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Foreword

On behalf of the organisers and the dedicated Technical Advisory Committee, I'm honoured to welcome you to the 20th International Symposium on Aerodynamics, Ventilation, and Fire in Tunnels, now in Scandinavia for the first time. Since 1973, this symposium has been the key event for idea exchange and learning in the field. This year, we received a record number of paper submissions, leading the committee to carefully review and select the best, which have been organized into the following sessions:

- CFD/1-D Modelling
- Design Methods Using Artificial Intelligence and/or Machine Learning
- Digitalisation
- Equipment
- High Speed Rail Tunnels & Hyperloop Systems
- Innovations in Ventilation Design and Control
- New Energy Carriers
- Platform Screen Doors
- Railway Case Studies
- Road Tunnel Case Studies
- Road Tunnel Refurbishments
- Smoke Control and Critical Velocity
- Smoke Management and Egress (Tenability)
- Sustainability in Underground Design and Construction
- Testing and Commissioning

Sincere thanks to the authors, the key-note speakers, the delegates, the exhibitors, the technical advisory committee, and the organisers. As a result of the contributions, work and passion for aerodynamics, ventilation, and fire in tunnels, this symposium offers an excellent opportunity to experience and to discuss, so that we collectively can raise the bar, for the very state of the art.

Dr Rune Brandt
Chairman of the Technical Advisory Committee

On digitalisation for tunnel-ventilation design, procurement, installation, commissioning, and maintenance

R. Brandt, S. Frey, J. Funnemark , S. Thumm, HBI Haerter, Switzerland

1 ABSTRACT

Digitalisation is advancing rapidly in the design and realisation of tunnel-ventilation systems.

BIM-models mimic the equipment, contain selected attributes, and need to be incorporated in the 3D coordination models prior to knowing the specific brand. For the design, 1D line charts and 2D drawings are also needed.

Regarding commissioning, tunnel-ventilation-system simulators (TVSS) enable complete testing of the tunnel-ventilation-control system in an office environment, which ensures completeness and results in sizable savings.

In the light of Industry 4.0, condition monitoring systems (CMS) apply independent data transmission that external maintenance partners can benefit from without risking interfering the SCADA system.

2 INTRODUCTION

Based on experience from several projects, the use of digitalisation for the planning and realisation of tunnel-ventilation projects is described. The paper summarizes experiences, advantages, and pitfalls regarding the application of digitalisation. All phases are considered i.e. from the design phase over procurement and installation to commissioning and maintenance.

In the design phase, the main specifications of the ventilation components are determined of the actuators (fans etc.) as well as the sensors. This results in the main layout of the tunnel-ventilation system. Moreover, the functionality of the ventilation system for various types of operation is defined.

It shall be noted that the design of the civil works and of the tunnel-ventilation system might have large impacts on each other. Consequently, the tunnel-ventilation design should be carried out to a high degree of detail during the preliminary design of the civil works.

During the design phase, all aspects of operation including the definition of the minimal operating conditions need to be defined, as e.g. described by Brandt (2020) (9) regarding smoke management. Following the recommendation by PIARC (2011) (8), this will inevitably result in a somewhat advanced control system. One of the difficult matters concern the longitudinal flow control, see Frey, Lempp and Zimmermann (2020) (10).

Section 4.3 of the paper describes how tunnel-ventilation-system simulators (TVSS) are used for the testing of the proper functioning of the over-arching ventilation-control system. The highest level is the so-called digital twin TVSS that is a digital copy of the tunnel with all installed sensors and actuators.

It is evident that the physical, logical, and contractual interfaces of the ventilation system need to be clear already at the design stage. Moreover, the documentation (e.g. regarding BIM requirements, see chapter 3) and test requirements need to be clarified at an early stage of the project. This also includes the required submissions during and at the end of each project phase: preliminary design, detailed design, tendering, procurement, testing and commissioning (see chapter 4), final documentation and post inauguration (see chapter 5 Industry 4.0 and aspects of predictive maintenance).

3 BIM (BUILDING INFORMATION MODELLING)

3.1 Introduction

With a focus on the civil aspects, DAUB (1) provides an overview of the processes for applying BIM to the design and construction of underground structures. Following on to this, research projects were launched to deepen the understanding and application of BIM in tunnel construction B191 (2), which entail the overview in Figure 1. This was further developed to propose the specific requirements for BIM in case of operation and maintenance of road tunnels, BASt 2023 (3).

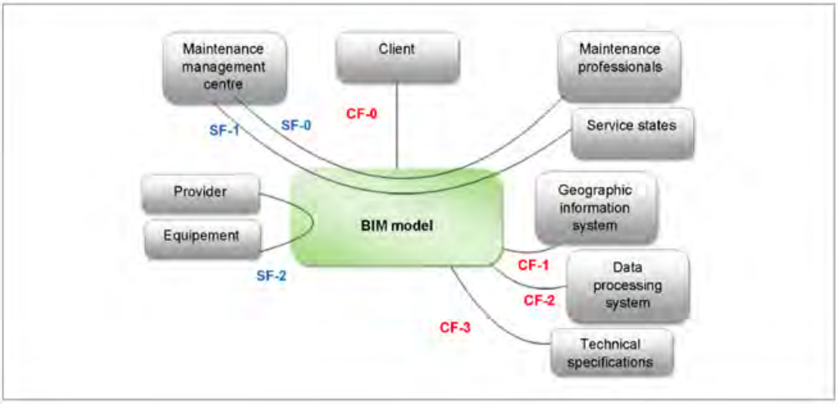


Figure 1: Overview of interactions with the BIM model, from (2). SF = service function, CF = constraint functions.

3.2 BIM models

In simple terms, BIM can be considered as 3D CAD modelling with the addition that the individual models have so-called attributes. The main principle of the attributes is that they contain the information, which has utmost relevance for interfacing with the civil structure and the other parts of the electro-mechanical equipment. This means that already at the design stage such BIM-models need to be generated.

The attributes for a generic jet-fan BIM-model could be as follows:

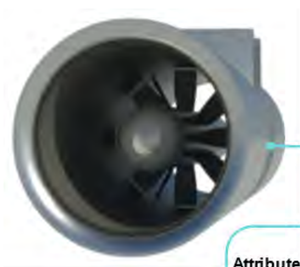
- Component identification number
  (to be used throughout the entire duration of the project)
- Maximum dimensions: length and diameters
- Minimum static thrust in forward and reverse direction at nominal air density
- Maximum electrical power requirement
- Supply voltage
- ….

Moreover, the following attributes can be helpful for the coordination with other disciplines:

- Place holder for the specific equipment identification number, which will be altered according to which specific jet fan is installed.
- Minimum distance from the road surface
- Minimum distance from the ceiling
- Minimum distance in-between jet fans of the same group
- Exclusion zones for adjacent equipment in particular for the in- and outlet sides of the jet fan
- Weight
- Direct on-line (DOL) or operated with variable speed drive (VSD)
- …

The list of attributes should be kept as short as possible but still being as comprehensible as required. Consequently, all other design criteria shall not be included in the list of attributes, see example Figure 2. In addition to the list of attributes, the BIM-model may directly show information e.g. by indicating the nominal thrust on its surface or even the detailed information on the jet-fan and/or motor sign plate.

The BIM-model will contain numerous further attributes that are visible to the designer and the BIM-modellers. When generating tables by extracting information from the BIM-model, one challenge is only to receive the BIM-information of relevance and not to be overloaded with unnecessary information.



Attribute	Value	Unit
Inner diameter	800	mm
Thrust	995	N
Fire rating	F200	-
Power	45	kW
Voltage	400	V
Efficiency	IE3	-
...	...	...

Figure 2: Generic BIM-model of a jet fan for the preliminary design stage

The BIM-model can also contain specific maintenance instructions, information on performed maintenance (e.g. bearing replacements, renewal of consumables) and therefore allow for optimized spare parts storage.

3.3 BIM in ventilation stations

As can be inferred from the acronym BIM (Building Information Modelling), the term was invented for buildings. The simplicity for buildings and hence ventilation stations is that they can normally be defined using one global coordinate system that can be used to define the positions of the BIM-models of the equipment.

Fanjul and Sierra (2020) (17) reports on experiences applying BIM for ventilation stations of the Doha Metro. Here, four types of clashes are described:

- *Hard clashes*
  - *The ones detected when two components are sharing the same space – Example: a fire pipe running through an Axial Fan lifting beam in a dedicated Tunnel Vent System room*
- *Soft clashes*
  - *The ones detected when the buffer zone, space proofing or tolerance of an element has been breached by another element*
- *Workflow or 4D clashes*
  - *The ones involving conflicts due to unaligned Contractors Work Scheduling or to different timelines of inter-disciplinary activities (main risk: potential cascade effect on others)*
- *Other clashes*

3.4 BIM in tunnels

3.4.1 Introduction – Experience from E4 Förbifart Stockholm (E4FS)

Using BIM in tunnels is a much more difficult matter than for buildings, as the extent of the tunnel renders it inconvenient and too prone for inaccuracies to use one global coordinate system. Therefore, the tunnel is defined with a chainage typically along the centre line of the project. Consequently, the BIM-models for the tunnel equipment cannot be incorporated in the overall design model before the alignment and all tunnel cross sections are known.

For the large infrastructure project E4 Förbifart Stockholm (E4FS), BIM was applied already from the design stage; Figure 4 provides an overview of the tunnel-ventilation equipment.

In E4 Förbifart Stockholm (E4FS), concrete foundation structures were to be constructed in the ceiling of the tunnel for each:

- jet fan (foundation structures with inserted screws threads for anchor bolts) and
- ceiling-mounted traffic sign (lane signs, variable message signs etc.)

Having specified the position of these, during the preliminary design, generic BIM models of jet fans and signs were incorporated in the coordination model.

For the procurement of the electromechanical equipment, the contractors obtained the 3D coordination model (Model 1) with all civil structures but without equipment. In the course of the construction of the tunnel, some aspects of the civil design were changed. This led to some changes of the positions of egress routes, positions of jet fans and of signs. All these changes were scrutinised and agreed with the responsible persons of each relevant design discipline. There were also some local changes to the alignment of the tunnel. Moreover, some of the seventeen (17) ventilation stations were optimised. All these changes led to Model 2.

During detailed design of E4FS, the specific brands of each equipment were determined. This meant that the generic models of the jet fans and the signs were replaced by genuine ones that were more detailed. For the subsequent clash control, also the other important elements were included e.g. luminaries, cable trays, and pipe works including their sprinkler heads for the fixed fire-fighting system. At this design stage, the tunnel ventilation also included cable connection boxes and auxiliary cable trays in the model. It was decided, however, to simplify the modelling of the cables by showing them as simple lines in order not to overload the models visually. The feeder cables for radio transmission and linear-heat sensors were also incorporated into the model at this stage as well as all other equipment in the traffic space e.g. radars, tunnel-closing features and the sensors for the ventilation control: anemometers, air-quality sensors (CO, NO_2, NO and visibility) and smoke detectors.

The positions of the sensors in the traffic space i.e. anemometers, air-quality sensors and smoke detectors were defined at the preliminary design stage on the basis of Model 1. Benefitting from the 3D visualisation, the positions of some of these sensors were verified and in case needed optimised in corporation with the contractors during detailed design using Model 2.

Some BIM-models had their component identification number assigned to them already during preliminary design, whereas others obtained this during detailed design. All components can be extracted from the BIM-model to a list including their component identification number.

In E4FS, the BIM-models in the coordination model focused on clash control and hence not on electrical and logical interface management.

The coordination model was updated weekly, so that all disciplines could observe progress and ensure adequacy.

3.4.2 3D CAD
Setting aside the attributes, the BIM-models constitute 3D CAD models. From the equipment perspective, it is beneficial when the 3D civil models also show their relevant limitations e.g. to be penetrated (for holes and support) and the maximum loads that they can support. The 3D models are particularly advantageous to conduct clash control of elements that are situated in more than one plane.

3.4.3 2D drawings versus 3D CAD
For simple room layouts, the overview is quickly established using conventional 2D drawings that sometimes are accompanied with vertical and horizontal planes. Moreover, 2D drawings are required for the purpose of defining the emergency egress routes in case of fire in any type of building.

It is possible to generate the required 2D views on the basis of the 3D models, but some care is needed to eliminate the information from the CAD-layers in the model that are irrelevant.

3.4.4 1D line charts versus 3D CAD
During the preliminary design stage, the philosophy in E4FS was only to work with 3D models. It is possible from the BIM-model to extract the positions of all equipment and

their associated component identification. The coordinates, however, were cartesian in x-y-z, which is less beneficial in terms of assessing distances between groups of jet fans etc. Consequently, 1D line charts were used as the governing information for the ventilation-system design, but it was ensured that the 3D model reflected the 1D design.

During detailed design, it was concluded that the different contractors and design disciplines had to have access to the positions of equipment and egress routes defined in the classical manner as road distances. These were denominated MDL (Master Data Lists) and were contractually binding for all parties involved. Changes to the MDL were often firstly agreed informally and subsequently communicated in a formal manner.

One conclusion is that classical line charts are difficult to extract directly from the BIM-model but are of utmost importance for ensuring the overall design. Consequently, they have to be developed and updated in parallel with the 3D BIM coordination models. A general conclusion is that efforts should be made to automate and simplify the translation of the information between 3D BIM models and 1D line charts.

3.5 Procurement aspects regarding BIM

Several research projects have been devoted to the application of BIM models with the prime focus on civil works, see e.g. DAUB (2019) (1) and B191 (2023) (2). Moreover, practical experience including the application of BIM for procurement and billing has been reported by Bircher and Stauch (2023) (7).

Regarding equipment, the focus is on optimising its positioning as well as the subsequent operation and maintenance. A guideline for aspects to observe has been prepared by BASt (2023) (3).

4 COMMISSIONING TUNNEL-VENTILATION-CONTROL SYSTEMS

4.1 Introduction

In addition to the conventional performance testing, a series of tests for the interfacing of the individual components and/or subsystems with the tunnel SCADA system and subsequently with the overarching regional traffic-management system are required.

4.2 Acceptance test hierarchy in E4FS

4.2.1 Introduction

Testing of the control system are divided in three main test categories (FAT, SAT and OAT) each with their individual subtests. The prime principle is that a subtest needs to be completed in a satisfactory manner prior to proceeding to the subsequent test.

Before conducting an acceptance test or a witnessed test with the client, the supplier has to have conducted own internal tests in a successful manner, which need to be documented and submitted to the client.

4.2.2 Acceptance tests

Acceptance tests are performed on type-objects, sub-systems, the SCADA system, and the regional traffic-management system.

In E4FS, test cascades were prescribed by the client in order to ensure that all interfaces in particular to the SCADA and the regional traffic-management system would function in an impeccable manner.

At the first level (FAT1), conventional factory-acceptance tests were carried out. Subsequently, the interfacing of equipment was tested in the client test facility installing whenever possible samples of the equipment to be installed in the tunnel. For the ventilation dampers, the actuator was used. For the fans, however, a smaller electrical motor was connected to the variable speed drive.

At the second level (FAT2), the software to be used in the seventeen ventilation stations was tested. Unnormal operating scenarios and degraded modes were tested ensuring an adequate response for all possible operational situations. Conducting these tests in a lab environment proved incredible efficient, enabled rapid interaction in case of software improvements and ensured substantial testing.

The overarching tunnel-ventilation-control system was also tested using the tunnel-ventilation-system simulator (TVSS) that was made at disposition by the client. This enabled testing of conventional and extreme scenarios as well as ensuring adequate rapid response e.g. when regulating the longitudinal flow in case of fire. In E4FS, the ventilation-control system operates each individual jet fan and demands specific air flows from the ventilation stations.

The third level (FAT3) concentrated on the interfaces between the SCADA system and the already tested sub-systems. The fourth level (FAT4) tests the interface to the regional traffic-management system. Certain equipment has direct interface to both systems. For one not-ventilation-related equipment, it was discovered that it could interface with both systems independently but not concurrently. Consequently, this equipment error could be rectified at an early stage.

The site acceptance tests (SAT) follows by and large the same cascade as for the FAT. However, due to the size of the project, SAT is conducted for each power-supply zone prior to conducting it for the entire tunnel system or at least for one traffic direction. E4FS has 32 power-supply zones.

Having successfully completed FAT and SAT, a period with test operation is to be conducted, which also includes various full-scale testing that are to be endorsed or even approved by different authorities. Moreover, operator training is being conducted. Operation acceptance test (OAT) is the final test of all aspects and hence a prerequisite for the inauguration.

4.3 Tunnel-Ventilation-System Simulator (TVSS)

4.3.1 Introduction

In order to be classified as a tunnel-ventilation-system simulator (TVSS), the physics has to be simulated within the TVSS to an adequate level of accuracy.

Classical testing of the software for the tunnel-ventilation-control system by forcing input values and observing the response is valuable initial testing but cannot be classified as being a tunnel-ventilation-system simulator.

As described in chapter 2 Introduction, the complexity of any tunnel-ventilation-control system requires thorough testing. The first step of this is to check that the interaction between the control system, the sensors (e.g. air-quality sensors, anemometers), and the actuators (e.g. jet fans) functions as envisaged. The next step is to ensure that the reactions envisaged in the design of the ventilation system are carried out. This has to be investigated also for situations with equipment failures and/or inadequate response.

Exhaustive testing is required, as tunnel-ventilation-control systems typically are tailor made for each individual tunnel. In case of final testing, complete testing has to be resumed subsequent to bug-fixes, as it typically cannot be excluded that the software changes will not have any impact on any other aspects of the software. Consequently, complete testing on site is very time and resource (human and energy) intensive.

In some constituencies (e.g. Austria according to RVS 09.02.31 (11)) witnessed fire tests have to be carried out in the tunnel prior to inauguration. However from practical reasons, it is impossible to conduct a fire test which reflects the design condition of e.g. a 50 MW fire. Therefore, such scenarios have to be tested in another manner e.g. using a tunnel-ventilation-system simulator (TVSS).

The tunnel-ventilation-system simulator (TVSS) can also be used to test the response in case of extreme events during normal operation e.g. due to excessive pollution levels and/or ambient conditions (wind, temperature, background pollution levels etc.). Moreover, complete testing the response due to known or unknown equipment failures can be tested using a TVSS.

4.3.2 TVSS based on commercial simulation programs

The Cross-City Tunnel (Sydney) has challenging constraints on the tunnel-ventilation system, as no flow may exit any of the eight (8) tunnel portals, see Figure 3. In order to obtain this objective, the flow is controlled in all tunnel sections ensuring that vitiated tunnel air is only emitted at the single portal-air extraction. Due to general project delays, the envisaged site-testing time was reduced from about half a year to two weeks. This prompted the development of a tunnel-ventilation-system simulator that was used to test the control-system software. The TVSS was based on the simulation program RTV by EQUA, which had been used for the design and already was tested against another recognised program RoadTUN and an in-house development NETZ. The testing revealed numerous software bugs in the ventilation-control software that were corrected during the testing period. The final commissioning on site was conducted in two weeks during which only one parameter had to be adjusted. For more information, see Riess, Altenburger and Sahlin (2006) (6).

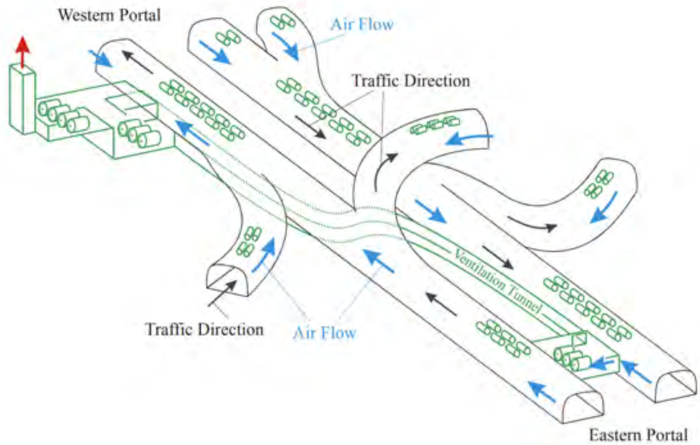


Figure 3: Cross-City Tunnel (Sydney, Australia): Inflow at all portals at all times, from Riess, Altenburger and Sahlin (2006) (6)

Based on the good experience from Sydney, it was decided that the tunnel-ventilation-control system of E4FS (E4 Bypass Stockholm) should be tested using a tunnel-ventilation-system simulator. Also in this case, the simulation basis was a commercial software i.e. IDA Tunnel, which can be considered as the successor of RTV. The client awarded a contract to the software manufacturer, EQUA, to provide a user interface (HMI) and a software interface based on the communication protocol UPC UA. As stated in the call for tender for E4FS, this TVSS was provided free of charge to the contractor responsible for delivering the control system, who was required to conduct exhaustive witnessed tests of the tunnel-ventilation-control system; see test hierarchy in section 4.2.

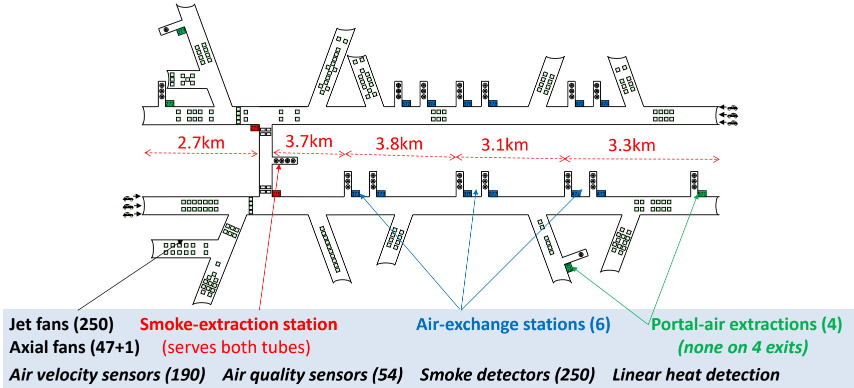


Figure 4: E4FS – Förbifart Stockholm (southern section), overview

4.3.3 TVSS imbedded in the software of the tunnel-ventilation-control system

From a procurements point of view, it can be difficult to demand using a certain software for the TVSS. Moreover, the interfacing with the control-system software can be cumbersome. Consequently, HBI has in several projects adopted the approach to include a high-level description of the simulation program that then is to be programmed by the control-system contractor, so that it can be used for the testing of the control system.

This approach was successfully carried out in the following projects:

- Engelberg Basis tunnel, Leonberg (DE),
  see U. Willberg and A. Schieβl-Pecka (2018) (13)
- Tunnel Schwarzer Berg, Eltmann (DE),
  see M. Wehner and E. Krokos (2015) (14)
  and E. Krokos and M. Wehner (2014) (15)
- A3 Katzenberg, Würzburg (DE)
- A99 Tullen Allach, Munich (DE)

One uncertainty by this approach is to ensure that the programmed simulator provides sensible results, which can be mitigated when the contractor programming the TVSS has the possibility to compare simulation results with those by the tunnel-ventilation designer. A further risk is that the simulator may not be available early enough in the project to benefit from it in a timely manner.

4.3.4 TVSS as stand-alone digital twin

4.3.4.1 Principle

The ultimate approach is to have a digital twin of the tunnel with its tunnel-ventilation system. It interacts directly in real time with the control system and visualizes the results directly in the user interface (instantaneous values only), see principle in Figure 5. This is also called "software-in-the-loop" (SIL) and can be used as "hardware-in-the-loop" (HIL).

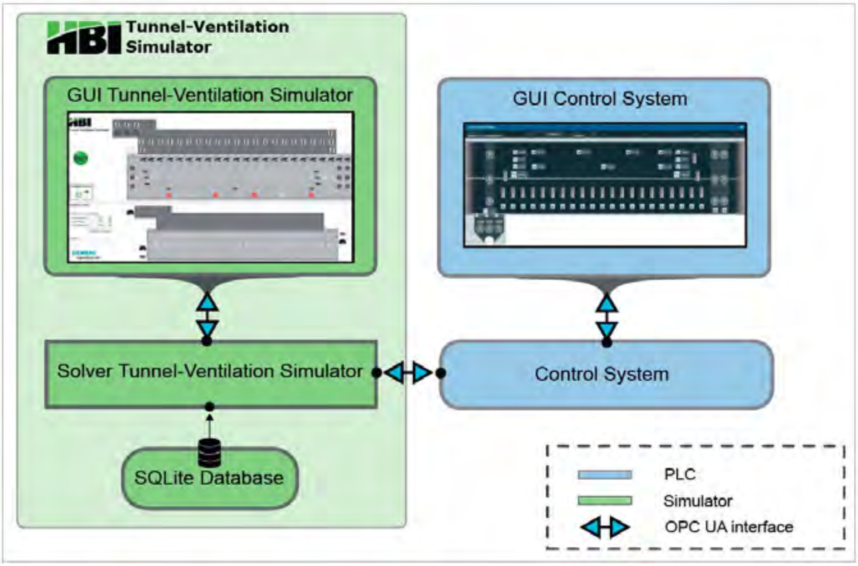


Figure 5: Digital twin tunnel-ventilation-system simulator as "software-in-the-loop" (SIL) can be used as "hardware-in-the loop" (HIL)

In order to be useful, the TVSS will be created prior to the programming of the control system. Consequently, it will have its own HMI. In the quality assurance, the results of the TVSS shall be compared with those from the design of the tunnel-ventilation system.

For reasons of numerical stability, the HBI-TVSS has a number of pre-programmed fire positions. In addition to sensors for air quality (e.g. CO, NO_2 and visibility) and smoke detection, the HBI-TVSS incorporates a linear heat-detection system. In this manner, the ventilation-control system has all the required information to provide the settings of the actuators (ventilation equipment). No manual interaction is required.

As for the genuine ventilation-control system, each sensor and actuator can be operated in various modes:

- Physical mode: can only read the information from the control system
- Virtual mode: can read and write information from/to the control system
- Forcing level:
  - None: gives calculated values to control system
  - Forced: gives forced values to the control system
- Functioning mode:
  - Automatic: the control system specifies the setpoint of the actuator
  - Manual: the user specifies the setpoint via the HMI of the control system
- Operating mode:
  - Remote: the control system determines the setpoint of an actuator
  - Local: the TVSS determines the setpoint of an actuator
  - Servicing: the setpoint is specified using the HMI of the TVSS

In addition to the pure simulation mode, the TVSS can be operated in mixed modes incorporating the physical sensors or actuators, see Figure 6.

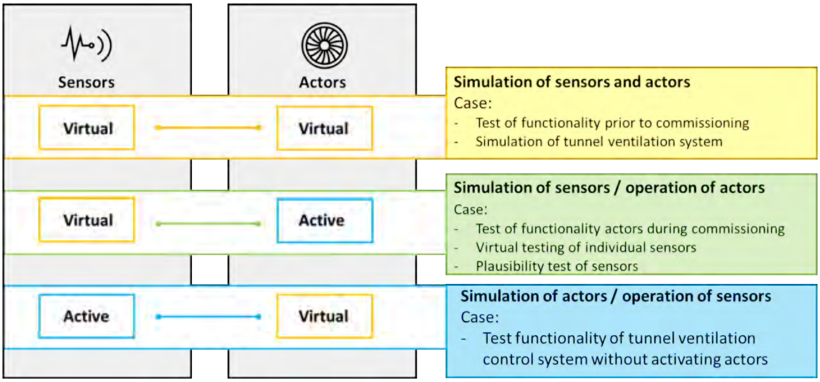


Figure 6: HBI-TVSS simulation modes

4.3.4.2 Case stories

Kaisermühlentunnel crosses the Austrian capital Vienna and had to be refurbished permitting only few tunnel closures, which should be of a maximum duration of half an hour. Considering that the tunnel was a complex tunnel network, see Figure 7, a tunnel-ventilation-system-system simulator, see Figure 8, was developed to test the ventilation-control software. This solution was endorsed by all parties involved including the system integrator, see (15).

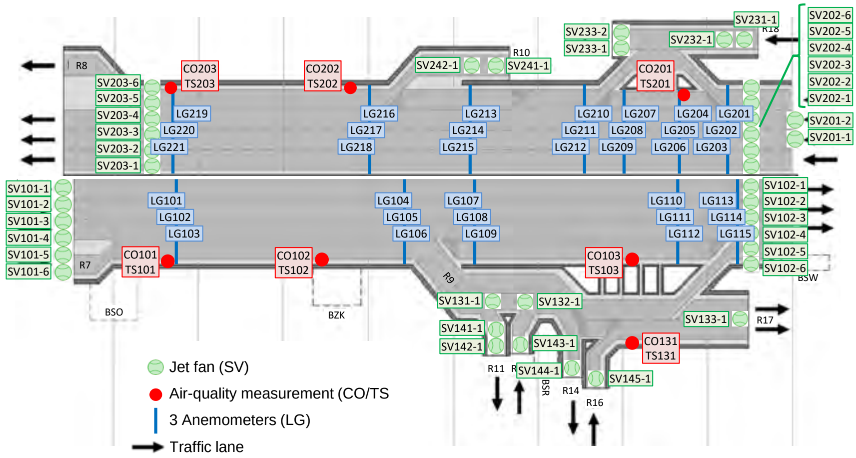


Figure 7: Kaisermühlentunnel (AT), tunnel-ventilation layout

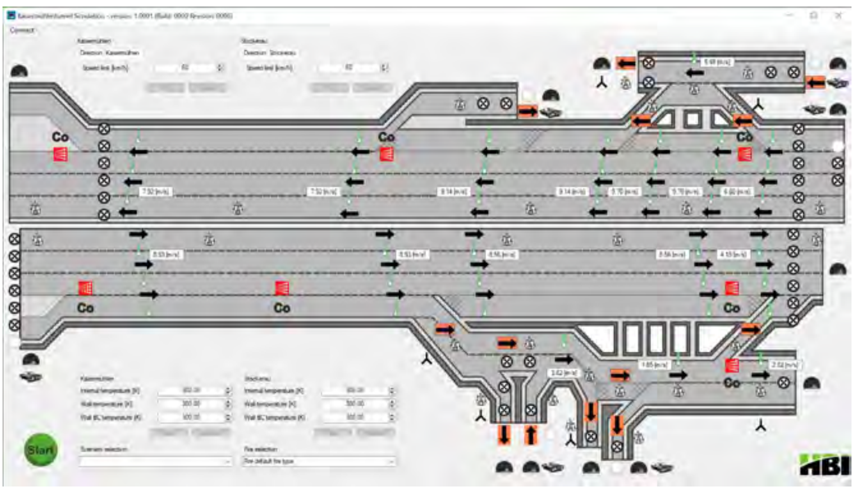


Figure 8: Kaisermühlentunnel, HMI for the digital twin tunnel-ventilation-system simulator

Einhausung Schwamendingen is a vital highway crossing Zürich (Switzerland), which had to be converted from an partly open road to a tunnel (see Figure 9) whilst being open to traffic respectively have only few tunnel closures of short duration. Therefore, this transition process included numerous migration steps. The resulting variants of the ventilation-control software were tested using a tunnel-ventilation-system simulator. For further information, see Petschen et al. (2023) (4).

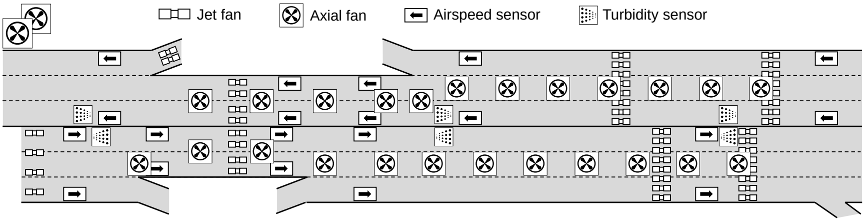


Figure 9: Einhausung Schwamendingen (CH), tunnel-ventilation layout

The tunnel Kriegsstrasse (DE) has two access ramps as well as two intermediate exit ramps. Moreover, the west-bound tunnel tube connects to an underground parking facility (TK), see Figure 10. The tunnel is ventilated longitudinally using jet fans. The experiences by using the tunnel-ventilation-system simulator are described by Thumm and Wehner (2021) (5). 286 scenarios incorporating the automatic ventilation control during normal operation as well as in case of fire were tested. Discrepancies compared to the defined requirements in particularly regarding the safety of the tunnel users were found, which led to determination of changes to the ventilation-control software. These changes were incorporated in a timely manner prior to installation on site.

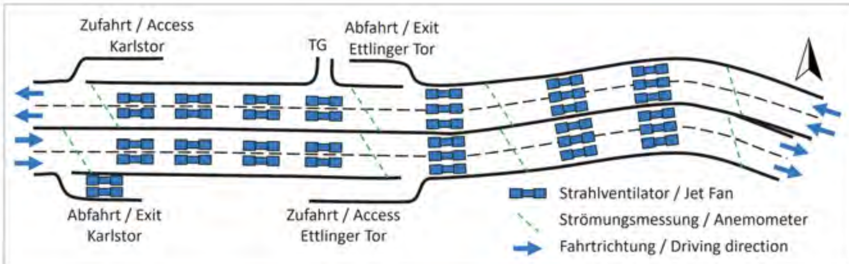


Figure 10: Tunnel Kriegsstrasse (DE). Traffic routing and positions of jet fans and anemometer. TG = underground parking facility

Real life installations as well as the tunnel-ventilation simulator connected to the SCADA system can be observed in the Tunnel Digitalisation Center (TDC), see Petschen et al. (2023) (4).

5 INDUSTRY 4.0 AND ASPECTS OF PREDICTIVE MAINTENANCE

Maintenance of equipment is typically performed on regular e.g. annual basis, during scheduled tunnel closures. Without any specific information on equipment status or failures, maintenance operations may not be adequately prepared. Moreover, components may be replaced prematurely as potential faults or malfunctions cannot be addressed without additional tunnel closures.

From an automation perspective, the SCADA system is referred to as level 2 and the regional traffic-management system as level 3; see section 4.2.2 regarding the testing at these levels. Level 4 also called Industry 4.0 also incorporates an end-to-end digitalisation of the equipment to the management and maintenance system. Kuhn et al. (2020) (18) and Jung (2020) (19) report on ways to realise this for tunnel-ventilation sensors. These often already have numerous digital information that then can be made available e.g. via a gateway to a service partner, who then will not have access to the lower level systems (2 and 3).

The level 4 Condition Monitoring Systems (CMS) deliver detailed data on the equipment, which then can be accessed by using a data-communication system that is independent of the SCADA system. With this architecture, external parties may access the data of the CMS but cannot influence any of the equipment controlled by the SCADA system. In this manner, in a Swiss test program regarding the application of CMS, additional vibration sensors are attached to a fan, see Frey (2021) (16). Subsequent to pre-processing, the data is made accessible via SINEMA RC/MindSphere and hence independently of the SCADA system. In a similar manner, the application of CMS for a jet fan and an emergency door is being tested and can be seen in the Tunnel Digitalisation Center (TDC), Petschen et al. (2023) (4). One difficulty has been to have an adequately stable mobile phone connection to the CMS-installations in TDC. Further reporting on TDC can be found in Jung, Celebi and Petschen (2023) (20).

6 CONCLUSIONS

BIM-models are more difficult to incorporate in tunnel design than for buildings. Nevertheless, they are becoming industry standard and are extensively used in particular for clash control. Benefitting from carefully selected attributes, interface management can be carried out to civil structures and other equipment including the control system. Based on experience, the design shall not be conducted using merely 3D models. 1D line charts and 2D drawings are also required.

Regarding commissioning of the tunnel-ventilation-control system, a cascade of testing has been described. One important aspect is the application of tunnel-ventilation-system simulators (TVSS) to enable complete testing in an office environment, which results in a high confidence level of the system and requires much less resources than site testing. The testing shall be complete and hence also incorporate unusual scenarios.

Following the ideas of complete digitalisation (Industry 4.0), enables the transmittal of almost unlimited amount of data, which then can be analysed for the predictive maintenance. The resulting conditions-monitoring systems (CMS) apply an independent data transmission so that there is no risk of interfering the SCADA system nor the regional traffic-management system. In this manner, external maintenance partners can access the data and assist in optimising the maintenance.

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