USING A REAL TIME SIMULATOR IN A LARGE AND COMPLEX ROAD TUNNEL FOR TIME AND COST SAVINGS

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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, a Real time tunnel-ventilation simulator has been developed that links the genuine tunnel-ventilation controller (soft- and hardware) with the simulation tool. In this simulation mode, the Real time tunnel-ventilation simulator receives fan settings from the simulator tool and computes the resulting values of flow speed, air quality, temperatures etc.

1. INTRODUCTION

1.1 E4 Stockholm Bypass

56 km of tunnel tubes compose the road tunnel E4 Stockholm Bypass, see overview in Figure 1. There are two unidirectional tunnels and one is 2 km E4 North and the main tunnel E4 South 15 km. 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. See figure 1.

The tunnel system is to be monitored and controlled by the regional traffic-control centre (Swedish: TS, Trafik Stockholm). To handle all local technical systems, the tunnel is to
be fitted with a local control and monitoring system, a modern and powerful Distributed Control System (DCS). The control system supervise and controls approx. 20 technical systems. For example 24 h CCTV, detection systems such as automatic fire-detection system, air quality and detection-systems for incidents and stopped vehicles. Alarms in general initiated when a stopped vehicle is detected. The alarm gives information of with position and provides CCTV streaming video for the tunnel operator. Specific action plans are to be used by the traffic control centre. They are pre-programmed to handle all technical systems i.e. ventilation during fires and accidents, including consideration of the aspect congested traffic conditions.

![Figure 1: Overview of E4 Stockholm Bypass](image1)

![Figure 2: Overview of the Tunnel Ventilation system](image2)
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 with adjustable shovels each with a nominal flow rate of 200 m³/s are being installed. As shown for the northbound tube in the schematic below Fig.3. Each main line has three air exchange stations each with a capacity to extract 600 m³/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 m³/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. See figure 2.

![Figure 3: Northbound tube: maximum ventilation mode during normal operation](image)

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.

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.

2.2.1.1 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 Fig. 4. 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 4: Overview of controllers for normal operation](image)

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 Fig. 3. In this manner, the risk of undesired tunnel closure caused by too bad in-tunnel air quality is minimised.
2.2.1 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:

- Active smoke control. All sub controllers is active during Standard Fire ventilation mode to maintain a Set point value of 3 m/s.
- 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 Fig. 5. 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 loops ensuring a velocity of 1 m/s towards the main line.

Figure 5: 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 Fixed Fire Fighting System (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 operator in TS.

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 in the DCS. The tunnel portals are not closed to traffic at pre-alarm and evacuation is not initiated. Pre-alarm is detected by a smoke detector and can be handled 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. Benefits with a Tunnel Simulator

To Save Money and Reduce Time, (shortened Smart) we must have a tool in an early stage which is during time used for the FAT (Factory Acceptance Test). In this project the solution is to use a Simulator for shortening the testing time. Swedish Transport Administration (STA) estimates that it will shortening tests by 2 to 3 months.

The complexity of the Tunnel Ventilation programming has to be understood. The tunnel system which consists of E4FS-North Northbound, E4FS-North Southbound, E4FS-South Northbound and E4FS-South Southbound. There are several operating modes and everyone has to be tested and verified. That counts for every VTS and SMS. For Normal operation there are Normal Ventilation, Maintenance Ventilation and Maximum Ventilation modes. For Fire operation there are Standard Fire Ventilation, Minimal Fire Ventilation, Maximum Fire Ventilation, Adjustable Fire Ventilation and Fixed Fire Ventilation modes. There are 11 sub controllers which are connected and operating
depending on different air quality for each VTS (approx. 40). The controllers are also in
operation for Fire operation mode in every SMS. (approx. 250). Another aspect that has
highest priority is to ensure a safe operating Tunnel Ventilation Systems. By using a
simulator it is possible to ensure that smoke management strategy is working properly.

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.
Therefore, STA wants to be prepared for this kind of request. If everything has been
verified and software debugged in an early stage, then it is acceptable to take on this
challenge to open early when it occurs.

4.1 Simulation Tool IDA RTV

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 in stationary flow simulation program also
enables specifying control loops using logical libraries, see Fig. 6. It has 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.

![Figure 6. Controller logic in the RTV software.](image)

4.2 Tunnel simulator

The IDA RTV program will be at disposition for the contractor that is awarded the
contract for Control System and Communication which enhance to build the tunnel-
ventilation control system together with operation or surveillance for more than 20
technical systems. 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 prescribed as a testing tool during the FAT.

The contractor will be requested to interface the IDA RTV model with the Control System hardware and software environment in order to be able to conduct Factory Acceptance Tests (FAT). 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 Fig. 7.

Example: Application logic orders in the Distributed Control System (DCS) sets 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 in the DCS from the simulator.

![Figure 7. Overview of functions for a tunnel simulator](image)

5. Work process for the contractor

STA will deliver a PC with IDA RTV with the dynamic software model of the tunnel installed, but without the IDA RTV control routines. The IDA RTV software contains software for the four different tunnel tubes for FS-North and FS-South. The PC will also include 3D files containing physical layout made in Project Wise (Software tool for building construction).

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 Control System. 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 contractor has to manage the time step of the numerical model and its feedback. 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.

The contractor shall implement a software interface i.e. OPC DA for communication with all control units to produce a real-time tunnel simulator. The tunnel simulator will mimic the Model Tunnel Simulator and its sensors response to the same accuracy as the real tunnel. The contractor shall implement all control functions in his hardware solution (PLC and HMI-server) with its software solutions and link it to the Model Tunnel Simulator. In the control system programs for Normal Operation and Fire Ventilation will be made. Process pictures with measured values and control panels are made in the HMI-server. In the Software Developer PC it is possible to get a 3D graphic views of the tunnel tubes with dynamic traffic flow, smoke and heat spreading. In the PC it is also possible to set traffic speed, traffic flow and start fires at different locations in the 3D model. This makes a Real-time Tunnel Simulator (RTS).

From the HMI, authorized users can view the current status for all variables i.e. Sensors, Main Fans, Jet Fans and parameters that have an impact on the simulated process. Also from the HMI-software, 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 educating simulator for operators to handle tunnel fires.

5.1 Testing during Factory Acceptance Test (FAT)

In earlier projects STA could only test individual objects as Jet Fans, Fan stations and sensors for the tunnel ventilation in FAT. Therefore testing of the tunnel ventilation system had to be done when everything else are on site. During commissioning there are approx. 20 other technical systems under testing phases, so all actions had to be planned carefully.

Now STA will use the Real Time Tunnel Simulator (RTS) with its 3D real-time environment and the dynamic display of jet fans, Fan stations, traffic, air quality values, airflow, smoke and temperature development giving the same feedback as you are monitoring and controlling a real tunnel.

There are many the good reasons to use a RTS. The tests described could be done by client and the contractor in an early stage and errors could be detected and eliminated. Environmental ventilation and fire scenarios can be studied in an office environment. The control engineer have a simulated model that gives feedback and there is time to check your software during the development process. Fire can be activated at any location in the traffic tunnel, by a software function in the development PC. There are a total of ca.
250 fire cases to be checked. This type of testing and extent can’t be tested in the SAT stage during commissioning. It is not possible to achieve fires on that scale. In reality it is only possible to make a few fire tests, often with cold smoke.

With the RTS fires could be set on different locations anywhere and traffic flow can be adjusted from zero to flowing traffic with different types of vehicles for heavy gods or just ordinary cars.

This tool, will verifies that the software and the hardware of the control system functions as planned.

5.2 Testing during Site Acceptance Test (SAT)

Site Acceptance Test (SAT) will finally be conducted in order to confirm that the control of the Tunnel Ventilation system fulfils the design objectives with our goal to minimize time. When SAT begins then there will be debugged and tested programs for Normal Ventilation and Fire Ventilation. Now everyone involved are familiar with the Control systems HMI and the different ventilation strategies. The Fire Ventilation tests could be reduced to random sample tests which verifies the simulator model with the real tunnel. The Normal Ventilation tests could also be reduced to random sample tests. Minor deviations could be handled by the controllers which will always achieve the set point for air velocity or air quality.

Real Time Tunnel Ventilation Simulator provides the following benefits

Reduces time, an estimation is 2-3 months for the Stockholm Bypass.

Enhance safety by ensure that application logic in the Control System operates without any failure and on time.

Debugging means time and cost saving. The Cross City Tunnel Sydney, AU. There were only two weeks for the SAT, and it was conducted with good results. Much of the fault search could be addressed during the FAT stage and only one parameter needed to be adapted in the SAT.

Reduces the need for complex Fire tests before opening.

Environmental ventilation and fire scenarios can be studied in an office environment during the FAT period.

The 3D real-time environment and the dynamic display of all jet fans, blower stations, traffic, air quality values, air flows, smoke and temperature development gives a reality feedback as when you are operating a real traffic tunnel.

Fire can be activated at different locations in the tunnel. There are a total of ca. 250 fire cases to be checked.
This type of testing and extent can’t be tested in the SAT stage of the plant.
Traffic flow can be set from zero to flowing traffic.

6. Training of Traffic operators and approval for other authorities

As a bonus, the RTS will also be used for the training of various kinds of professions, such as Traffic operators and maintenance personnel. There will not be any more cost to fulfil this because the software that is develop can be used either by ordinary hardware or by converting the code to a soft PLC and use it on an virtual server.

The RTS can also be used for checking against the Swedish Transport Agency of the safety measures handled by the tunnel ventilation system.

BE SMART = Be Exceptional - Save Money and Reduce Time. Use a simulator to find faults and save time

With this paper there is also a video from our practical tests which shows the PLC with its application logic, connected to IDA Tunnel simulator. The video shows a Fire scenario with traffic in real time and how smoke spreads where dynamic values increase and Jet Fans starts.

7. References


