s to 2 m/s. The Swiss FEDRO guidelines and implementation instructions [4], [5] state that the system must be designed for 1.5 m/s but operated at 1 m/s. [6] refers to an optimal velocity of 1.2 +/- 0.2 m/s, as turbulence is low and stratification is accentuated by limiting the dilution of hot gases.

As an alternative to the above values, one can determine the allowed airspeed range based on safety considerations (e.g. the maximal airspeed maintaining stratification) and additional thresholds given by the actual ventilation system (e.g. measurement uncertainty). According to [6], air speeds lower than 0.5 m/s lead to increased concentrations of toxic gases and to high temperatures close to the fire. Hence, velocities lower than 0.5 m/s must be avoided. Furthermore, this limit allows to reliably avoid an inversion of airspeed. The effective limit has to account for measurement uncertainty, signal processing times, discrete controls as well as for the inertia of the system itself. Therefore, the lower limit of airspeed must be at least 0.7 m/s. Regarding the upper threshold, no clear limit can be identified in literature, as there is a transition zone in between stable stratification and its destruction. According to [3], destratification occurs, in case of a truck fire, at airspeeds of about 1.5 m/s to 2 m/s. For smaller fire loads, stratification will be destroyed at even lower speeds as buoyancy forces are less pronounced. Another indication for maximum airspeed is given by the evacuation speed of tunnel being about 1.5 m/s. In conclusion, for the sake of safety, an airspeed of 1.5 m/s must not be exceeded. When considering the multiple side effects e.g. measurement uncertainty, inertia etc. the maximum allowed airspeed for the ventilation system must be 1.3 m/s. So, the identified airspeed range for smoke management in bidirectional / congested tunnels is 0.7 m/s to 1.3 m/s. On one hand, this appears to be slightly lower than the values given by the cited design codes but represents a more robust solution regarding destratification, on the other hand, the allowed range is slightly larger and therefore easier to respect.

3. MODULATION OF THE AIRFLOW BY JET FANS

To maintain or modify the airflow in a tunnel, most of the time a force needs to be exercised. The force needed to obtain a specific airspeed is related to the difference between the airflow that would naturally occur and the desired airflow. In longitudinal ventilation systems, this force is usually produced by jet fans. The velocity change caused by a jet fan is mostly depending on the developed thrust, the initial air velocity and the overall resistance to the flow (tunnel geometry, losses due to vehicles). Figure 1 (left figure) shows the temporal evolution of airspeed caused by two different jet fans (thrust 500 N and 1000 N) in a 1000 m long, two lane (cross section 58 m^2) tunnel for two different filling levels (0% and 50%). The calculation assumes an initial velocity of 0.5 m/s. On the right, the figure shows the impact of filling-level and HGV-portion on the maximum velocity (95%-value) obtained by the 1000 N jet fan as well as the corresponding time needed to accelerate the flow. Variation is from 0% filling level to 100% filling level i.e. 100% HGV.

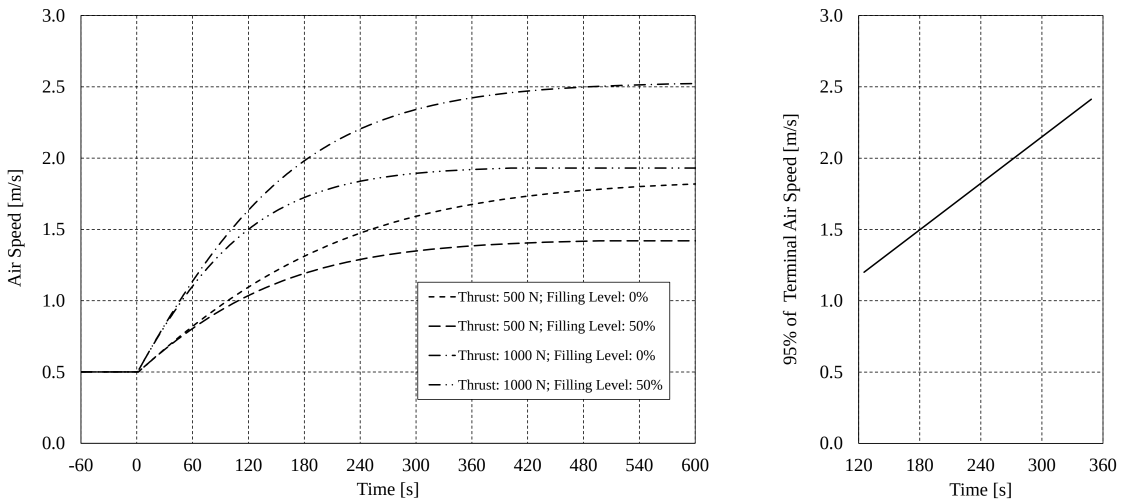

Fig. 1: Left: Velocity evolution induced by different jet fans in a tunnel (1000 m, two lanes) for zero vehicles and a filling level of 50%. Right: Variation of maximum velocity (95%-value) and of corresponding acceleration time as function of resistance due to vehicles (filling level varying from 0% to 100%).

The following two formulas allow to calculate the resulting airspeed either as a complete, implicit calculation or as a simplified explicit calculation. The simplified approach considers an empty tunnel and typical values for the fan efficiency/montage factor, inlet/outlet-loss coefficients and tunnel friction factor.

$$u_2 = \sqrt{2\frac{(u_{jet}-u_2)Q_{jet}\eta_{jet}}{A_{Tunnel}\left(\lambda\frac{L}{D_h}+\zeta_{in}+\zeta_{out}+\zeta_{traffic}\right)}+u_1^2} \qquad u_2 = \sqrt{\frac{Thrust}{1.15\,A_{Tunnel}\left(0.01\frac{L}{D_h}+1\right)}+u_1^2}$$

When trying to achieve the desired airspeed range (see section 2), the quality (stability over time) as well as time needed to approach the airspeed range is governed by the unitary thrust and total number of jet fans as well as the type of drive. Ideally, the ventilation system would have infinite power being controlled specifically to meet the exact demand. Practically, the power is limited, can only be controlled to a certain degree (depending on the drive) and is subject to finite switching operations. The solution can be optimized by matching the jet fan size and its drive to the tunnel and the desired airspeed range.

Fans having a high thrust compared to the tunnel's resistance cause a fast change in air velocity and allow for a high total change in airspeed. This is ideal for quickly approaching the target airspeed. As a down-side, such fans require constant switching operations (considering a direct on-line drive) when trying to remain in the desired airspeed range, potentially harming the fan over time, what can be compensated by using other fans installed in the tunnel. As those fans may be in a less advantageous position regarding the smoke front and its propagation, their use may be unwanted. Also, jet fans with lower thrust require fewer switching operations, as their impact on the flow is small. This also allows for smoother airspeed once within the desired range. Unfortunately, the initial instauration of the desired airflow will take much longer even when using multiple jet fans, as their start-up times must be distributed over time to prevent the cumulation of start-up currents. Depending on the implementation of the control system, the delay in start-up can cause an undesired behaviour as the number of fans to start may be changed by the control system whilst not all of fans are activated, i.e. the cycle time of the control system is smaller than the activation of all fans (e.g. activating 10 jet fans with a 5 second delay needs 45 seconds).

Based on the above, powerful fans with variable speed drives appear to be the optimal solution, as they combine large power availability and control options. Nevertheless, such a solution has some disadvantages: electronics as additional source of failure, VSD heat dissipation, VSD harmonics, limitation in cable length and the larger space required for the installation of more powerful (bigger) jet fans. Dahlander (pole changing) motors allow for finer control as at the lower speed, i.e. 50% about 25% of the nominal thrust is available. On the other side, the logics of the control system tend to get complex and the number of switching operations tends to get even bigger than using direct on-line motors. Also, number of cables increase being an issue especially in refurbishment projects.

If one intends to use low level drives such as direct on-line without having to accept constant switching operations, the effect of one jet fan on the air flow should not exceed 50% of the allowed range (e.g. 0.3 m/s when considering the range determined in section 2). When accepting constant on/off operations, jet fans having higher thrust can be chosen. In such a case, one must pay attention to not exceed the maximum number of commutations (e.g. 6 starts within 60 minutes).

When accepting the flaws of variable speed drives, their use in combination with rather powerful fans appear to be the best solution regarding longitudinal airflow control. In any case, the optimal solution appears to be tunnel and owner specific as besides the aerodynamic aspects the compatibility of the drive with the energy supply system (start-up current, voltage drop, harmonics), the boundary condition in the technical rooms (space, HVAC) and cost do matter. In order to choose the optimal solution, this kind of analysis should be part of the system design.

4. ASPECTS OF FLOW MEASUREMENTS

For longitudinal airflow control, the traffic space must be equipped with velocity sensors. The measured data represents the input to the longitudinal airflow control algorithm. The sensors themselves should be capable of capturing all relevant airflow quantities within the traffic space as accurate as possible. However, turbulence produced by (circulating) vehicles makes the measurement an ambitious task. As soon as traffic slows down and eventually stops due to an incident, representative air measurement values are to be expected [7]. On the other hand, plausible values are essential at the moment of a fire alarm to enable the initiation of the ventilation system.

Sensors must be installed in groups of 3 in adjacent tunnel cross sections of the traffic space. Each cross section has 1 transversal measurement or 2 single point sensors (each placed on one of the side walls). Spacing the sensors at a distance of 15 to 20 m prevents an interaction in between the measurements and reduces the chance that all sensors are blocked / impacted simultaneously by vehicles. Figure 2 shows an installation example for transverse as well as pointwise airspeed measurements. State of the art velocity sensors use the doppler effect (ultrasonic technology) to determine the airspeed as well as the airflow direction.

According to the length of the tunnel several groups of sensors are installed. In a single tube tunnel velocity is measured at minimum by two groups of 3 measurements. This allows to select the measurement position with respect to the incident position whilst still having nominally 3 measurements for plausibility check.

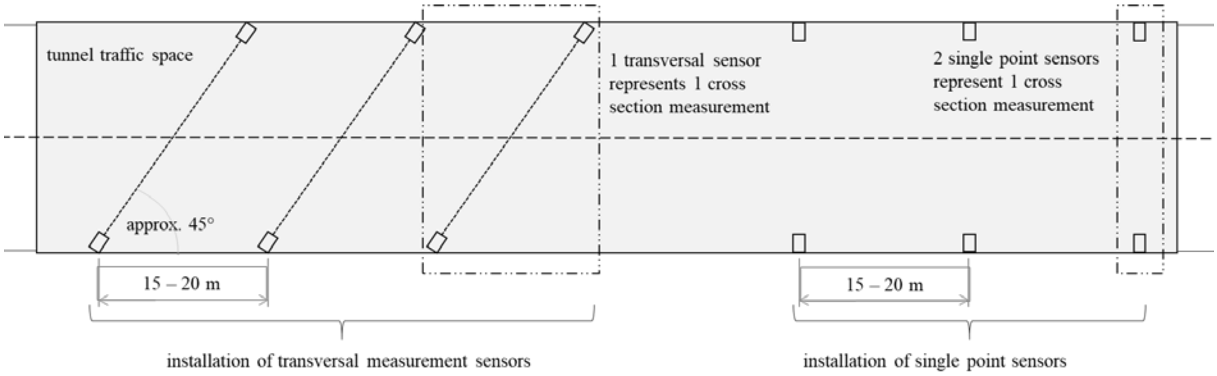

Fig. 2: Installation of velocity sensors in the traffic space of a tunnel

The raw data of the sensors is processed by time averaging and correcting the measurements for the representative airflow inside the traffic space. The correction factors consider the installation situation and are permanently stored in the PLC. During commissioning, the comparison of the measurement and the global airflow (reference airspeed) allows for calculating correction factors. To do so, a network measurement (e.g. with 36 sensors placed according to Log-Tschebycheff) is used. Figure 3 depicts these typical steps of signal processing. In addition, a plausibility check / the calculation of an average value per measurement position is performed.

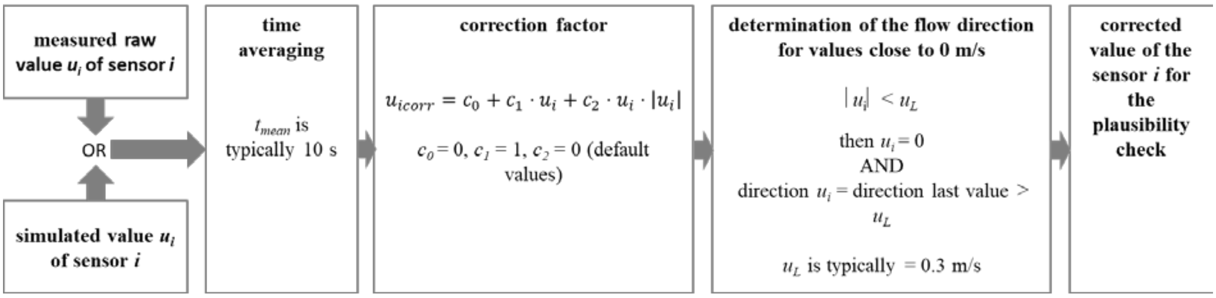

Fig. 3: Averaging and correction factors of measured velocity data for transversal sensors

Using the algorithm presented in Figure 4, the time averaged and corrected data is checked for plausibility and at the same time averaged. As an improvement to prior versions, the plausibility check is based on a dynamic tolerance as for high flow rates, an absolute tolerance suitable for airflow control at 1 m/s may be too restrictive. Furthermore, the algorithm allows to get rid of several if/else loops. To exclude measurements located in smoke, a parallel temperature measurement can be used.

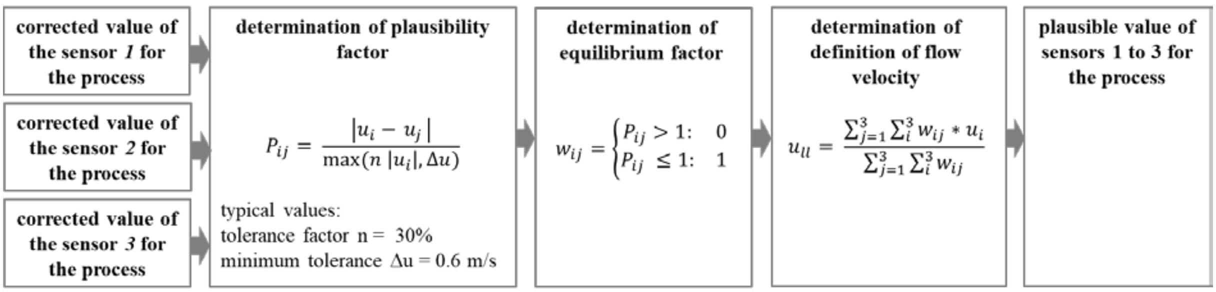

Fig. 4: Plausibility check procedure for airflow measurements

Without process values, a ventilation system with longitudinal airflow control will not start up properly. So, care must be taken when defining of Δu and $n\,|u_i|$. As guideline, Table 1 shows the availability of airflow measurement data as function of Δu and $n\,|u_i|$. The analysis was performed for measurement data from a bidirectional tunnel with traffic during a total of 6 hours. The analysis is performed for a measurement position consisting of 3 adjacent transverse measurements. Raw data is acquired every 2 s so in total, 10’807 values are available. As one can see that in that case, a valid airflow measurement is available during roughly 97% of the time if a minimum tolerance of 0.3 m/s and a tolerance factor of 0.3 are selected. We do recommend that such type of analyses is conducted to tune initial values one, sufficient data is available.

Table 1: Influence of the values Δu respective n on the availability of process data

	Δu [m/s]						
n [%]	0.1	0.2	0.3	0.4	0.5	0.6	0.7
10	31.4%	15.4%	6.1%	2.3%	0.8%	0.4%	0.1%
20	16.7%	10.3%	4.9%	2.1%	0.8%	0.4%	0.1%
30	10.2%	6.4%	3.3%	1.5%	0.6%	0.3%	0.1%
40	6.5%	4.2%	2.0%	0.9%	0.4%	0.1%	0.1%

Accuracy can be increased if those thresholds are reduced once the traffic is no longer moving inside the tunnel. Nevertheless, a fully functional airflow control must prime absolute accuracy.

In the experience of the authors, principle factors influencing the quality and availability of airflow measurement data are:

- Installation of the sensors free of obstacles and not influenced by irregular airflow. Jet fans or changes in the tunnel cross section may cause the latter.
- Proper commissioning and parametrization.
- Determination and documentation of the correction factors.
- Unappropriated choice of thresholds used for the plausibility check results in the exclusion of too much data and thus result in scarce availability of the ventilation system.

To ensure availability of process data as well as good accuracy of the airflow measurement, simultaneous plausibility checks are recommended. One delivering input data, suitable for the control system and another with smaller tolerances used once the airflow is sufficiently stable. The latter process also allows for detecting malfunctions of single sensors. To do so, times of low traffic volume can be used.

5. CONTROL ALGORITHMS

According to [8], model predictive control would be best for the control of the longitudinal airflow. At the same time, [8] concludes that a PI-type controller suites very well the actual needs whilst being a widely known and accepted principle. Nevertheless, the adjustment of the parameters of a PI controller is a challenging task. During the design and the commissioning, the following aspects should be considered:

Controllers with high resolution and quick response time do not imperatively lead to good results due to inertia of the air mass (approx. 132 t for a 2’000m m tunnel) and due to the time lag until the jet fan's thrust acts properly on the airflow.

The calculating of the parameters P and I for the PI controller according to Ziegler/Nichols has often shown adequate results. Whilst implementing those factors, attention needs to be payed to the use of the correct units as sometimes, the in pre-implemented controllers are based on specific units. Experimental determination or optimisation of the factors P and I is difficult, since two dependent factors are involved. Furthermore, experimental conditions can be unstable, which makes it difficult to interpret the results. If one still intends to do so, the experimental setup for the tests must be clearly defined and respected. Starting with a control offset of 3 m/s will result in a longer time until a stable condition is reached than starting from 0.5 m/s. Since no design code handles this fact, we suggest using an offset of 2.5 m/s for the test cases. The aim is then to reach stable conditions within 3 to 5 minutes.

Figure 5 shows for a tunnel with extraction system and longitudinal airflow control, a properly set-up PI controller and a suitable ventilation system (powerful jet fans equipped with VSD) allow to limit the deviation to the target speed to 10%. The figure also shows the capacity of the system to obtain an equilibrium state within less than 2 minutes after incident detection. The figure also shows that it is not required to delay the initiation of airflow control with respect to the extraction system as the control performs very well even during the start-up time.

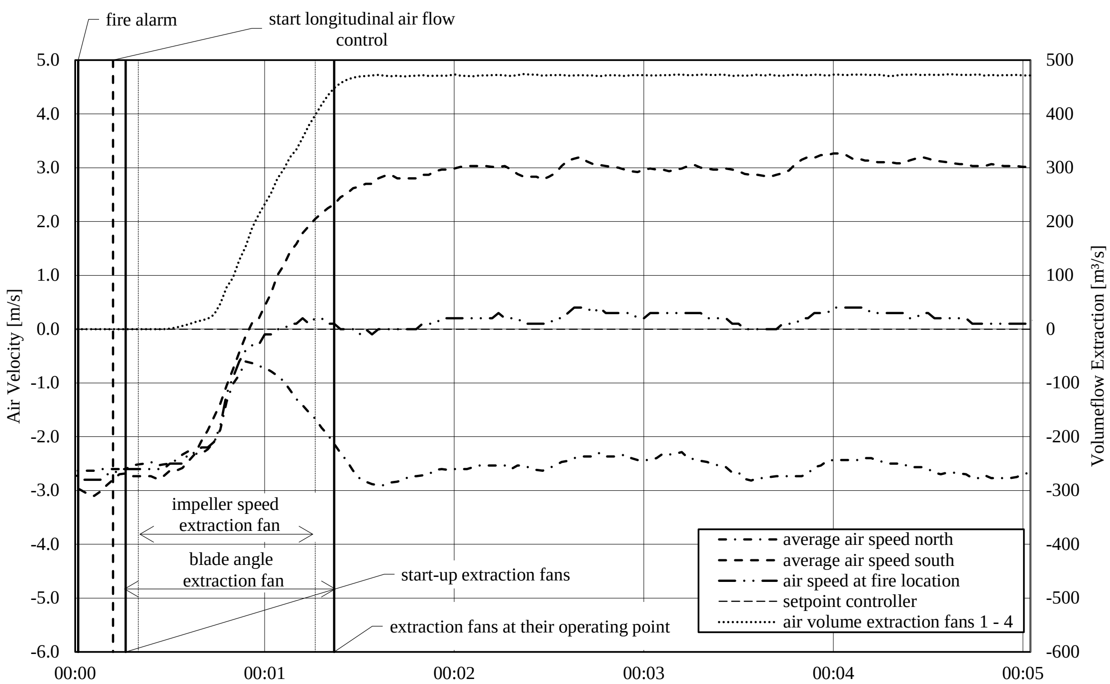

Fig. 5: Development of air speeds and extraction air volume flow for simultaneous start of extraction system and longitudinal air flow control. Starting from approximately -3 m/s airspeed, stable conditions are reached around 60 s after the ventilation system was started.

Recently, real time hardware in the loop systems have been developed enabling better testing of the control system. For complex projects with limited time for testing and commissioning on site, the use of such tunnel ventilation simulators combining a simulation of the aerodynamics including the interaction with the ventilation equipment of a tunnel with the real control system is beneficious.

6. SUMMARY AND CONCLUSIONS

In case of a fire incident in a bidirectional road tunnel or a tunnel with congested traffic, airflow control is vital for the safety of the tunnel users. The design as well as the implementation of such a system is demanding and multiple factors need to be considered.

First and foremost, the target airspeed hast to be defined, either based on design codes or based on safety and implementation considerations. We here conclude that for longitudinal smoke management in case of bidirectional traffic / congested traffic, the airspeed must be kept in between 0.7 to 1.3 m/s with an ideal value of 1.0 m/s.

The quality and the ease of the ventilation system to respect the target airspeed depends on the combination of tunnel geometry, jet fan size and drive technology. Whilst small fans can most often be of direct on-line type, such a solution may need many jet fans and will need much time to obtain the target airspeed. On the contrary, powerful jet fans will either be repeatedly switched on / off or must probably be equipped with variable speed drives as the airspeed increase due to the fan is much higher than the allowed airspeed range.

Besides the fans, a reliable and sufficiently precise input is needed for the airflow control system. Ultrasound airspeed measurements are most often used. But to match the needs for longitudinal airflow control, at least two measurement positions, each one with three independent measurements should be installed. To maximise the use, the measurement values need to be corrected to the effective flow rate inside the traffic space. When processing the measurement data, a plausibility check must be integrated when calculating the average airspeed whereas the threshold factors must to be chosen with care.

Regarding the control system, a PI-type controller as a state-of-the-art system suits very well the needs of longitudinal airflow control. The calculation of the P and I factor based on Ziegler/Nichols is recommended as an optimization of the parameters on site is quite tricky and no standards exist. In case of a properly designed system, the quality (i.e. speed, precision, and robustness) of the longitudinal airflow control is very high and therefore a real beneficial for the safety of a tunnel.

7. REFERENCES

[1] Österreichische Forschungsgesellschaft Strasse/Schiene/Verkehr, Richtlinien und Vorschriften für das Strassenwesen (2014). *RVS 09.02.31 Tunnel Equipment, Ventilation System.*

[2] Forschungsgesellschaft für Strassen- und Verkehrswesen, Arbeitsgruppe Verkehrsmanagement (2019). *Empfehlung für die Ausstattung und den Betrieb von Strassentunneln mit einer Planungsgeschwindigkeit von 80 km/h oder 100 km/h, EABT-80/100*.

[3] Centre d'Etudes des Tunnels CETU (2003). le dossier pilote des tunnels partie 4. *Ventilation.*

[4] Bundesamt für Strassen ASTRA. Richtlinie 13001 (V2.03 2008). *Lüftung der Strassentunnel*.

[5] Bundesamt für Strassen ASTRA (2020). *Fachhandbuch 23001 Betriebs und Sicherheitsausrüstung (FH BSA).*

[6] PIARC Technical Committee 3.3 Road Tunnel Operation (2011 R02). *Road Tunnels: Operational Strategies for Emergency Ventilation*.

[7] Grässlin, U., Nodiroli, G., Drost, U. (2013). *Airflow measurement in road tunnels*. Bundesamt für Strassen (ASTRA).

[8] Altenburger, P., Riess, I., & Brandt, R. (2013). *Control of longitudinal airflow in road tunnels in case of fire.* Bundesamt für Strassen (ASTRA).