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Ventilation of the E4 Stockholm Bypass

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Abstract: *56 km of tunnel tubes comprise the road tunnel E4 Stockholm Bypass. The main line is 17 km long and the twelve connecting ramps have individual lengths of up to about 2 km. The ventilation system encompasses: 250 jet fans, 47 axial fans, one large low-pressure fan, 62 positions with triple anemometers and 54 air-quality sensors. Fire detection is conducted with linear heat sensors and smoke detectors.*

Frequently occurring traffic congestion of the 140 000 vehicles daily cannot be excluded. Considering, the very onerous air-quality criteria, longitudinal ventilation of such a network is a challenge. Air-quality requirements have to be met in the tunnel and outside the portals with minimum energy consumption. It is not trivial to decide between using the fresh-air stations or to take in the not entirely fresh air via the entry ramps.

As a mitigation measure against fire during traffic congestion, a fixed fire-fighting system (FFFS) will be installed. A research project was carried out in order to find the most appropriate ventilation strategy. In spite of the complex tunnel structure, simple control principles were developed.

In case of fire, active ventilation control based on measurements of flow velocities will be used. Detailed descriptions of the control principles including data treatment and system-selection priorities have been elaborated. Equipment failures are catered for and plausibility tests of the flow-velocity measurements carried out.

In the tunnel ventilation simulations, the control procedures are mimicked. In this manner, all possible including less realistic scenarios have been simulated in order to test the robustness of the ventilation-control routines.

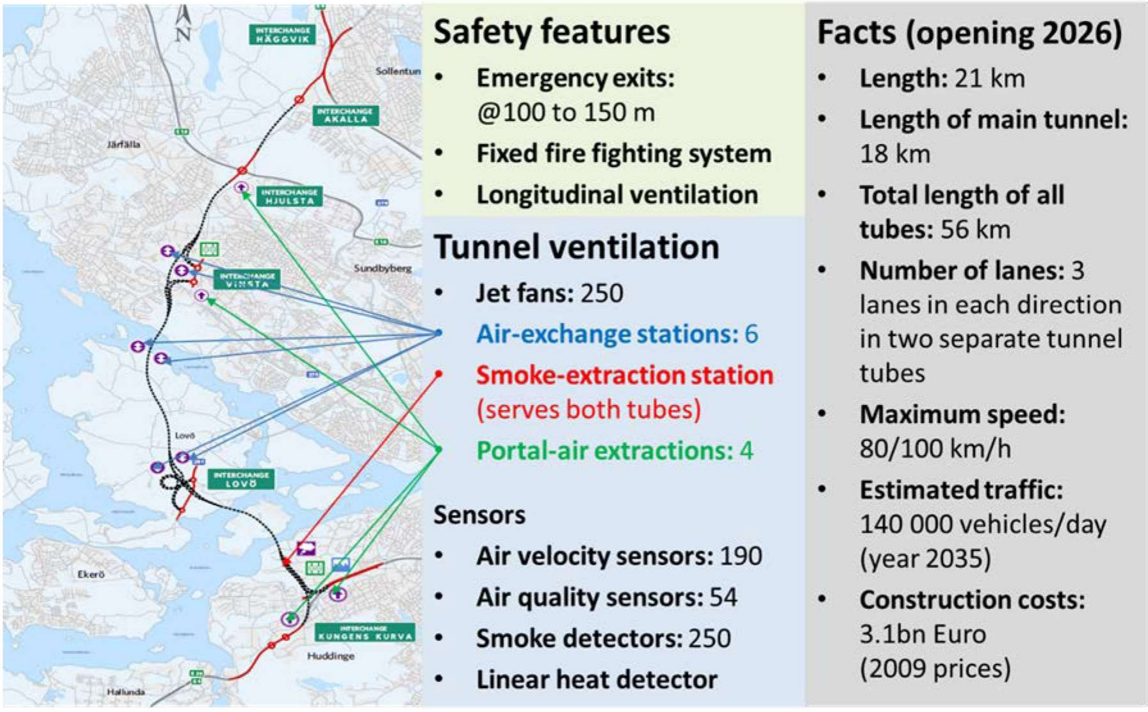
For test purposes and the commissioning (FAT and SAT), a tunnel-ventilation simulator is being developed that links the genuine tunnel-ventilation controller (soft- and hardware) with the simulation tool. In this mode, the tunnel-ventilation simulator receives the fan settings from the external control program and computes the resulting values of flow speed, air quality, temperatures etc.

Keywords: *road tunnel, ventilation control, simulator, FAT/SAT*

1. Introduction

1.1. E4 Stockholm Bypass

56 km of tunnel tubes comprise the road tunnel E4 Stockholm Bypass, see overview in Figure 1. The main line is 17 km long and the twelve connecting ramps have lengths up to about 2 km. As traffic congestion of the daily 140 000 vehicles cannot be excluded, a fixed fire-fighting system (FFFS) will be installed. [3] provides a description of the project and five envisaged contracts for the installation of the electromechanical equipment e.g. contract FSE903 concerns the tunnel-ventilation equipment including local control of fan building, whereas contract FSE901 delivers the control system including the sensors used for the tunnel-ventilation control.



Safety features

- **Emergency exits:** @100 to 150 m
- **Fixed fire fighting system**
- **Longitudinal ventilation**

Tunnel ventilation

- **Jet fans:** 250
- **Air-exchange stations:** 6
- **Smoke-extraction station** (serves both tubes)
- **Portal-air extractions:** 4

Sensors

- **Air velocity sensors:** 190
- **Air quality sensors:** 54
- **Smoke detectors:** 250
- **Linear heat detector**

Facts (opening 2026)

- **Length:** 21 km
- **Length of main tunnel:** 18 km
- **Total length of all tubes:** 56 km
- **Number of lanes:** 3 lanes in each direction in two separate tunnel tubes
- **Maximum speed:** 80/100 km/h
- **Estimated traffic:** 140 000 vehicles/day (year 2035)
- **Construction costs:** 3.1bn Euro (2009 prices)

Figure 1 - Overview of E4 Stockholm Bypass, see also schematic Figure 2.

1.2. Ventilation system

The longitudinal ventilation system encompasses 250 jet fans operated by frequency converters enabling them to give full thrust in both directions. Moreover, 47 identical axial fans each with a nominal flow rate of 200 m^3/s are being installed. One portal-extraction station is due to recently discovered bad rock quality currently being changed to use a large low-pressure GRP-fan situated in the stack.

As shown in the schematic below (Figure 2), each main line has three air-exchange stations each with a capacity to extract 600 m^3/s of vitiated air and subsequently to supply the same amount of fresh air. The fans in the fresh-air stations can be reversed to be used for smoke extraction.

Moreover in order to reduce the extent of smoke spread in case of fire, a smoke-extraction station that has a fourth redundant fan is envisaged. This is the only ventilation station that serves both main-line tunnels. The design smoke-extraction capacity is 600 m^3/s. Four of the exit portals have portal-air extractions with the purpose of minimising the impact of vitiated tunnel air on the environment.

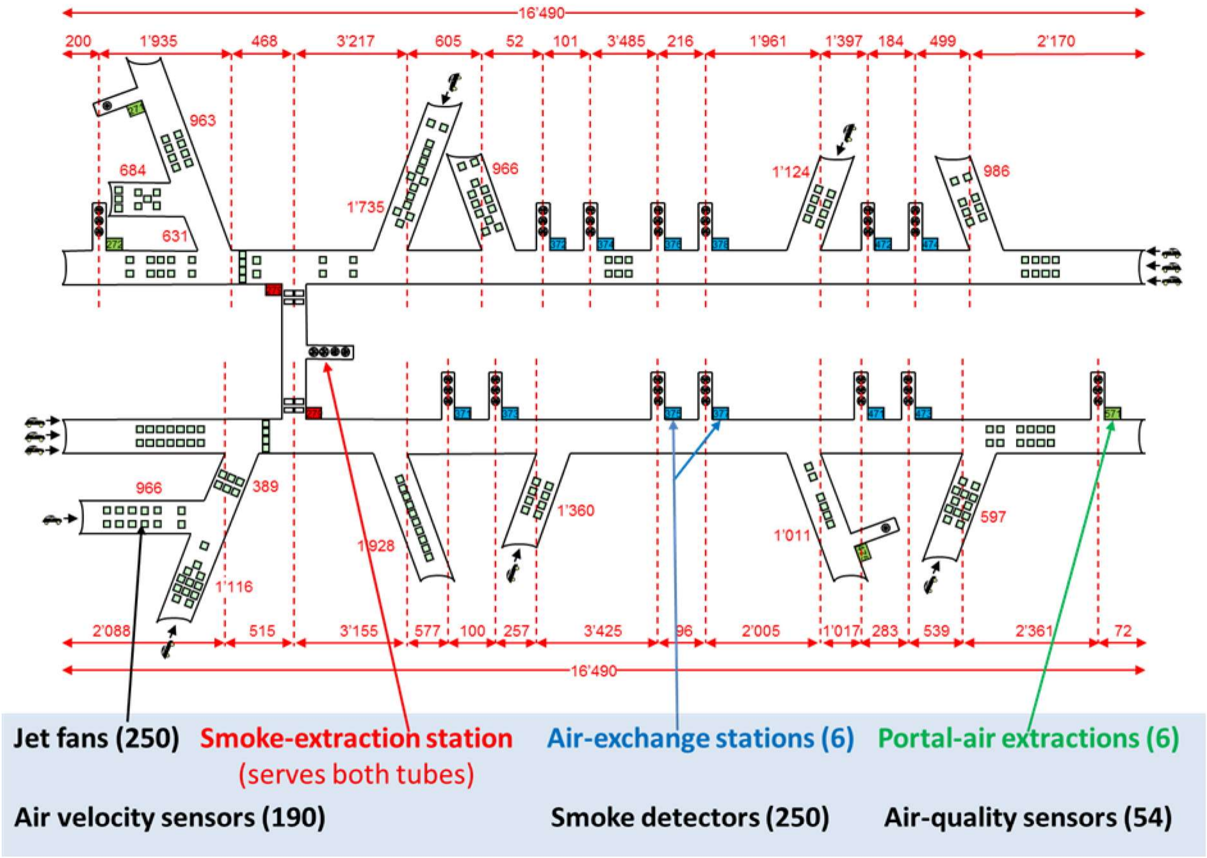


Figure 2 – Schematic overview of tunnel-ventilation system with indication of length [m] (red numbers)

The in-tunnel air quality is monitored by 54 air-quality sensors that are placed on strategically important locations though maximum 1 km apart. Each sensor measures visibility as well as concentrations of NO_2 , NO_X and CO.

In particular for the active control of the longitudinal flow in case of fire, the 62 positions with anemometers are of paramount importance. Consequently, they are tripled in order to enable automatic plausibility checks. Fire detection is conducted with linear heat sensors and smoke detectors.

Brandt et al. [4] offers a more detailed description of the ventilation system and its control.

2. Normal ventilation

2.1. Internal air-quality challenges

The exact air-quality limits have been debated for years and are not yet decided. Based on numerous simulations on E4 Stockholm Bypass assuming the decided ventilation system, it was proposed to permit a maximum air-quality limit of NO_2 = 1000 $\mu g/m^3$ [5]. However, an earlier study [6] comparing the operation costs with the benefit in terms of lower mortality rates suggested much lower values.

Considering that very onerous air-quality criteria are being expected, longitudinal ventilation of such a network is a challenge. Air-quality requirements have to be met in the tunnel and for the portals at minimum energy consumption. It is not trivial to decide between using the fresh-air stations or to take in the not entirely fresh air via the entry ramps.

2.2. Controller principle for internal air quality

It was found that a step-wise controller would be the most appropriate control principle as this is robust and yet flexible. Due to the frequency converters, the jet fans can operate at partial load, which normally leads to lower power consumption than having fewer jet fans operating at full load [2].

The tunnel is divided into logical ventilation technical sections (*VTS*). For the ventilation during normal operation, the *VTS* are combined to larger normal operation sections (*NOS*). Each *NOS* has at least one air-quality sensor and ventilation equipment assigned to it. The same ventilation equipment can be assigned to several *NOS* with the priorities of their usage depending on the specific section *NOS*.

Each ramp and each portal-air extraction has its own sub-controller, see Figure 3. The input comes from the air-quality and air-flow sensors. In total, the main controller of the northbound tunnel alone consists of 11 sub-controllers. The setup for the southbound direction is similar.

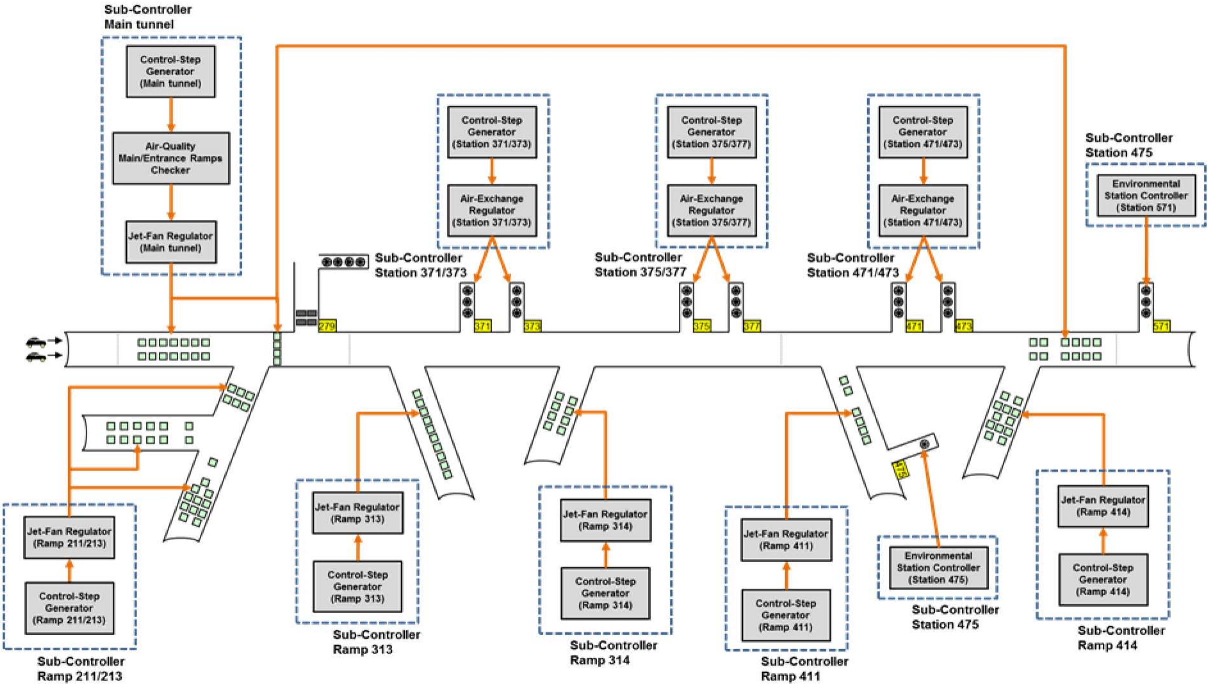


Figure 3 - Overview of controllers for normal operation in northbound tube

Each sub-controller reacts and works independently of other sub-controllers and has its unique Control-Step Generator (*CSG*). The consequence of this is that for certain ventilation equipment, different steps i.e. different ventilation capacities could be required. The dilemma is that different sensors could give diverging instructions to the same actuators (fans). In order to resolve this, it was decided to assign the control to the sensors with the highest value. The combinations of sub-controllers may also result in conflicts that therefore have been identified and rules for their resolution defined.

In the main tunnel, the controller automatically assesses whether it is best to improve the air quality by increasing the flow rate or by using air from the ramp.

For a simple tunnel, it can be ensured that the step-wise controller provides maximum ventilation capacity when the highest control step is engaged. Due to the interdependencies, this is somewhat more complex in this type of configuration. Consequently, in case a control step higher than the maximum would be desired, the maximum ventilation capacity is engaged for the main line and all connecting ramps. In this manner, the risk of undesired tunnel closure caused by in-tunnel air quality exceedances minimised.

2.3. Minimising impact on ambient air

As a result of the analysis of the environmental impact assessment (Swedish MKB: Miljökonsekvensbeskrivning), vitiated tunnel air can be extracted out of the tunnel prior to four exit portals and exhausted through stacks. The objective is to respect the mandatory air-quality criteria and if possible to meet the air-quality target values, see table 1. However, there is no requirement to have e.g. a net portal inflow. Consequently, the strategy is at most to extract the vitiated tunnel air that flows towards the portal-air extraction. In fact, only a certain pre-set fraction of the flow approaching the air-extraction station is being extracted. The values for the pre-set fractions are adjusted regularly e.g. yearly based on results from a monitoring programme.

Measurements of the air quality outside the portal are used to assess whether or not it is worthwhile extracting the vitiated tunnel air at all. Recent dispersion modelling [7] has shown that it is permissible to have very low exit velocities at the stacks of the air-exchange stations, which minimises energy consumption and simplifies operation.

Table 1 Air-quality criteria and targets in Sweden

Averaging period	**PM_{10} [μg/m^3]**			**NO_2 [μg/m^3]**		
	Criteria (mandatory)	Target value	Comment	Criteria (mandatory)	Target value	Comment
Year	40	15	Not to exceed	40	20	Not to exceed
24h	50	30	Max exceedance 35 days/year	60	-	Max exceedance 35 days/year
1 h	-	-		90	60	Max exceedance 175 h/year

3. Smoke management

In case of fire, the smoke is always ventilated in direction of traffic and extracted at the first possible downstream location. If this station e.g. due to equipment failure is not available, the subsequent one is engaged.

Due to the different objectives compared to normal operation, smoke management sections called *SMS* have been defined. Except for the first *SMS* at the entry sections of the tunnel, all boundaries line up with those of the ventilation technical sections (*VTS*). In case of fire in the main line, following principles are applied:

- The smoke is always extracted from a ventilation station or blown out of the exit portal i.e. smoke management of the main tunnel is never occurring over a ramp.
- All non-incident ramps protect themselves by having a controlled flow velocity of 1,0 m/s towards the main tunnel.

An example of the smoke management is shown in Figure 4. A longitudinal flow velocity of 3,0 m/s in the direction of traffic is specified. The smoke is extracted at the smoke-extraction station. All ramps have their own control lops ensuring a velocity of 1,0 m/s towards the main line.

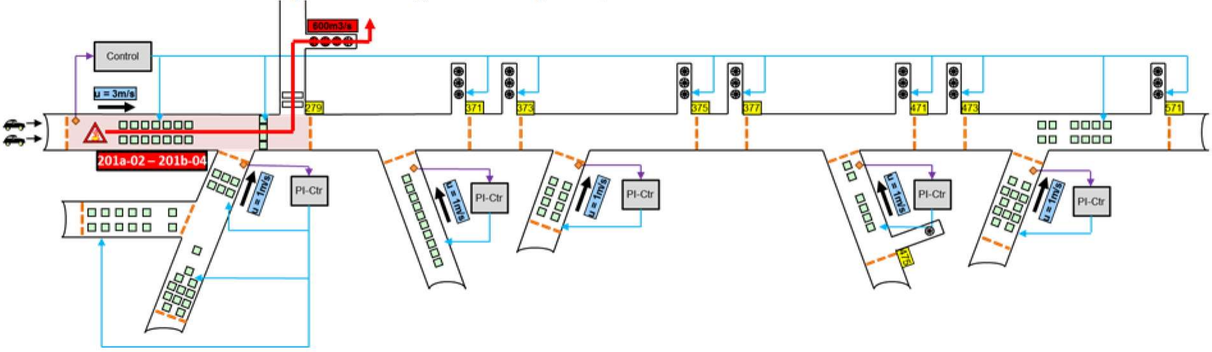


Figure 4 - Example of smoke management control loops for sector

Similarly, in case of fire in a ramp, smoke is always blown in direction of traffic and extracted at the first possible extraction point or blown out of an exit portal. The other ramps and connecting sections of the main tunnel protect themselves by ensuring a velocity of 1,0 m/s.

Automatic plausibility checks of the quality of the flow velocity measurements by the anemometers are being carried out using logical rules. If the flow measurements are judged of inadequate quality, the second set of anemometers is selected; and if they are also judged to be of inadequate quality, the velocity is calculated based on the measurements in the other tunnel sections and the air-extraction rates.

In case of fire, one of the following ventilation programs is selected:

- Standard Fire Ventilation with an air velocity of approx. 3,0 m/s
- Minimal Fire Ventilation with an air velocity of approx. 1,5 m/s; which is automatically selected, if the FFFS does not function and there is congested traffic.

The set points of the flow velocities are parameters used in the active control loops and if at a later stage other values are preferred, these can easily be changed by an authorised person. There will also be a possibility to select a fire-ventilation program with fixed fan settings.

The operator, typically on request by the fire brigade, can also select following programs:

- Forced Fire Ventilation i.e. maximum possible air velocity
- Adjustable Fire Ventilation: initially freezing all control settings and then manually changing set points of velocities or operating individual fans.

It is essential to engage the ventilation system quickly in case of fire. Therefore, the fire ventilation plan is initiated already in case of a pre-alarm. The tunnel portals are not closed to traffic at pre-alarm and evacuation is not initiated. Pre-alarm can be detected by a smoke detector or the linear heat detector and can be selected by the operator. If subsequently an alarm is raised, the fire zone corresponding to the alarm is applied and the full emergency plan including tunnel closures and evacuation is engaged.

4. Simulation Tool: IDA RTV

4.1. Introduction

The design of the tunnel-ventilation system and the testing of the control routines were carried out using the software Road Tunnel Ventilation (IDA RTV) by the company EQUA (www.equa.se). This one-dimensional instationary flow-simulation program also enables specifying control loops using logical libraries. It has therefore been possible to test all possible scenarios varying e.g. traffic, external winds and temperatures as well as the heat-release rate of fires. Moreover, system failures can be mimicked.

4.2. Tunnel simulator

The IDA RTV program will be at disposition for the contractor FSE901 that is awarded the contract to build the tunnel-ventilation control system.

The contractor will be requested to interface the IDA RTV model with his software-development environment in order to be able to conduct software factory tests. Here, the IDA RTV program will mimic the responses from the tunnel such as flow velocities and air qualities, see Figure 5.

Example: The application logic orders set-points for the fans, which are then sent to the simulator. The simulator calculates the airflow in the tunnel which also is a consequence of traffic flow, ambient conditions and fires etc.. The simulated air flows are sent back to the application logic so that it can instruct subsequent actions i.e. specify new fan settings.

The tunnel-ventilation system is very complex and extensive. The client and the contractor need adequate time to test that all requirements are appropriately catered for in the implemented software. To minimize the project risks due to tunnel ventilation, logic errors and/or resolve problems detected prior to the SAT (Site Acceptance Test), this tunnel simulator is used as a testing tool during the FAT (Factory Acceptance Test).

This, however, only verifies that the software of the control system functions as planned. Site testing (SAT) will finally be conducted in order to confirm that the control of the tunnel-ventilation system fulfils the design objectives.

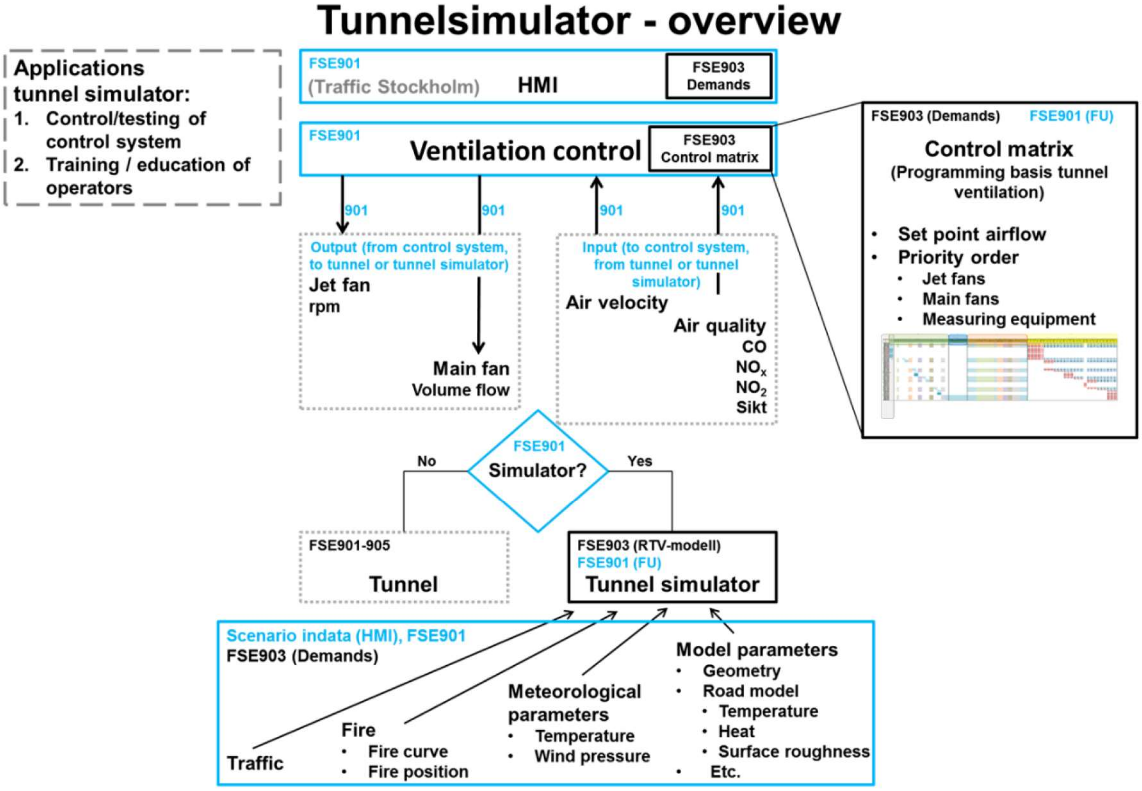


Figure 5 - Overview of tunnel simulator. Contractors [3]: FSE901 = controls and FSE903 = ventilation

4.3. Work process for the controls contractor

The controls contractor FSE901 (see [3]) shall implement the IDA RTV model (without the IDA RTV control routines) to produce a real-time tunnel simulator, which can handle IDA RTV files. The tunnel simulator will mimic the tunnel and its sensors physical response to the same accuracy as the simulator in IDA RTV. The contractor shall implement all control functions in a hardware solution (PLC), which is the real control system with its software solution called Real-time Tunnel Control. The Real-time Tunnel Control is subsequently interfaced with the tunnel simulator.

From the HMI (Human Machine Interface), authorized users can view the status for all variables and parameters that have an impact on the simulation. Also from the HMI, it shall be possible for authorised users to edit all variables and parameters that have an impact on the simulations.

This system of tunnel simulator, documentation, courseware and other support functions allows for useful operator training. The approved version of the control system and the final version of the tunnel simulator will be implemented in an operation simulator.

The additional effort required for the tunnel simulator lies in the development of the interface between the dynamic software model of the tunnel and the PLC. Often, the implementation of this interface can be based on the Open Process Control (OPC) standard. This reduces the need for manufacturerdependent coding. The interface of IDA-RTV has to manage the time step of the numerical model and alarms. For instance, the simulation model may not lag too far behind physical time. The numerical model sometimes has to negotiate system discontinuities using elaborate and time consuming methods, so that exceptions may occur, even if the average progress of the simulation model is considerably faster than real time.

Further details of the testing of the tunnel-ventilation control system and its development is described in Elertson [1].

5. Conclusion

The E4 Bypass Stockholm is a large road tunnel complex with in total 56 km of tunnel tubes. The main line is 17 km long and has several entry and exit ramps. The longitudinal ventilation of such a long and complex tunnel is a challenge for normal and smoke-management operation.

For normal operation, a step controller was developed that is composed of several sub-controllers. A methodology has been found to select the determining air-quality sensors. Although several sub-controllers rely on the same fans (actuators), a method to resolve potential control conflicts ensuring adequate ventilation in all tunnel sections has been found.

The longitudinal smoke management uses closed loop feedback to reach the specified flow velocity. Based on a priority system, alternative sensors (anemometers) as well as actuators (fans) are automatically engaged if required

During the FAT, the contractor verifies the software using the tunnel-ventilation simulator. This is for his benefit and ensures for the client that the implemented functions in the control system for the tunnel ventilation meets the requirements in the contract. In this way, application logic for tunnel ventilation is tested cost-effectively in an office environment. Doing this, systems, design errors, discrepancies and risks of application logic can be identified and corrected before the SAT begins.

In previous tunnel projects, the time for testing tunnel ventilation has been shortened because of pressure to open early considering the economic advantages for the public. The client has concluded that the money invested on a simulator is well worth in order to reduce time and to ensure quality. In a global context, the objective is to act in a smart manner. SMART = **S**ave **M**oney **A**nd **R**educe **T**ime.

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