# Ventilation of the E4 Stockholm Bypass

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## 1 ABSTRACT

The 17 km long E4 Stockholm Bypass road tunnel has several entry and exit ramps giving in total 56 km tunnel tubes. The longitudinal ventilation system involves 250 jet fans and 48 axial fans.

An advanced stepwise controller is used for normal operation that combines independent sub-controllers with an overarching selection of determining sensors. Rules for prevention of target conflicts of the actuators (fans) have been established.

Based on measurements of flow velocities, active ventilation control is used for longitudinal smoke management.

Detailed descriptions of control principles and system-selection priorities have been elaborated. Equipment failures are catered for and plausibility tests of the flow-velocity measurements carried out.

## 2 INTRODUCTION

### 2.1 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.

Frequent traffic congestion of the daily 140 000 vehicles is anticipated.

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.

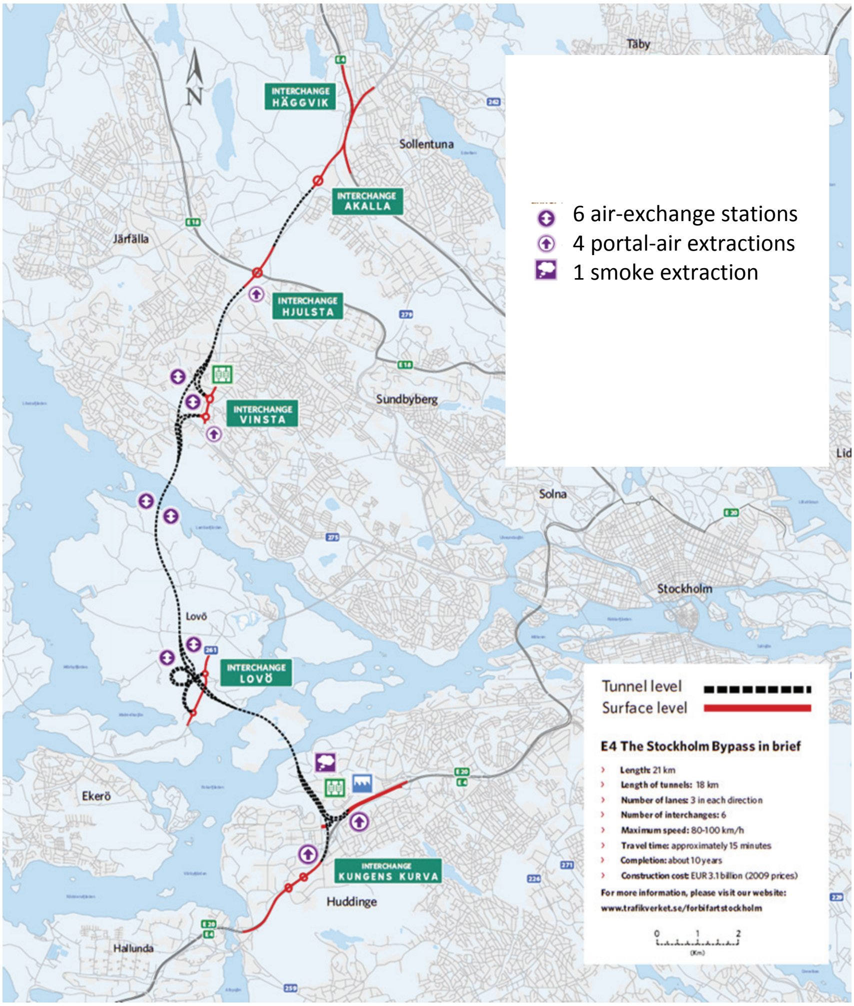


**Figure 1 Overview of E4 Stockholm Bypass (illustration from (3))**

## 2.2 Ventilation system

The longitudinal ventilation system encompasses: 250 jet fans, 48 axial fans, 62 positions with triple anemometers and 54 air-quality sensors. Fire detection is conducted with linear heat sensors and smoke detectors.

The jet fans are under frequency converters enabling them to give full thrust in both directions.

All ventilation stations use the same type of fan with a nominal flow of 200 $m^3/s$.

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 fully reversed and hence also used for smoke extraction.

Since it was considered that the distance from the south portal to the first air-exchange station would lead to smoke spread over a too long distance, a smoke extraction station is envisaged in-between, see Figure 1. This is the only ventilation station that serves both main-line tunnels. Although the design smoke-extraction capacity is 600 $m^3$/s, a fourth (spare) fan has been installed here to ensure availability.

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.

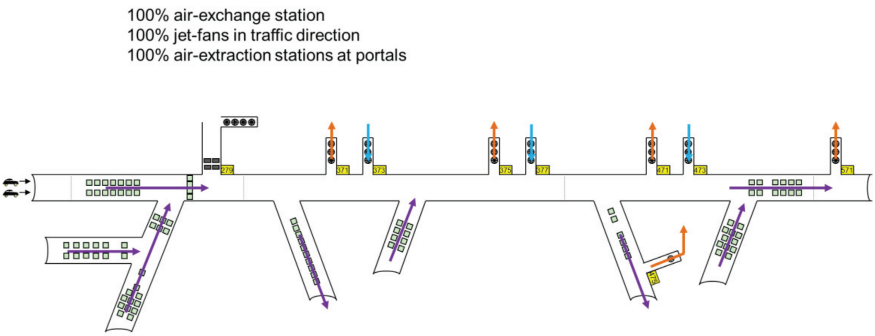


**Figure 2 Northbound tube: maximum ventilation mode during normal operation**

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 NO/NOx and CO.

In particular for the active control of the longitudinal flow in case of fire, the anemometers are of paramount importance. Consequently, they are tripled in order to enable automatic plausibility checks.

All portal areas were studied and where deemed beneficial, up to 50 m long separation walls or similar efficient measures between the two tunnel tubes are planned. These reduce flow short circuit at the portals to a minimum, which is of benefit during normal ventilation as well as in case of fire.

## 3 NORMAL VENTILATION

### 3.1 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.

### 3.2 Controller principle for internal air quality

Various principles are used for the control of the internal air quality in road tunnels. It was found that a step-wise controller would be the most appropriate one as this is robust and yet flexible.

The principle is a continuous measurement of the air quality and for each component (visibility, concentrations of NOx/NO and CO) to define air-quality target values called *AQV*. In case that the air pollution exceeds *AQV+*, which is a value higher than *AQV*, the ventilation capacity is stepped up. In order to have a stable controller, hysteresis is considered such that the ventilation capacity will be stepped down; when the air pollution is lower than *AQV-*, which is lower than *AQV*. Moreover, after a new ventilation step has been engaged, the tunnel ventilation will always operate for a minimal duration of $t_{CSG}$.

In total five steps have been defined with step 0 corresponding to no mechanical ventilation and step 5 is 100 % mechanical ventilation. During normal operation, the jet fans are operated in parallel. Due to the frequency converters, they can operate at partial load, which normally leads to lower power consumption than having few jet fans operating at full load (2). Similarly, in the air-exchange stations, the several fans are rather operated at partial load than few at full capacity. It is, however, ensured that the minimum running speed for safe operation of the fan is respected. Moreover, critical frequency bands are avoided.

The fan operation also ensures that the operation time as well as the number of starts of the fans will be similar, which is important for the lifetime of the equipment. If a fan is out of service, another one is automatically selected.

### 3.3 Example for the northbound tunnel

The application of the step-wise control philosophy to this tunnel network is explained on the basis of the example for the northbound tunnel.

The tunnel is divided into logical ventilation technical sections called *VTS*. For the ventilation during normal operation, the *VTS* are combined to larger sections called normal operation sections *NOS*, see Figure 3. 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*.

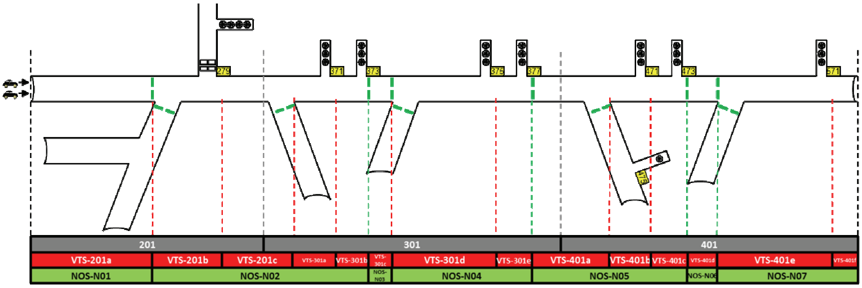


**Figure 3 Normal operation sections NOS (green) composed of ventilation technical sections VTS (red); construction contract sections (grey)**

From the example NOS-N07, it is seen that the ventilation equipment is also allocated with priorities, see Figure 4. In this case, the jet fans in the entire main line together with the closest air-exchange station will be operated first. Secondly, the next upstream air-exchange station and finally the far upstream air-exchange station will be engaged. For each ventilation step, the capacities of the actuators i.e. jet fans and the air-exchange stations have been pre-set.

 

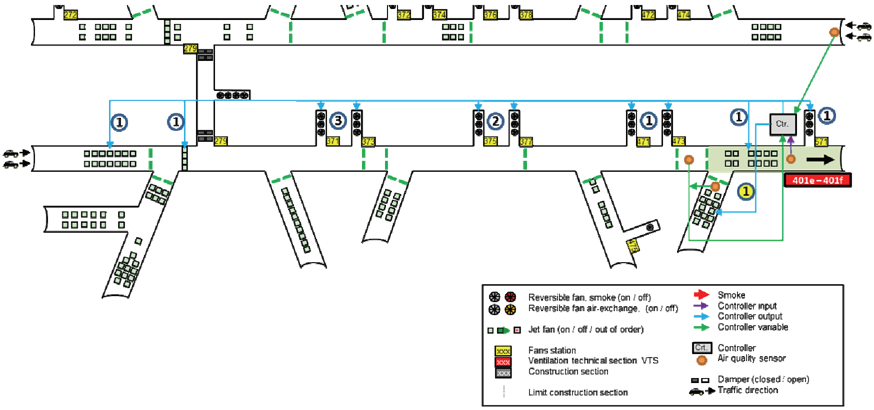


**Figure 4 Normal operation control loops for sector NOS-N07=401e-401f**

The principle of the controller for the entire main line is the same. Each ramp and each portal-air extraction has its own sub-controller, see Figure 5. 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.

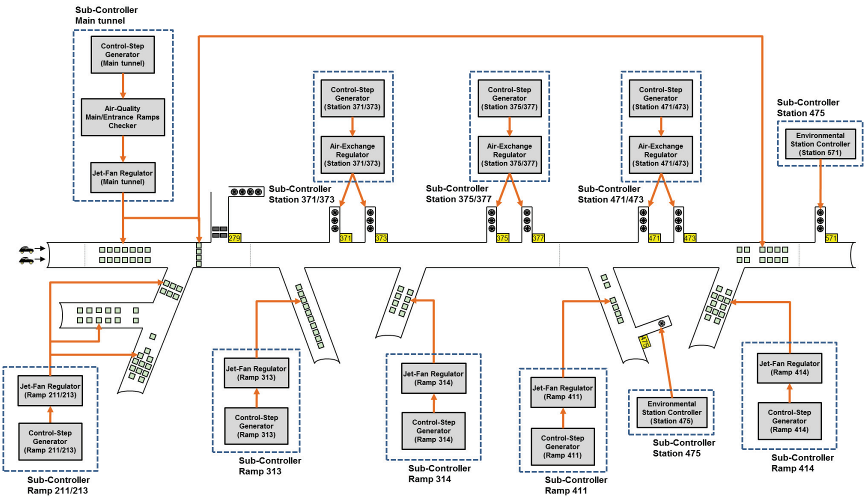


**Figure 5 Overview of controllers for normal operation**

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, see Figure 6.

When the threshold air-quality value (*AQV+*) is exceeded at one sensor, the associated ventilation equipment is firstly identified. Secondly, the sensor with the highest value for that ventilation equipment is found and the ventilation step to be applied established. Based on this, the ventilation equipment operates at the desired capacity.

The combinations of sub-controllers may also result in conflicts that therefore have been identified and rules for their resolution defined. As seen in Figure 7, there are only few potential conflicts.

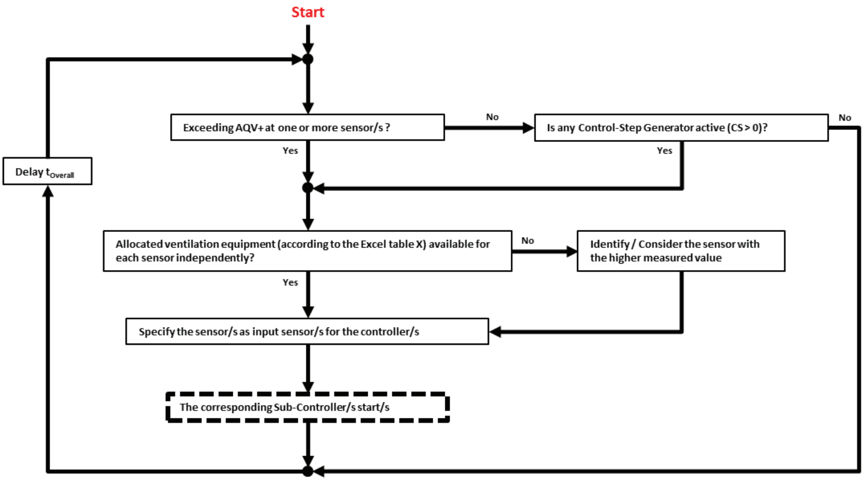


**Figure 6 Flow chart for selection of sensors and associated ventilation equipment. CS = control step**

| | | Any GO-Sensor in the Main tunnel | Any GO-Sensor in the Ramp 211/213 | Any GO-Sensor in the Ramp 313 | Any GO-Sensor in the Ramp 314 | Any GO-Sensor in the Ramp 411 | Any GO-Sensor in the Ramp 414 | Any GO-Sensor in the sectors 301c - 301e | Any GO-Sensor in the sectors 401a - 401c | Any GO-Sensor in the sectors 401d - 401e | Sensor +20411=583GO001 | Sensor +20401=583GO006 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sub-Controller Main Tunnel | Sub-Controller Ramp 211/213 | Sub-Controller Ramp 313 | Sub-Controller Ramp 314 | Sub-Controller Ramp 411 | Sub-Controller Ramp 414 | Sub-Controller Station 371/373 | Sub-Controller Station 375/377 | Sub-Controller Station 471/473 | Sub-Controller Station 475 | Sub-Controller Station 571 |
| Any GO-Sensor in the Main tunnel | Sub-Controller Main Tunnel | | Just for Main tunnel Sensors in sections: 201b - 301b | | Just for Main tunnel Sensors in sections: 301d - 301e | | Just for Main tunnel Sensors in section: 401e | | | | | |
| Any GO-Sensor in the Ramp 211/213 | Sub-Controller Ramp 211/213 | | | | | | | | | | | |
| Any GO-Sensor in the Ramp 313 | Sub-Controller Ramp 313 | | | | | | | | | | | |
| Any GO-Sensor in the Ramp 314 | Sub-Controller Ramp 314 | | | | | | | | | | | |
| Any GO-Sensor in the Ramp 411 | Sub-Controller Ramp 411 | | | | | | | | | | | |
| Any GO-Sensor in the Ramp 414 | Sub-Controller Ramp 414 | | | | | | | | | | | |
| Any GO-Sensor in the sectors 301c - 301e | Sub-Controller Station 371/373 | | | | | | | | | | | |
| Any GO-Sensor in the sectors 401a - 401c | Sub-Controller Station 375/377 | | | | | | | | | | | |
| Any GO-Sensor in the sectors 401d - 401e | Sub-Controller Station 471/473 | | | | | | | | | | | |
| Sensor +20411=583GO001 | Sub-Controller Station 475 | | | | | | | | | | | |
| Sensor +20401=583GO006 | Sub-Controller Station 571 | | | | | | | | | | | |

**Figure 7 Potential ventilation-equipment conflicts (orange). Green – no conflicts; Grey = non-existing combinations**

Once the sensors have been specified as the determining ones, the corresponding Sub-Controller activates its "Control-Step Generator". Here, only the ones that are responsible for ensuring the in-tunnel air quality are engaged and hence not those of the portal-air extractions ("Sub-Controller Station 475" and "Sub-controller Station 571").

 

Having established which sensor that is in charge and the ventilation equipment at disposition, ”Control-Step Generator” specifies the control step (*CS*) to be active, see Figure 8. The starting point is the active control step that then can be increased or reduced.

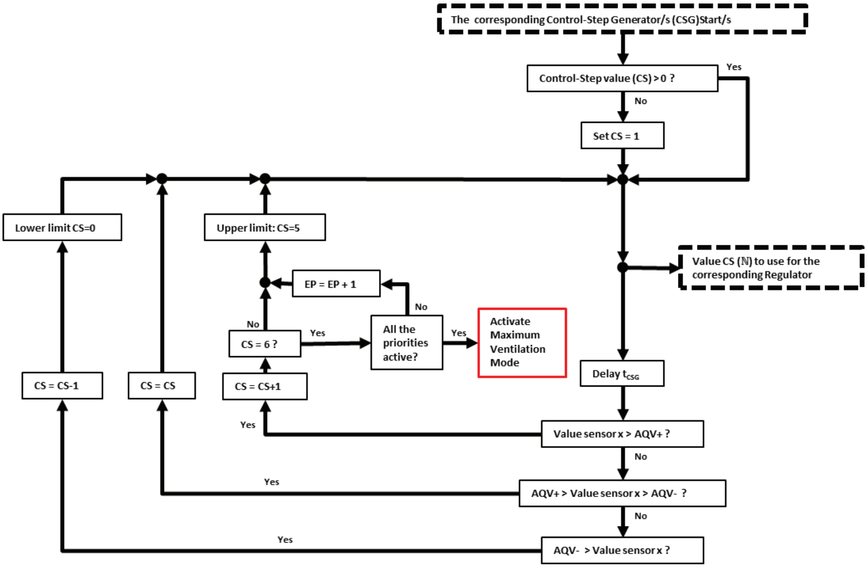


**Figure 8 CSG (Control-Step Generator). CS = Control Step. EP = priority of air-exchange station (1 to 3)**

As shown in the example Figure 4, the air quality can be improved by using air from the ramp or increasing the flow rate in the main tunnel. In order to find the optimal solution, the component “Air-Quality Main/Entrance Ramps Checker”, as shown in the flowchart Figure 9, was developed. This component checks, if the air flow in the ramp is cleaner than the air flow in the main tunnel. If the condition of ”air cleanliness” is satisfied, it is efficient and fast controlling the pollution in the main tunnel by using the air flow from the entrance ramp.

The control principle for normal operation is summarised in Figure 10. Moreover, a typical air-quality profile in the main line of the tunnel is shown in Figure 11.

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 one is desired (see Figure 8), 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.

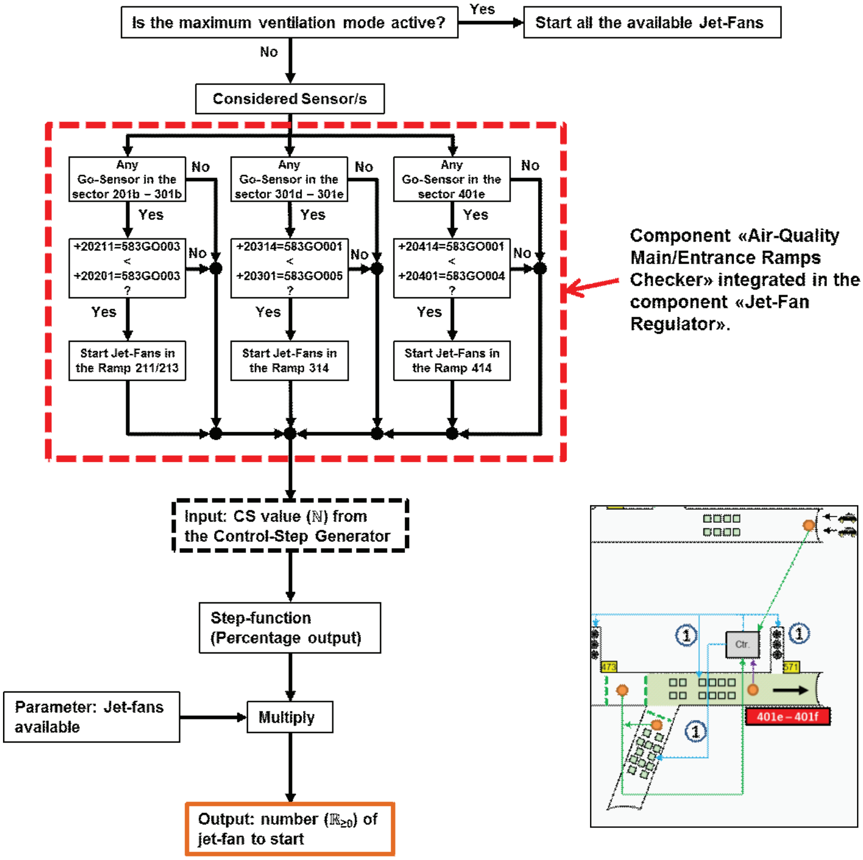


**Figure 9** Air-Quality Main/Entrance Ramps Checker. Inserted situation from Figure 4. GO = air-quality sensor.

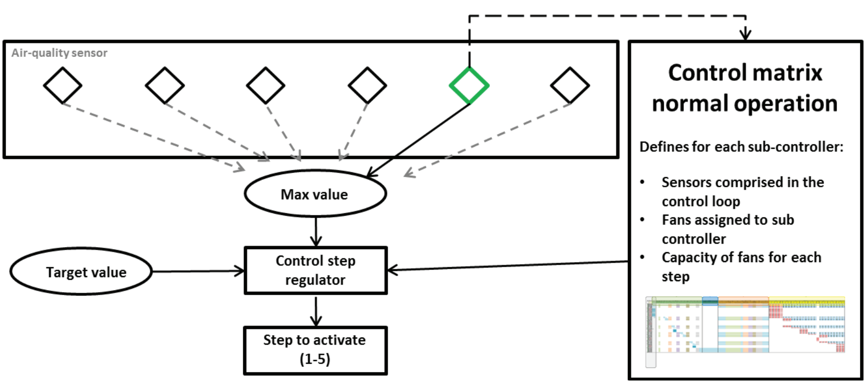


**Figure 10** Principle of ventilation control during normal operation

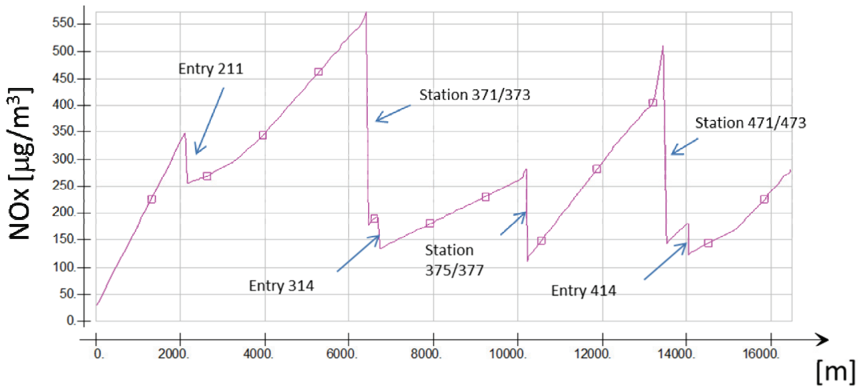


**Figure 11 Typical profile of NOx concentration in main tunnel**

### 3.4 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, which is considered in the control loop; see Figure 12. 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. These are compared with values from the sensor just upstream the station. Moreover, only a certain pre-set fraction of the flow approaching the air-extraction station is being extracted. For each portal-air extraction, the fraction of flow to extract is a parameter in the control system that can be altered.

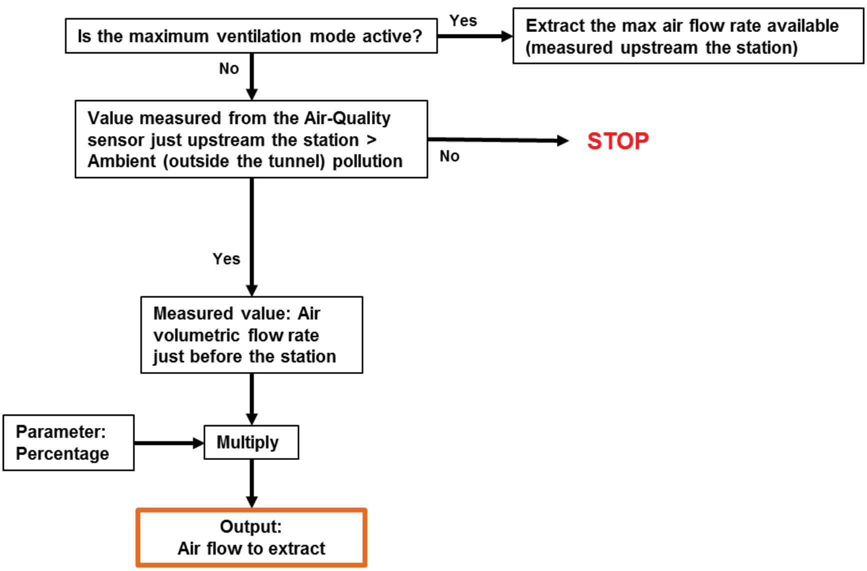


**Figure 12 Portal-air extraction controller**

The stacks of the air extraction (at portals and inside the tunnel) are partitioned in order to be able to ensure a high exit velocity of the flow even when operating the stations at partial load.

## 4 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 is out of order, the subsequent extraction station is selected. In addition to the air-extractions used for normal operation, there is one dedicated smoke-extraction. Moreover, the fresh-air supply stations are reversible so that they can be used for smoke extraction as well.

Due to the different objectives compared to normal operation, smoke management sections called *SMS* have been defined, see Figure 13. 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 order to enable blowing the smoke out of the entry portal, a *SMS* that extent to the first emergency exit i.e. about 150 m from the entry portal has been defined.

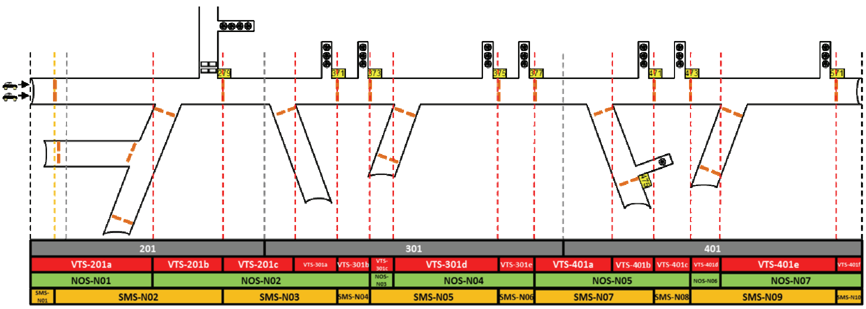


**Figure 13 Smoke management sections SMS (orange) composed of ventilation technical sections VTS (red); Normal operation sections NOS (green); construction contract sections (grey)**

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 is never 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 14. A longitudinal flow velocity of 3 m/s in direction of traffic towards the fire 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.

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.

 

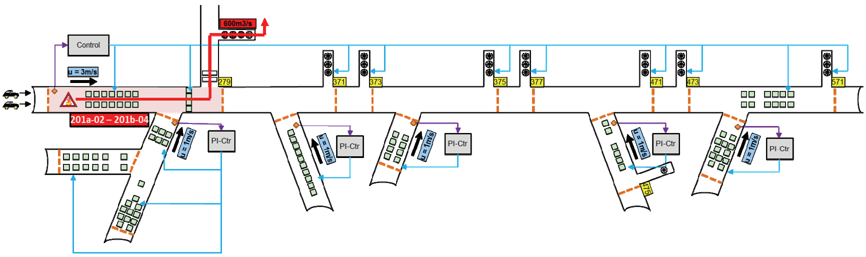


**Figure 14 Smoke management control loops for sector SMS-N02=201a-02-201b-04**

For this purpose, the smoke-management sections *SMS* have been subdivided into fire ventilation zones, see Figure 15. When possible, the boundaries have been selected to correspond with the emergency exits, as the FFFS will also use these as zone boundaries. Each jet fan and group of anemometers needs to be in clearly distinguished fire ventilation zones.

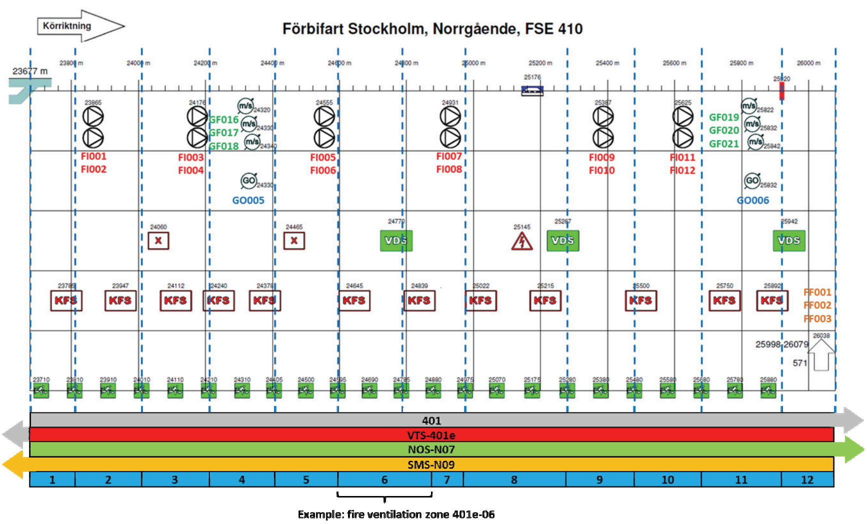


**Figure 15 Fire ventilation zones (blue) as subsets of smoke-management sections SMS (orange)**

The fire detection is associated with a fire ventilation zone. Depending on the fire ventilation zone, the priority of anemometers to use as well as of the actuators (i.e. fans) to engage is selected according to a table.

In case of fire, the objective is to use the jet fans that are far away from the fire. Therefore in contrast to the philosophy for normal operation, the jet fans used for smoke management are operated in serial and not as during normal operation in parallel.

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.

The principle of the active ventilation control of the flow velocities based on measurements in the tunnel is shown in Figure 16.

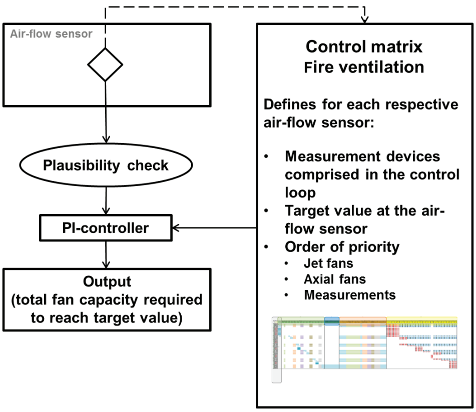


**Figure 16 Principle of active flow control for smoke management**

In case of fire, one of the following 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.

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 as well as 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.

## 5 SIMULATION TOOL: IDA RTV

The dimensioning 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 wind and temperatures as well as the heat-release rate of fires. Moreover, system failures can be mimicked.

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). 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.

Details of the testing of the tunnel-ventilation control system and its development is described in Elertson (1).

## 6 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 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. Moreover, 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 shown.

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.

## 7 REFERENCES

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