COMISSIONING OF THE VENTILATION CONTROL OF THE E4 STOCKHOLM BYPASS

R. Brandt; HBI Haerter, CH
L. ELERTSON; Swedish Transport Administration, S

ABSTRACT

56 km of tunnel tubes compose the road tunnel E4 Stockholm Bypass. The main line is 17 km long and the twelve connecting ramps have lengths of up to about 2 km.

Frequent 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 for the portals at minimum energy consumption. It is not trivial to decide using the fresh-air stations or to take in the not entirely fresh air via the entry ramps.

In case of fire, active ventilation control based on measurements of flow velocities is being 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 as well as 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 simulation 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: ventilation control, commissioning, tunnel-ventilation simulator

1.   INTRODUCTION

1.1.   E4 Stockholm Bypass

56 km of tunnel tubes compose 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.
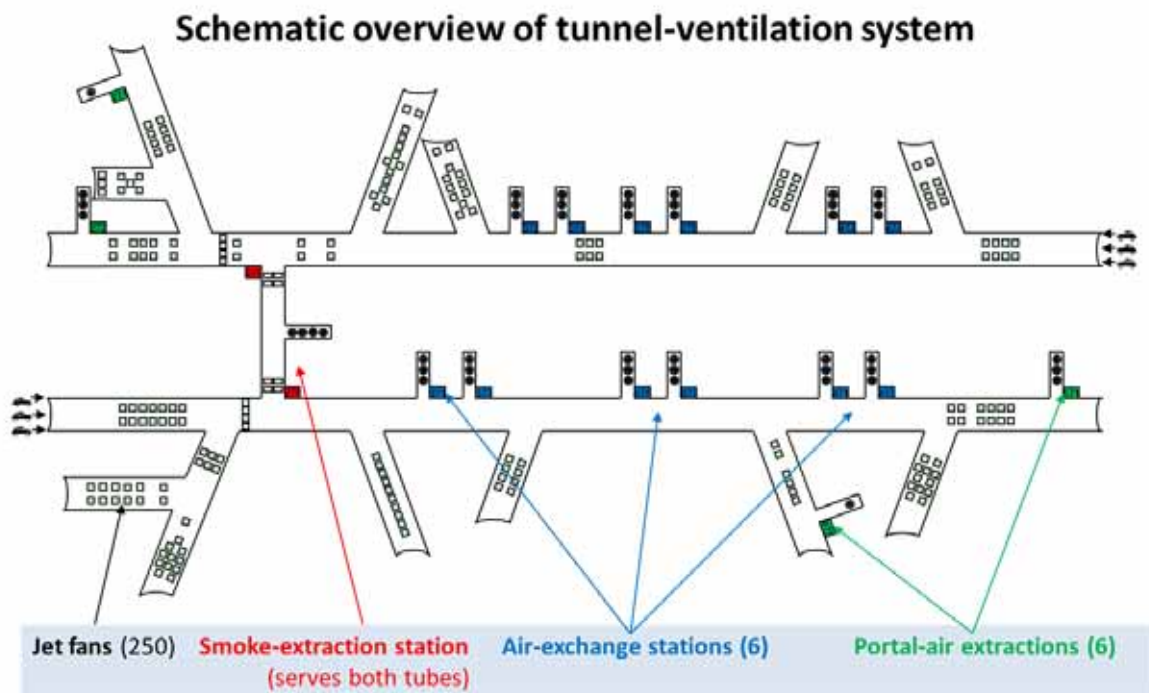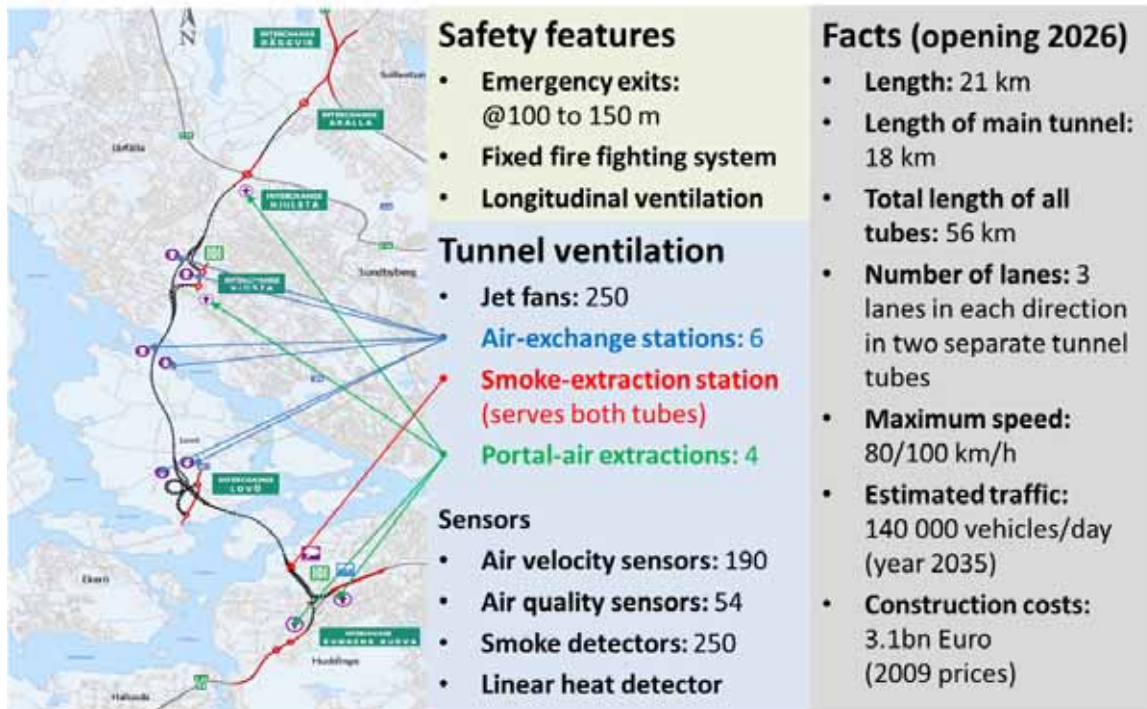
**Figure 1:** Overview of E4 Stockholm Bypass

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, 48 identical axial fans each with a nominal flow rate of 200 m^3/s are being installed.

As shown for the northbound tube 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 length with smoke 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 to be able to minimise the impact of vitiated tunnel air on the environment.

100% air-exchange station
100% jet-fans in traffic direction
100% air-extraction stations at portals
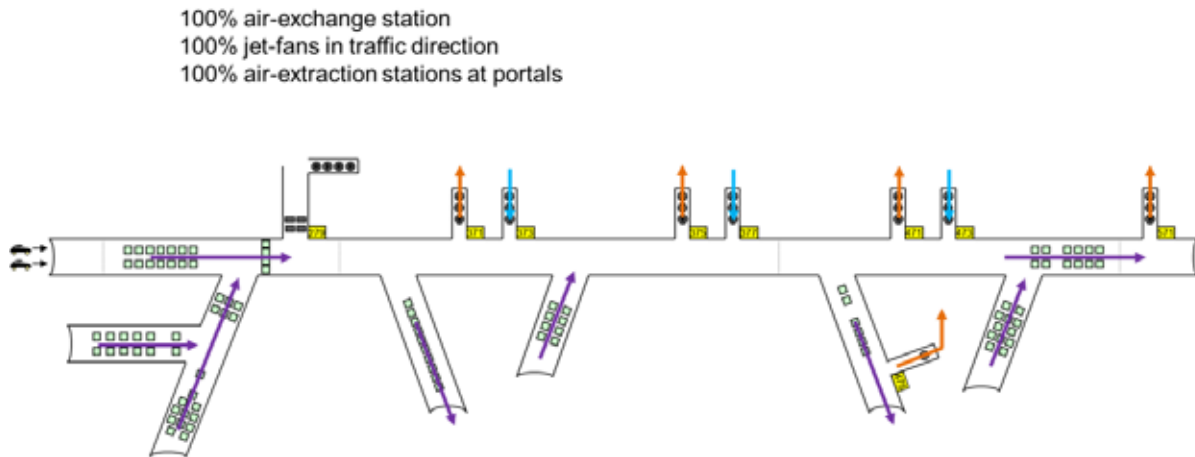
Figure 2: Northbound tube: maximum ventilation mode during normal operation

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 NOx 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] offer a more elaborate description of the ventilation system and its control.

2. NORMAL VENTILATION

### 2.1. Internal air-quality challenges

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 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.

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 triple 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 consists of 11 sub-controllers.
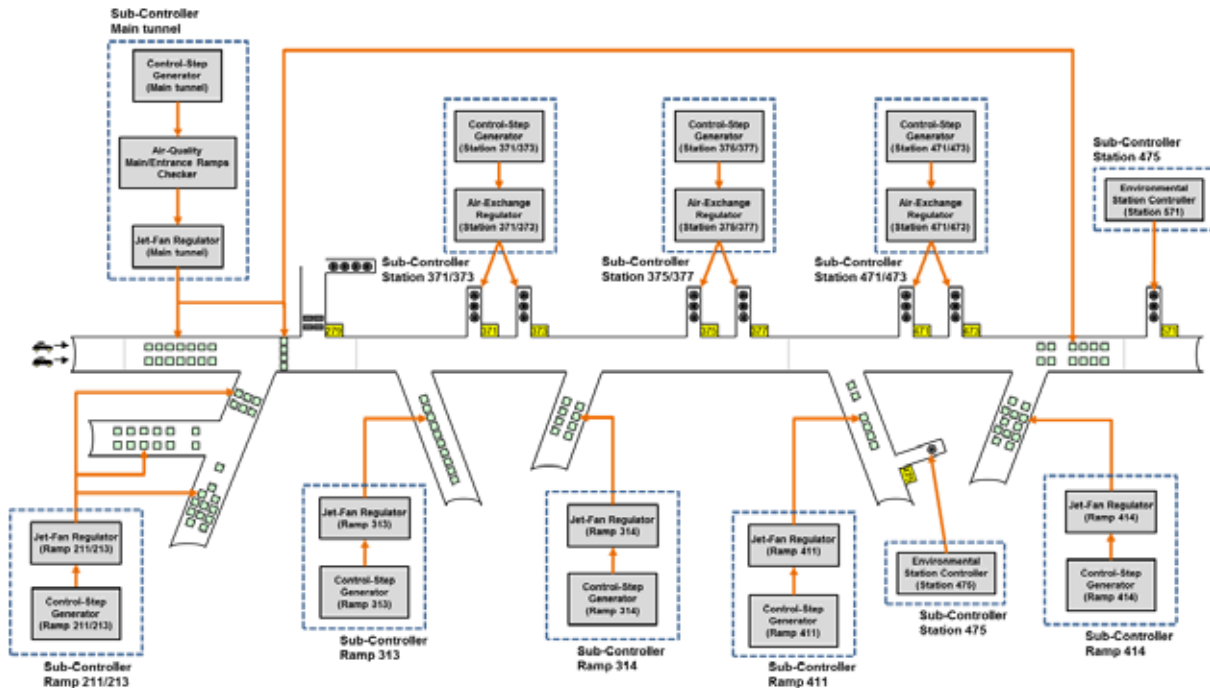
Figure 3: Overview of controllers for normal operation

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, as shown in Figure 2. In this manner, the risk of undesired tunnel closure caused by too bad in-tunnel air quality is minimised.

2.3.   Minimising impact on ambient air

As a result of the analysis of the impact on the environment (Swedish MKB: Miljökonsekvensbeskrivning), vitiated tunnel air can be extracted at four exit portals. Here, the strategy is at most to extract the 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. Moreover, 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.
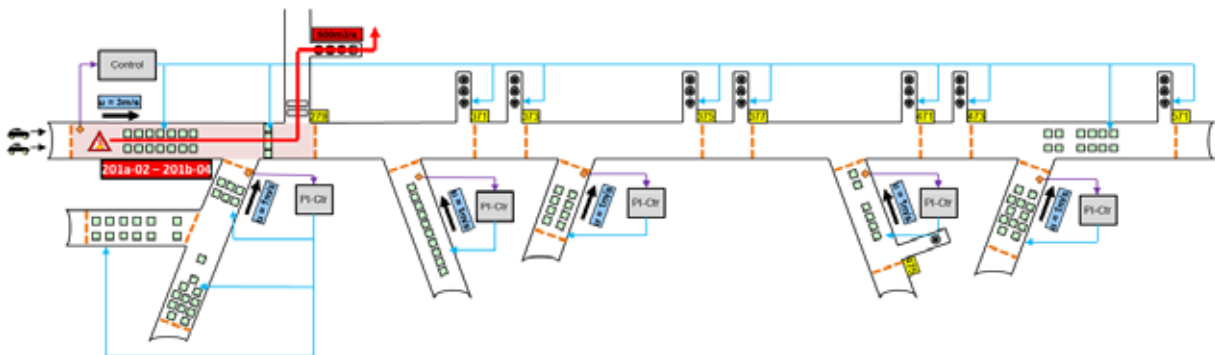
3.   SMOKE MANAGEMENT

In case of fire, the smoke is always ventilated in direction of traffic and extracted at the first possible downstream location. If this station is out of order, 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 m/s towards the main tunnel.

An example of the smoke management is shown in Figure 4. A longitudinal flow velocity of 3 m/s in direction of traffic is specified. The smoke is extracted at the smoke-extraction. All ramps have their own control lops ensuring a velocity of 1 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 respectively blown out of an exit portal. The other ramps and connecting sections of the main tunnel protect themselves by ensuring a velocity of 1 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 automatically selected

- Standard Fire Ventilation with an air velocity of approx. 3 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.

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) from 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 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 (i.e. the sensors) but also the actuators (i.e. the fans), see Figure 5.

Example: Application logic orders a jet fan to start, orders are sent to the simulator. The simulator calculates, with the aid of a mathematical model, the airflow in the tunnel which also has effect on the traffic flow. The simulated air flow gives the response caused by the jet fan that is sent back to the application logic from the simulator.

The tunnel-ventilation system is very complex and extensive. The client and the contractor need reasonable time to try to cover all requirements in the appropriate software. To minimize the risks to tunnel ventilations, logic errors and/or problems detected until the SAT (Site Acceptance Test), a 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.
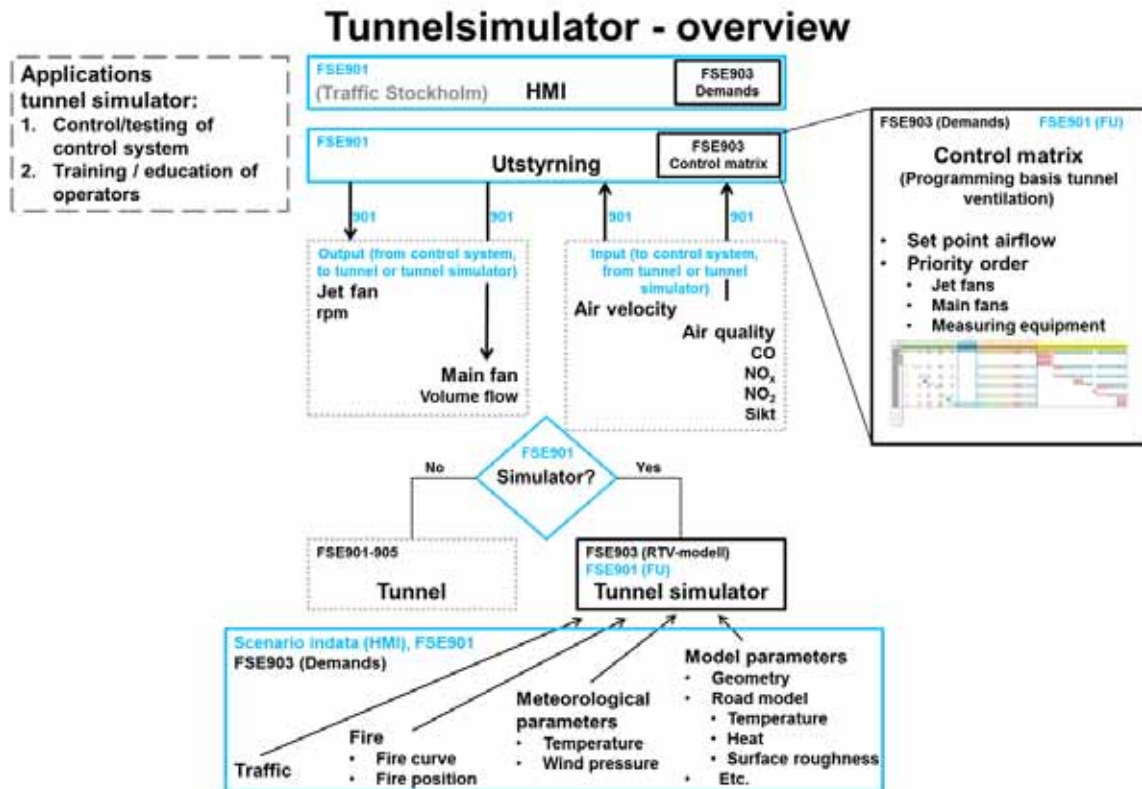
Figure 5: Overview of tunnel simulator

4.3. Work process for the contractor

The contractor 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 then implement all control functions in a hardware solution (PLC), which is the real control system with its software solution called Real-time Tunnel Simulator. The Real-time Tunnel Simulator is then linked to the Model Tunnel Simulator.

From the HMI, authorized users can view the current status for all variables and parameters that have an impact on the simulation. Also from the HMI, it shall be possible from authorised personnel to edit all variables and parameters that have an impact on the simulation.

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 manufacturer-dependent coding. The interface of IDA-RTV has to manage the time step of the numerical model and alarms. For instance, the simulation model lags 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 tunnel-ventilation simulator for his own 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. We have concluded that the money invested on a simulator is well worth in order to reduce time and to ensure quality. In a global context, our goal is to act in a smart manner.

BE SMART = Be Exceptional - Save Money And Reduce Time

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