Flow measurement for tunnel ventilation

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1 ABSTRACT

For tunnel ventilation, understanding the airflow in the tunnel is of utmost importance. For modern road tunnel ventilation systems with flow control, precise and reliable online measurement of the flow velocity is essential. Precise acceptance test flow measurements in ducts and tunnels validate the ventilation system design and fan performance, determine calibration factors for installed anemometers for the online measurement, and determine and validate controller parameters for flow control.

This paper describes methods for installed online flow measurements in tunnels, and temporary measurements for on site acceptance testing, compares resulting precisions and uncertainties, advantages and disadvantages, and challenges encountered in practice.

2 INTRODUCTION

Traffic tunnels are usually open on both sides, to not obstruct the traffic flow. That is a distinction from buildings and underground mines, which are or can be closed for traffic and flows. In building ventilation systems, the air stands still when the system is switched off and closed by dampers. In tunnels, there is mostly an airflow determined by meteorological conditions such as barometric pressure, wind on portals, and buoyancy. Moving traffic in the tunnel is often the most decisive force that influences the flow. In case of a fire, the fire dynamics may become determinant. Those forces are generally unpredictable. An operating mechanical ventilation is only one of the factors that influences the airflow. Thus, the airflow in a tunnel is a random variable. Operating a ventilation system without measuring the resulting flow in the tunnel is uncertain and may lead to unacceptable conditions, see e.g., (10), (18).

Operating a tunnel ventilation without measuring the airflow in the tunnel is like driving a car with closed eyes.

For an active flow control, as is required in modern road tunnel ventilation systems, a precise and reliable online measurement of in-tunnel flow is essential (2), (18). Even without flow control, the flow in the tunnel should be supervised and assessed, especially in case of extraordinary situations, such as fire events. Recording of in-tunnel flows may be demanded for an after-incident investigation.

Flow measurements are also part of acceptance tests of the ventilation equipment, namely the fans. Factory acceptance tests are described in many national and international standards. There are also site acceptance test standards for building HVAC systems, but those cannot be directly applied to tunnel conditions. With increasing use of simulation models for ventilation design and optimization, validating those models becomes also an important application of flow measurements.

Recording the values from the installed devices on the SCADA for all integral test scenarios is essential for the assessment and documentation of the performance for the control system, in particular for the performance of the flow control for different boundary conditions. The same applies for real fire incidents.

3 THEORY AND PRACTICE

The undisturbed turbulent flow in a straight round tube has a parabolic flow profile. By measuring the flow velocity in a representative point, the volume flow can be directly determined by multiplication with the cross-sectional area, as described e.g., by Aichelen in 1947 (1).

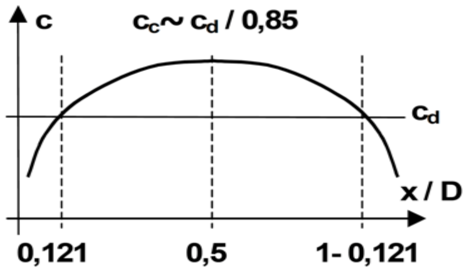

Figure 1: Undisturbed turbulent flow profile in a round tube

In practice, flows in tunnels and duct systems are not uniform, due to changes in profile, curves and obstructions, and reliably measuring a precise value that is representing that flow is a challenge, as was investigated in various research works, e.g., (6), (7), (9), (21). Only the longitudinal air velocity in the direction of the tunnel axis contributes to the tunnel flow, while turbulent flow also has velocity components perpendicular to the tunnel axis.

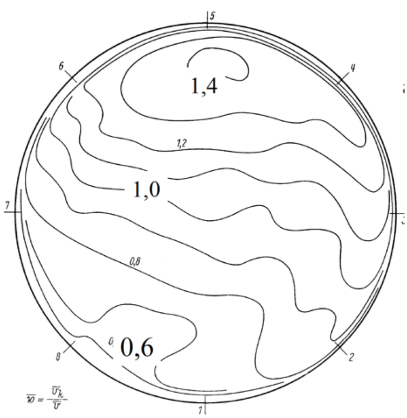

Figure 2: Flow profile in the cross section of an airduct after a bend (20)

Moreover, the flow in a tunnel is rarely in a steady state but is in a dynamic process due to fluctuations and changes in boundary conditions. Particularly in road and rail tunnels under operation, moving vehicles are strongly influencing the flow.

As an example, in Figure 3 the longitudinal flow velocities measured by different anemometers in a 2.5 km long road tunnel are displayed. The tunnel was closed between 20:15 h and 05:00 h; during that period, the flow was influenced only by external boundary conditions. The high fluctuations with changes in flow direction before 20:15 h and after 05:00 h were caused by the bidirectional traffic.

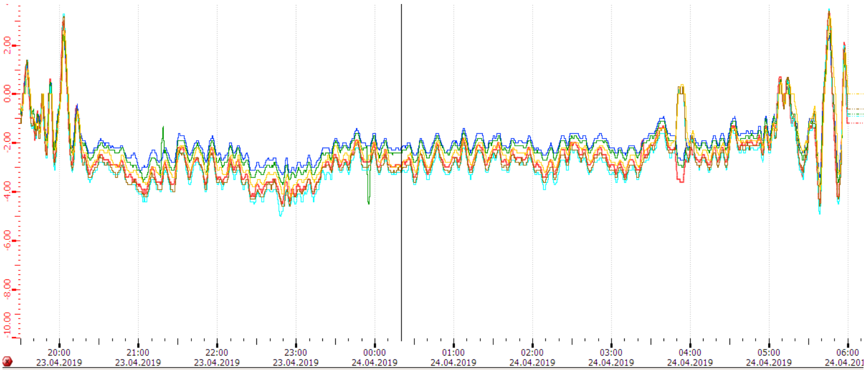

Figure 3: Measured longitudinal flow velocities during tunnel closure; x-Axis: time, y-Axis: air speed [m/s]

Most commonly, flows are measured with flow velocity measurements at representative points, and for each measuring point a corresponding area is defined. The precision of the flow measurement is very dependent on the number and location of the measurement points in the duct section. The more measuring points, and more distributed, the better the precision.

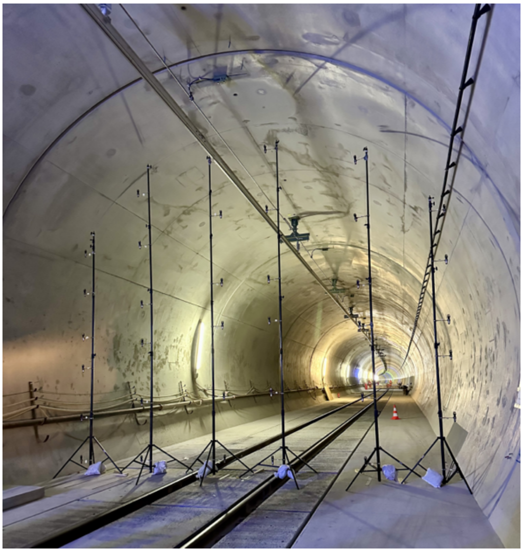

Figure 4: Measuring grid in a rail tunnel

Instead of point measurements, line measurements of the mean flow along a line in the cross section are applied in pipes, shafts and tunnels. The representation of the line measurement for the effective flow profile can be derived from more precise calibration measurements.

4 INSTALLED AND TEMPORARY MEASUREMENTS

In a tunnel without bifurcations, air supply and exhaust, or leakage, there is a uniform mass flow, and measuring the flow in one cross section would be sufficient. In practice, the flow is measured at multiple locations in each branch, for redundancy and to allow for plausibility checks. Fluctuations in the air density, particularly in long tunnels, must be considered by measuring the temperatures and converting it into a mass flow balance. In tunnels with an exhaust, the flow must be measured in both branches, and for redundancy purposes, also at the exhaust fans, while taking into account the duct leakages.

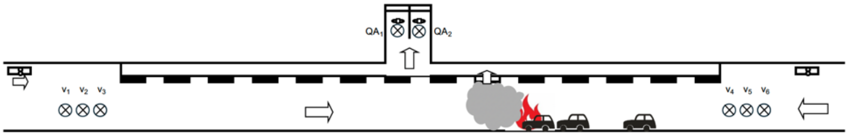

Figure 5: Schematic of flow measurement in a tunnel with point smoke exhaust

For flow control applications, a high reliability is required. For instance, during a fire incident in a road tunnel, downstream of a fire the temperature is increased, locally accelerating the airflow, or trucks may be blocking a cross section. Therefore, an automatic plausibility check algorithm must identify and exclude such deviated flow values that would skew the mean tunnel flow velocity, which is the guide value for the flow control.

Tunnel flow is measured either by line measurements across the tunnel section or with at least two-point measurements at the tunnel walls. Point measurements are more sensitive to correct placement and require a higher effort for signal processing. Anemometers must be installed at adequate distances from jet fans, portals, changes in cross sections (e.g., lay-bys), any obstructions such as signals, and preferably in straight tunnel sections without curves.

The flow velocity, respectively smoke spread, can also be indirectly measured by dynamic evaluation of recorded signals from installed in-tunnel smoke detectors, respectively visibility measurement during smoke tests and real fire incidents.

Temporary measurements serve for:

- Site acceptance tests (SAT) of tunnel ventilation fans.
- Validation of design and simulation models.
- Calibration of installed instruments.
- Evaluation of controller parameters

Temporary measurements must provide a higher precision than installed instruments, but do not need to comply with requirements on durability under tunnel conditions.

5 MEASURING METHODS

Adequate devices measuring the three-dimensional flow in a tunnel cross section directly, like e.g. laser doppler anemometry, are very elaborate and applicable only in test facilities like scale wind tunnels, but not in real tunnels on site.

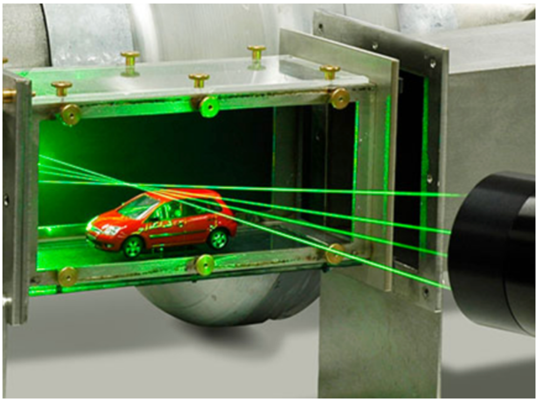

Figure 6: Laser Doppler Anemometry in a scale wind tunnel (Dante Dynamics)

Most methods for precise temporary measurements are based on multiple point measurements, arranged in grids where the measuring points are measured either step by step or preferably simultaneously.

Figure 7: Flow measuring grid in road tunnel

For point measurements of high flow velocities, the flow velocity can be derived from the dynamic pressure, which is the difference between measured total pressure and static pressure, e.g. in the form of Pitot tubes and static pressure taps, or Prandtl tubes. This is the standard application for flow measurements in fan inlet bellmouths, but also in airducts and other applications, e.g. on airplanes. Dynamic pressure measurement is very simple and robust, but must be precisely aligned with the airflow direction, and is sensitive to blockage by dirt or ice.

Figure 8: Pitot tubes in a fan inlet bellmouth for flow measurement

Prandtl tubes have also been applied for installed flow measurements in tunnels, but due to the low resulting dynamic pressures at low velocities, in comparison with overlaying traffic induced pressure fluctuations, the resulting precision is lower than with other measuring principles as described below.

Figure 9: Vane anemometer fixed to a grid frame in a rail tunnel

Vane anemometers are commonly used for temporary measurements. Vane anemometers have been installed in some road tunnels, but due to high maintenance effort for rotating mechanical parts, they are not appropriate for harsh tunnel conditions or for very low flow velocities. Hot wire anemometers are very precise when measuring low flow velocities, but do not provide any directional signal, are sensitive to dirt, and are only available as hand-held instruments.

For installed flow measurements in rail, transit and road tunnels, where the instrument must not impair moving vehicles, ultrasonic line measurements have been proven to be most suitable. Two ultrasonic transducers, which are typically installed at an angle of 45°... 60° to the tunnel axis, alternately function as sender and receiver. Different transit times result for each sonic impulse depending on the flow velocity and direction. In the forward direction, the runtime is shortened; in the opposite direction, it is extended. The flow velocity is determined by the differences in ultrasonic transit time.

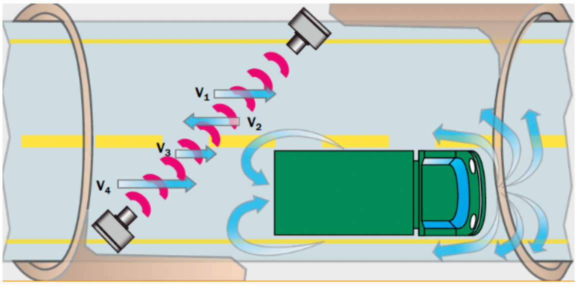

Figure 10: Ultrasonic line anemometer schematic (Sick)

Measuring the airflow along a beam in a plane, provides more precise information about the representative flow in the tunnel cross section than point measurements, but requires precise adjustment of senders/receivers. The senders/receivers need to be installed as low as possible, not too close to the tunnel ceiling, but over the height of road vehicles and trucks. Signal beam reflexes from the tunnel ceiling must be avoided. Interruption of the beam by passing overheight vehicles must be filtered out by adequate signal processing.

Pseudo point measurements can be set up with ultrasonic line anemometers with short measuring distance.

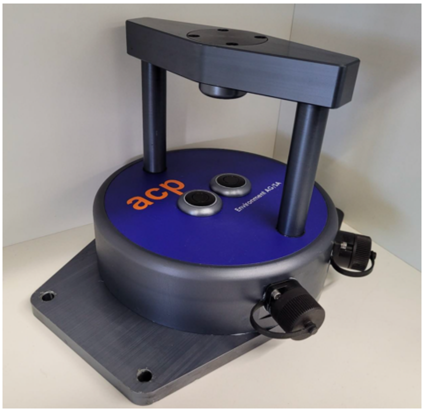

Figure 11: Ultrasonic point anemometer (ACP)

The mean volume flow can also be measured by measuring concentrations of an inert tracer gas (e.g., SF_6) that is injected with a constant mass flow and diluted by the airflow. Tracer gas measurements are applicable only for steady state flows. They have been used e.g., for determining the leakage of exhaust ducts in tunnels or for measuring resistance and friction coefficients.

Figure 12: Tracer Gas injection in a road tunnel

6 ACCURACY AND MEASURING UNCERTAINTY

Any measurement has only a limited accuracy. The determination of measuring uncertainties is described in the ISO Guide to the expression of uncertainty in measurement (15), in the NIST Guideline (16), as well as in various fan testing and measuring standards, e.g., (3), (5), (8), (11), (13).

A principal uncertainty is provided by the measuring instrument itself, due to limitations of the measuring principle, but also signal interference or distortion of the output signal. The precision of the temperature and pressure measurement to determine the air density must be considered additionally. Instrument accuracies are described in the datasheets. Additional errors occur when the signals are not recorded automatically, but read on a display and written down manually, especially when considering the fluctuations that always occur in a turbulent airflow.

If there are no requirements on the precision, grid measurements can be conducted by measuring manually one point after another, as was the traditional method for decades. The anemometer should be held to each defined measuring point as close as possible to minimize uncertainty about positioning. Most importantly, an additional reference measurement should be continuously recording the dynamic flow behavior while the grid measurements are carried out. If timely deviations occur, the results of the grid measurement must be corrected accordingly. With this method the uncertainty of a 5x5 point grid measurement in a typical tunnel is in the range of approx. ±20%. Without a continuous reference measurement, the errors can be much higher, depending on the time variations. When significant timely changes occur, the measurement must be repeated during more stable conditions.

When grid points are measured simultaneously and recorded continuously, an uncertainty of approx. ±5% can be achieved with a 5 x 5 point grid measurement in a tunnel without significant obstructions. More grid points increase the precision of the measurement, but also the necessary effort for the setup of the grid. Uncertainty of the precise tunnel geometry must also be considered. Usually, plans and drawings rarely represent the as-built situation precisely enough, therefore the geometry must be measured diligently on site.

Since the installation of grids is elaborate and blocks the tunnel cross section, a cross alignment of ultrasonic line anemometers has been established for acceptance test measurements in road and rail tunnels, as compromise between acceptable precision and practicability. This is described e.g., in the Austrian standard (4). Ultrasonic line measurements do not obstruct the tunnel, and people and vehicles can move past the installed measurement setup. With this method, an uncertainty of approx. ±5% can be achieved, depending on geometric conditions and obstructions. In contrast, in a defined wind tunnel with straight, unobstructed flow, the measuring uncertainty of an ultrasonic line anemometer is ±2%.

Figure 13: Cross alignment of ultrasonic line anemometers in a road tunnel

Guaranteed fan performance parameters are verified by Factory Acceptance Tests (FAT) on test benches, with defined accuracy according to testing standards such as (12), (14). Measurements in the tunnel are less precise. Measuring uncertainties for tunnel flow measurements are to be specified in the contract, and a diligent assessment of measuring uncertainties according to ISO GUM (15) should be part of the test protocols.

For tunnels with flow control, an uncertainty of less than ±10% of the measured value should be achieved by the installed anemometers, therefore the temporary measurement for acceptance tests and determination of calibration factors should have a measuring uncertainty of approx. ±5% or less.

7 ACCEPTANCE TESTS

Equipment performance tests in factories and on site prove whether the equipment meets the design criteria. Fan manufacturing tolerances must also be considered. Testing procedures and accuracies for Factory Acceptance Tests (FAT) are defined in national and international standards, such as (12), (14). It is important that the fans to be tested are exactly the same as those that are later installed in the tunnel, to avoid later discussions in case of deviations from required performance values.

On site flow measurements in tunnels determine the performance of fans at the installed conditions and are only a part of a series of acceptance tests, that may also include vibration and noise measurements (20). They show whether the designer has correctly modeled the system and considered adequate safety margins. For that, e.g., standard NFPA 130 for rail and transit tunnels (16) requires the calculation of the flow for the testing conditions ('cold flow') as part of the design process.

Prior to flow measurements, all leakages must be sealed, drainage duct siphons filled with water, and emergency exit doors closed. The tunnel must be either empty without obstructions, or with standing vehicles or trains corresponding to the design scenarios. Moving vehicles would influence the flow dynamics and must be avoided.

During acceptance test flow measurements, temperatures and barometric pressure also must be measured to determine the air density.

Precise temporary flow measurements do not serve only as an acceptance test for the ventilation system and validation of design and simulation models, but also for calibration of installed instruments and evaluation of controller parameters, if a flow control is implemented.

Calibration means comparison of an instrument with a more precise reference measurement. Point anemometers are to be calibrated in the factory in wind tunnels with defined measuring geometry. Ultrasonic line anemometers can only be calibrated for the same geometry on site. Installed instruments in tunnels are usually calibrated either with the cross alignment of two-line anemometers, or by a point measuring grid with at least 5 x 5 points in tunnel cross sections or 3 x 8 points in round cross sections, e.g. a fan inlet. Grid measuring points are defined in standards, e.g., ISO 5802 (13).

Precise flow measurements in tunnel exhaust ducts close to the open dampers serve for the determination of the system leakage, by comparing with the flows measured at the fans. Excessive leakage may lead to non-compliance with required exhaust volumes and would have to be improved by additional sealing of the ducts.

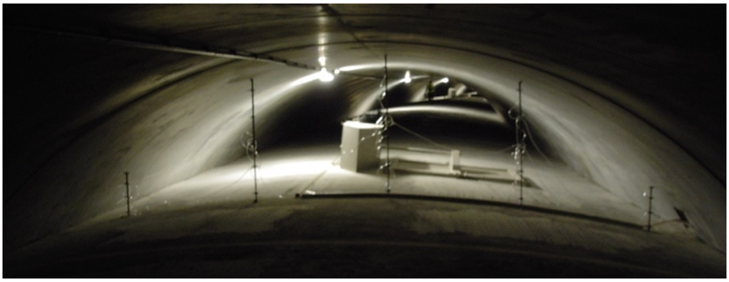

Figure 14: Flow measuring grid in a tunnel exhaust duct

Instead of measuring the flow in the duct, the flows from both sides to the exhaust point in the tunnel traffic space can also be measured, but that is more elaborate and less precise.

Ideally, the signals from the installed anemometers can be derived directly by connecting the SCADA system to the computer with the temporary measurement evaluation, to provide correct time synchronization. Temperature measurements are to be set up at tunnel portals and at the location of the temporary measurement. Signal time integration of installed and temporary measurements must be coordinated and should not be longer than approx. 10 sec., otherwise the dynamics cannot be adequately captured.

The procedure for acceptance test in a tunnel with longitudinal ventilation is as follows:

- Setup of temporary measurement devices and signal check
- Measure the natural airflow (with jet fans switched off)
- Switch all jet fans on in direction A, measurement of flow while ventilation is operating until flow has stabilized in a steady state condition
- Switch jet fans off and wait until flow velocity has stabilized at natural flow condition
- Switch all jet fans on in direction B, measurement of flow while ventilation is operating until flow has stabilized in a steady state condition
- Switch jet fans off and wait until flow velocity has stabilized at natural flow condition
- When time allows, additional measurements can be conducted, e.g. with only single jet fan operating, to validate the design model and fan performance

The same applies for tunnels with smoke exhaust. For the longitudinal flow measurements, the exhaust must be switched off and dampers closed.

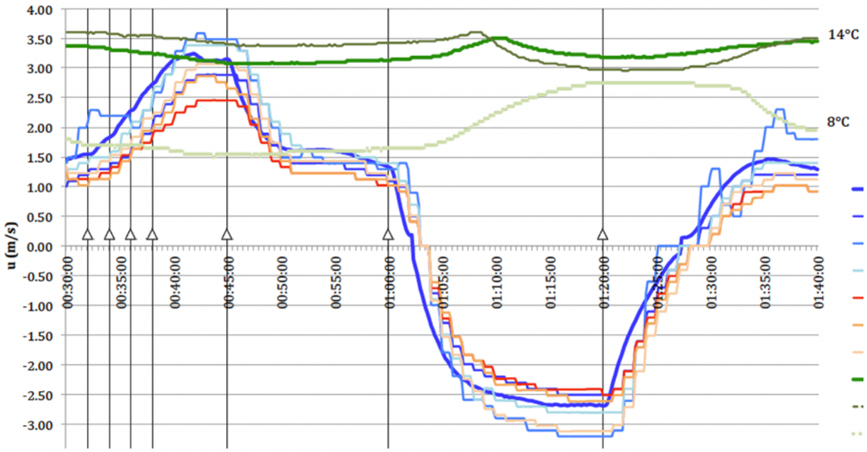

Figure 15: Recording of flow velocities and temperatures in a tunnel test

For tunnels with exhaust systems, installed flow measurements at the fans (see Figure 16) are also to be calibrated with precise temporary measurements at the fan inlets, usually with Prandtl tubes that are manually positioned at the grid positions one after another. The flow is relatively stable when the fans operate at nominal speed and would not justify the effort for installation of multiple point grids.

For systems with multiple fans in parallel operation, it is important to determine different calibration factors for different modes of operation that affect the flow situation. Therefore, a calibration measurement needs to be conducted for each exhaust flow condition.

For all tunnels with egress passageways to the adjacent tube, or to separate pressurized escape facilities like a parallel service tunnel or egress stairs, door opening forces and airflows in open doors must be measured while the tunnel ventilation is in operation in fire ventilation mode for different scenarios. The same applies for enclosed exit stairs or escalators in train stations. This flow measurement is usually done by handheld vane or hot wire anemometers, manually covering the whole door area. It is important to ensure that not only minimal design flow velocities are achieved, but that no backflow occurs at any point in the open door area, which in case of a fire might lead to smoke being sucked into the emergency exit despite operating over pressurization ventilation.

After the calibration factors derived from the temporary measurement are implemented in the control system, the signals from the installed anemometers can be used for additional flow tests. Of particular interest is the flow in the tunnel for all fire ventilation operational states that must be diligently tested. The performance of the flow control needs to be tested under different boundary conditions. For that, external forces can be simulated by means of mobile jet fans.

Figure 16: Mobile jet fan at tunnel portal for simulations of external pressures

During all ventilation control and integral tests, processed signals from installed flow measurements must be recorded on the SCADA system and documented in the test protocols (19), (20).

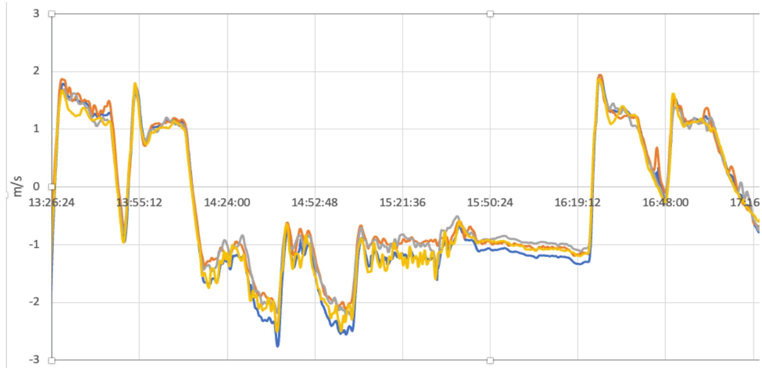

Figure 17: Example of recorded flow velocities during fire ventilation tests

Data from flow measurements can be used also for additional purposes:

- Evaluating the aerodynamic resistance of a tunnel with and without vehicles or trains for particular setups, by analyzing the decay curves after switching off the ventilation.
- Long term analysis of flows provide feedback on traffic patterns and meteorological forces.
- Comparisons across different tunnels allow for a more comprehensive understanding of tunnel ventilation performance and variations.
- Analysis of fire ventilation performance in real fire events

For acceptance tests in US mass transit ventilation systems, NFPA 130 standard (16) prescribes 'cold flows' to be established in the design calculations, which then can be measured under the same conditions. In the San Francisco Central Subway, which was opened by the end of 2022 (22), an innovative approach using ultrasonic line anemometers in cross alignment measuring simultaneously in multiple locations has been applied.

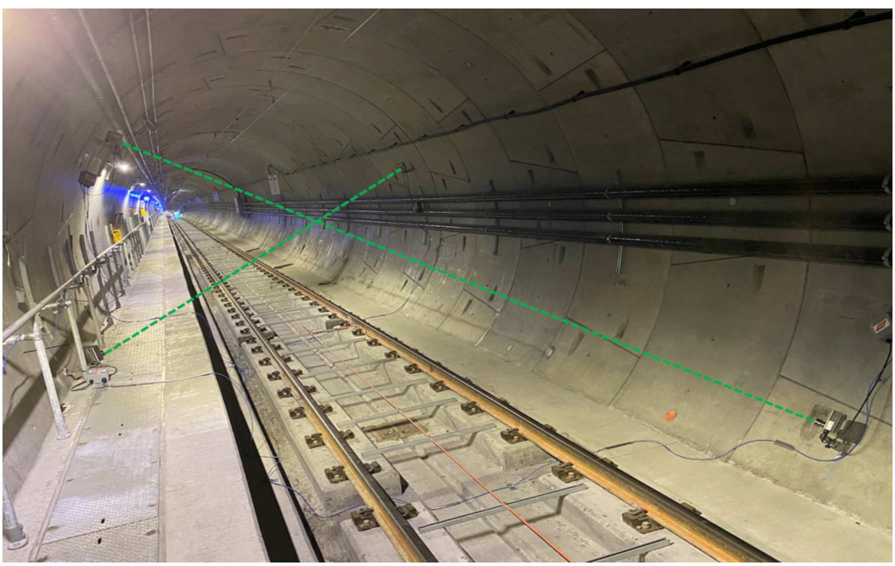

Figure 18: Cross alignment of ultrasonic line anemometers in SF Central Subway

Totally 8 ultrasonic line anemometers were temporarily installed in 4 test locations, with a 2-car MUNI Metro LRV train positioned in a tunnel branch to establish conditions according to specific design scenarios.

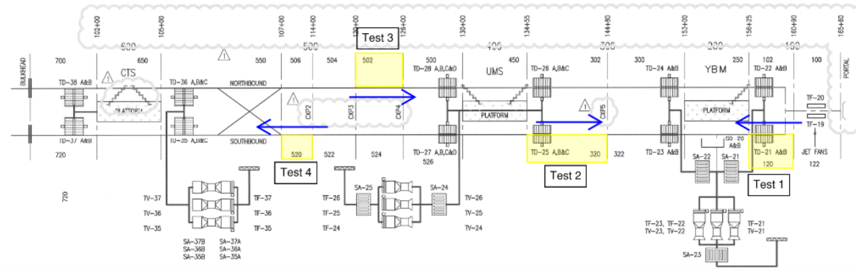

Figure 19: SF Central Subway ventilation system schematic with test locations

By continuously measuring the flow in all 4 branches, an unprecedented precision has been achieved. Considering the measured natural airflow, the test results have successfully validated the ventilation design, which had been conducted with 1-D SES simulations. All measured flows were within the range of measuring uncertainties.

Table 1: SFMTA flow measurement test results

Test	tunnel air temperature	density (kg/m3)	measured natural flow	measured with ventilation	calculated without nat. flow at measured density	at standard density	design	difference to design
	°F	lb/ft3	cfm	cfm	cfm	cfm	cfm	
1	62	0.078	138	820	808	838	778	7.7%
2	61	0.078	-199	1199	1215	1262	1253	0.7%
3	61	0.078	-177	1004	1020	1059	1028	3.1%
4	61	0.078	158	1047	1035	1075	1080	-0.5%

Considering the aging of the structure and equipment, it is recommended to regularly repeat air flow measurements at the described test locations to confirm that the system capacity meets the design criteria.

8 HOT SMOKE TESTS

The airflow in a tunnel is in first order one-dimensional. In complex structures, like underground stations or wide complex tunnel geometries, the three-dimensional flow and smoke spread in case of a fire, particularly smoke stratification, are of interest. Such cannot be measured with justifiable effort (see Figure 19).

Therefore, for visualization of airflows and smoke spread, hot smoke tests are proposed. Unlike in real fire tests, the smoke must not impose a health hazard, nor impair the equipment. The heat must not destroy equipment and structure, but the test smoke should provide enough heat to enable smoke stratification. This is of particular importance for validation of CFD models.

Figure 20: Hot smoke test in a road tunnel

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