On the design and control of complex tunnel ventilation systems applying the HIL tunnel simulator

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Abstract
For a complex road tunnel network, the ventilation system has been designed, implemented and tested. For design and optimisation of the control system, a one-dimensional numerical model has been used. With growing system complexity and demanding constraints of time and quality, system tests become increasingly important. They have to be performed based on the assumption that “it won’t work if it hasn’t been tested”. In order to have sufficient time to perform these tests, the control system has to be tested prior to installation. For this purpose, a numerical simulation model of the tunnel, ventilation system and control system is used. For later tests, the simulated control system is replaced by a Hardware-In-the-Loop (HIL) setup connecting the simulator to the actual Programmable Logic Controller (PLC) and control code that will be installed.

1 INTRODUCTION

The ventilation control during normal operation as well as during incidents has become an important issue. During an incident, the ventilation operation is usually fully automatic. Any failure may lead to severe danger to tunnel users. In normal operation, meeting the pollution criteria inside and outside of the tunnel may be a challenging task, as well. Breach of pollution limits may cause severe penalties on the tunnel operator.

Road tunnels – especially in an urban environment – tend to become very complex with several entry and exit portals, portal air extraction and forced recirculation to avoid portal discharge. The traffic flow may vary rapidly from light free-flowing to heavily congested traffic.

With penalties being applied for breaches of design conditions from the first day of tunnel operation, detailed tests of the control system prior to the tunnel opening become increasingly important. As the ventilation control system is required to cover all possible scenarios from normal operation, maintenance and incident modes to partial tunnel closures, numerous operational modes and levels have to be taken into account. Tests have to cover all possible transitions between operational modes and levels. They have to be performed based on the assumption that “it won’t work if it hasn’t been tested”.

Once the ventilation control system is installed, the time required to perform these tests is normally not available. The tunnel usually has to be opened to traffic as soon as possible. Therefore, the control system has to be tested prior to the installation on site. This can be done with the application of a tunnel simulator: a numerical simulation of the tunnel and ventilation system connected to a PLC running the “real world” control system. Thus, tests on site are minimised as much as possible. The tunnel is opened to traffic and the ventilation operation is on its optimum from day one.

2 VENTILATION SYSTEM

The application of a tunnel simulator for the design and commissioning of the ventilation system was tried for the first time on a very complex urban tunnel system. The tunnel consists of two separate tunnels with uni-directional traffic. The main tunnels include several entry exit ramps, so that the tunnel network has altogether eight tunnel portals.

2.1 Design conditions

In this project, the design and control of the ventilation system has to meet stringent requirements for normal conditions, such as:

- the tunnel ventilation system must supply a sufficient amount of fresh air for pollution dilution in order to meet the in-tunnel air quality requirements;
- the ventilation system must enable operation of the tunnel without air discharge at the portals;
- the ventilation system and its control must be designed for economy of operation throughout the full range of tunnel traffic conditions.

Penalties apply in the occurrence of a breach of these conditions. The key requirements seem to be partly contradicting, such as maximum pollution dilution and economy of operation.

2.2 Ventilation concept

For tunnel air discharge, a location in the vicinity of the main western tunnel portal was nominated. The ventilation is designed as a longitudinal ventilation system with fresh air entering the tunnel at all tunnel portals. In the main tunnels, the movement of air utilises the piston effect of the traffic and a series of jet fans distributed in the tunnel sections. At the eastern exit portal, the air is extracted from the eastbound tunnel and via a cross-ventilation station introduced into the westbound tunnel. Along the westbound tunnel, it mixes with additional fresh air coming from the entry portal and the two ramps before it is extracted into the main exhaust ventilation station (Figure 1).

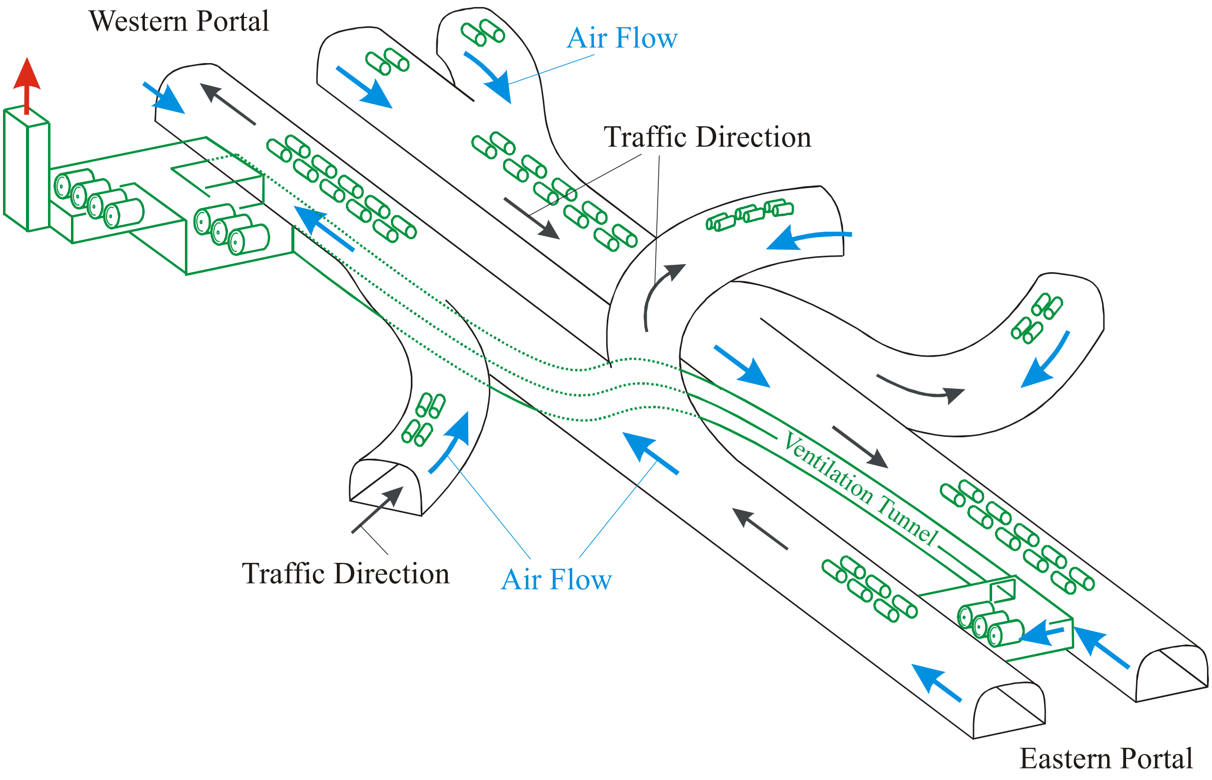

Figure 1 Complex tunnel ventilation system (normal operation) – schematic

In case of congested traffic, a slightly different concept is used. The vitiated air extracted from the eastbound tunnel is brought via a ventilation tunnel directly towards the main exhaust ventilation station, thus avoiding increased flow velocities in a congested westbound tunnel.

2.3 Operation modes

In order to control the ventilation system under all traffic and operating conditions, nine different operation modes have been defined, such as normal condition, one tunnel closed for incoming traffic, maintenance of one of the three ventilation stations under traffic, as well as several incident modes.

The change from one operation mode into another mode is done manually by the operator. However, it is not possible to change from each operation mode into any other mode, as some combinations do not appear reasonable, such as ‘eastbound tunnel closed’ to ‘westbound tunnel closed’.

2.4 Ventilation modes

Each operation mode includes up to eight ventilation modes – four modes for fluid traffic and four modes for partially or fully congested traffic. Additional sub-modes have been introduced in order to cater for traffic scenarios with increased fresh air requirement in a particular ramp. However, the number of different ventilation modes is slightly reduced as not all ventilation modes are available under all operation modes.

The change from one ventilation mode into another one is automatically triggered by

- expected power saving – comparison of the number of operating jet fans in the main tunnel with the power requirement for a different exhaust flow rate;
- pollution levels in the main tunnel – an elevated pollution level triggers the ventilation system to switch to a mode with increased fresh air supply in the main tunnel;
- traffic data – a combination of reduced average speed with high traffic density triggers the ventilation system to switch to a ventilation mode designed for congested traffic.

In order to avoid oscillation between ventilation modes, a minimum delay between ventilation mode changes is defined.

2.5 Summary

The ventilation design comprises of 56 jet fans, distributed in thirteen tunnel sections, and ten axial fans, installed in three large ventilation stations. The ventilation control system includes numerous operation modes and ventilation modes. The ventilation control system is fully automatic within each operation mode.

3 DESIGN, CONTROL AND INSTALLATION

3.1 Ventilation design

The required exhaust flow rates were calculated from the maximum fresh air requirement which occurs during congested traffic throughout the tunnel. During free flowing traffic, a reduced fresh air supply is sufficient to meet the in-tunnel air quality requirements.

The required number and location of jet fans was calculated using a one-dimensional steady state network model. The number of jet fans required to operate in each tunnel section was determined for predicted traffic scenarios as well as tunnel capacity. Some scenarios assumed selected sections of the tunnel being closed for incoming traffic. These scenarios may require additional jet fan operation for maintaining air intake at all tunnel portals. This trusted in-house model was subsequently used to validate the dynamic model.

3.2 Ventilation control system design

The ventilation control system includes the operation modes described in Section 2.3 and the ventilation modes given in Section 2.4. The control logic within a ventilation mode consists of

- fixed exhaust flow rates for the three ventilation stations;
- six independent control loops for the operation of the jet fans in the tunnel sections, either controlling the air flow to a given set-point or balancing the air flow in two adjacent tunnel sections (Figure 2).

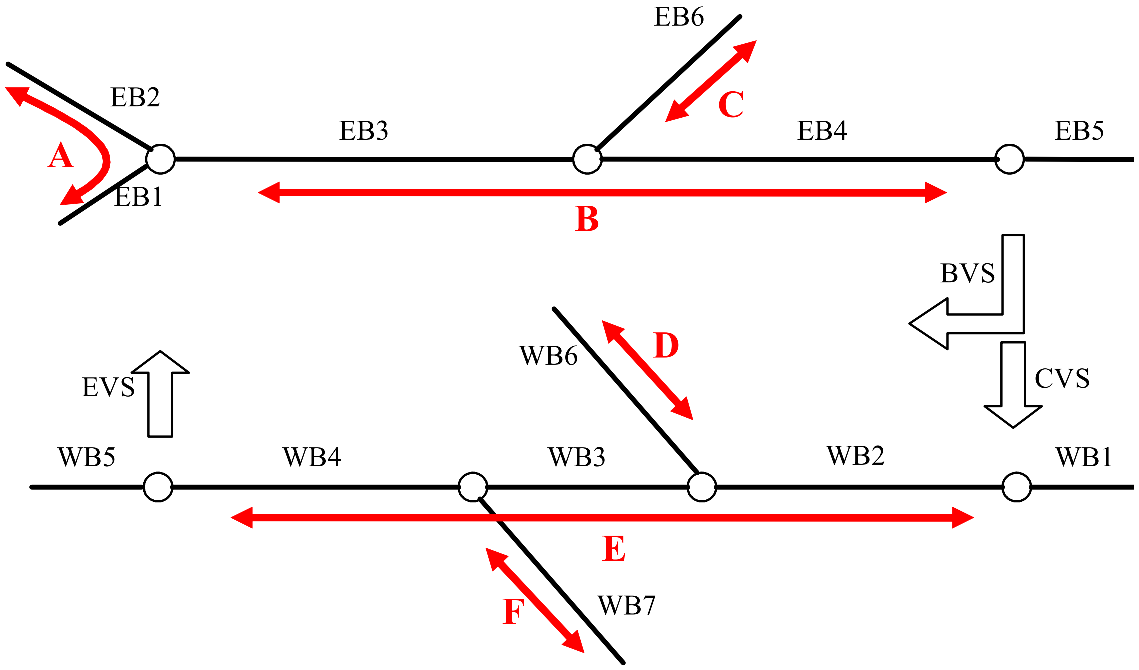

Figure 2 Control loop schematic

As each control loop is governed by two parameters, numerous parameters had to be analysed and tested during design and optimisation of the control system. This was done by utilising the IDA Road Tunnel Ventilation software (IDA RTV) (1) that provides a one-dimensional network model of the tunnel network, the ventilation system, the control system, the dynamic traffic flow, including vehicle emissions as well as pollution and air flow monitors.

Figure 3 shows the schematic representation of the tunnel in IDA RTV during the detailed design stage, containing the aerodynamic model of the tunnel as well as the control components. The eastbound tunnel is above, the westbound below. For both tunnels, traffic direction is from left to right. The model has a total of 20,544 variables, 154 of which belong to the control system. A typical simulation experiment covering 14 hours of system operation takes about 30 seconds of execution time. A total of 1500 time-steps have then been taken, ranging in size between 0.36 and 36 seconds. The variable time step differential-algebraic equation solver adapts automatically the step-size to the frequency content of the solution according to a tolerance parameter. Discrete events in driving functions and discontinuities in system equations are treated by special methods.

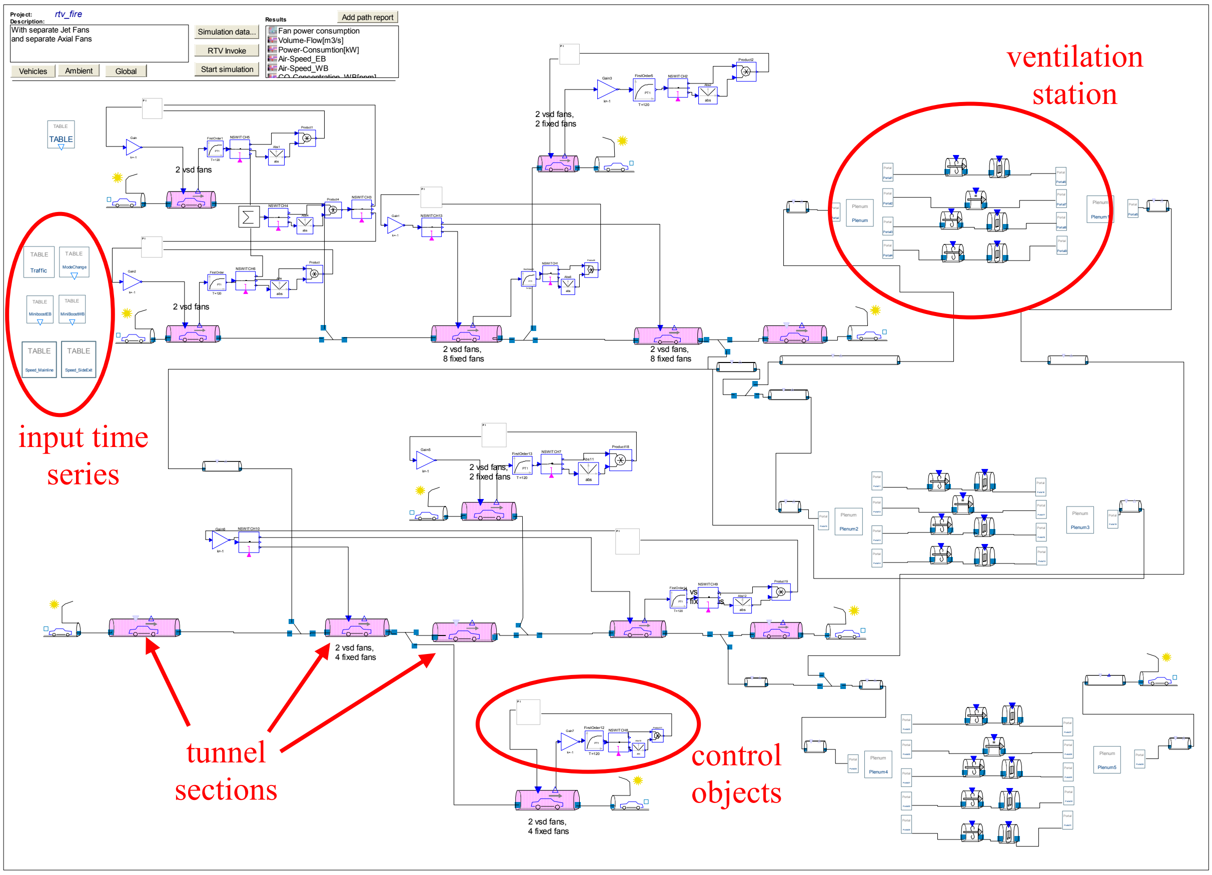

Figure 3 The detailed design system model

3.3 The HIL tunnel simulator

The electro-mechanical installations usually form the last part of the tunnel construction. The time schedule is very tight as the tunnel should be opened to traffic at the earliest possible date. Especially in a toll-financed project, any delay to the tunnel opening causes additional costs as well as loss of revenue.

Once the control system principles have been developed and control loops tuned in the simulation model, the code of the target PLC system can be written. This encompasses not only the ventilation related part of the control system but also a large number of other disciplines such as lighting, traffic management, CCTV surveillance etc. As with any computer programme, there will initially be a number of ‘bugs’. In addition to this, the real PLC implementation has to deal with several practical aspects of fan and damper operation, that are not worthwhile to model in the off-line control system model, such as component failure signals, position feedback loops etc. All in all, the correspondence between the conceptual control model and the real implementation cannot be taken for granted.

At this stage, a HIL tunnel simulator helps debugging and optimising the control system code. The full control code is loaded on the actual (hardware) PLC to be used in the tunnel. The feedback from the tunnel is simulated by the existing dynamic model. The simulation creates all relevant signals (CO, velocity, visibility, traffic density and traffic speed) that normally would be provided by physical sensors in the tunnel. Through an interface, simulated sensor signals are transferred to the PLC. According to these inputs, the PLC will determine fan and damper operation. These requests are transferred back to the real time simulation – the loop is closed.

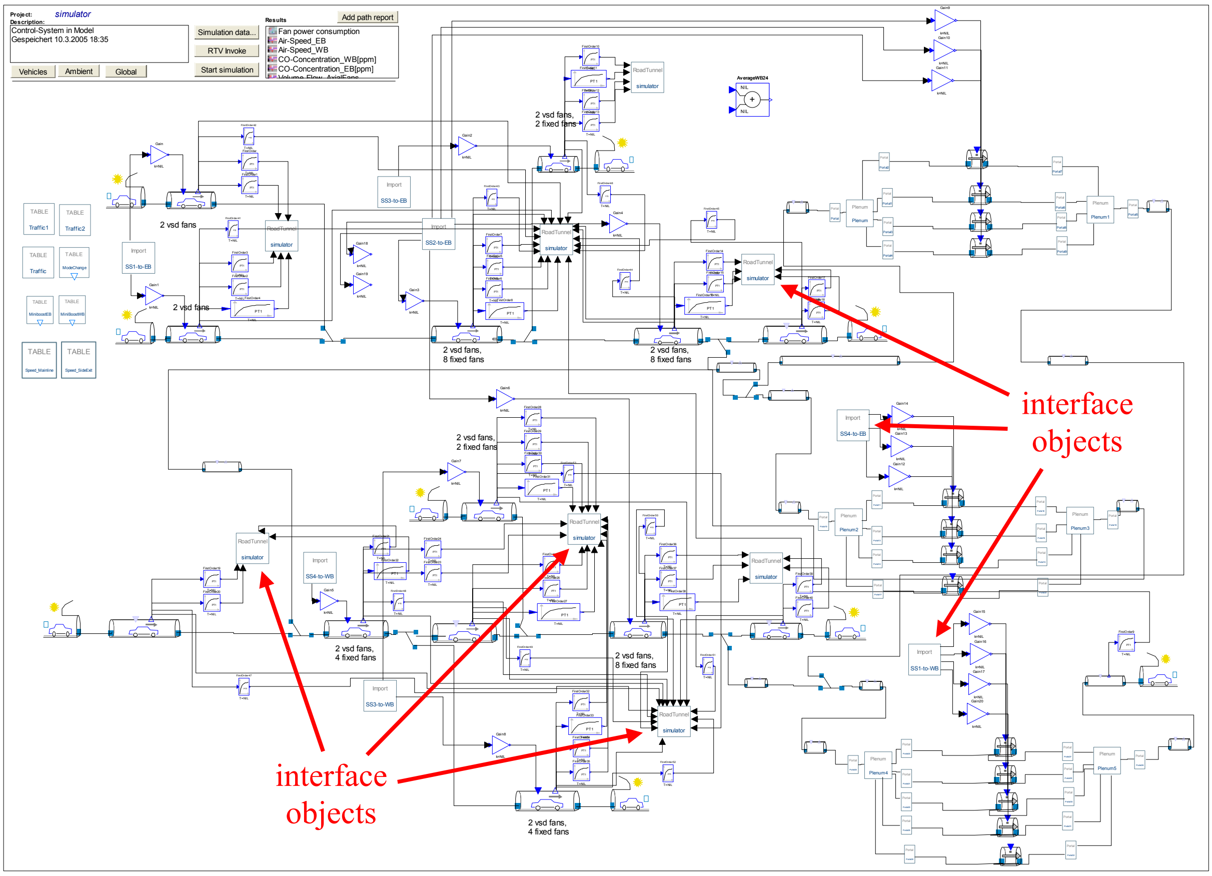

Figure 4 The system model for the HIL simulation

The architecture of the tunnel simulator, interfaces and PLC control unit is shown in Figure 5. The full system includes the control code development environment, which is installed on a separate PC and the tunnel-operator interface (HMI) – same as in the physical control room. The tunnel control system may be operated either using the control code development environment or the operator interface. However, the final HMI might not be available at an early stage of the control system tests. The tunnel simulator represents the physical reaction of the real tunnel, giving air flow signals and pollutions measurements according to the traffic scenario and the operation of the ventilation system. Time series of air flow, pollution and other signals as well as data on ventilation operation may be stored in the developer environment as well as in the tunnel simulator. Figure 4 shows the corresponding tunnel system model. In comparison to the model of Figure 3, control components have been replaced by real-time import and export objects, which govern data exchange with the physical PLC.

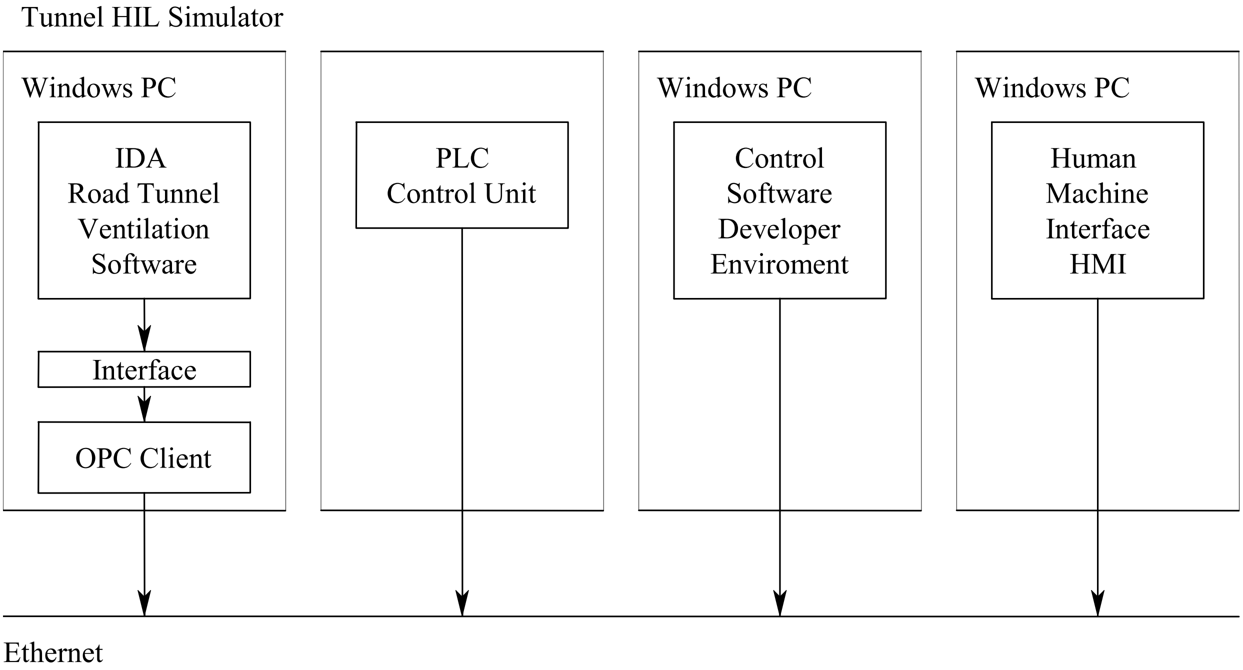

Figure 5 Tunnel HIL simulator schematic

The additional effort required for the HIL tunnel simulator lies in the development of the HIL 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, thereby reducing the need for manufacturer dependent coding. A few changes to the software model of the tunnel are also required, e.g. to convert units of simulated signals to those of the PLC implementation and to artificially provide feedback signals that are not covered by the virtual tunnel model. The HIL interface of IDA manages the timestep of the numerical model and alarms if 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.

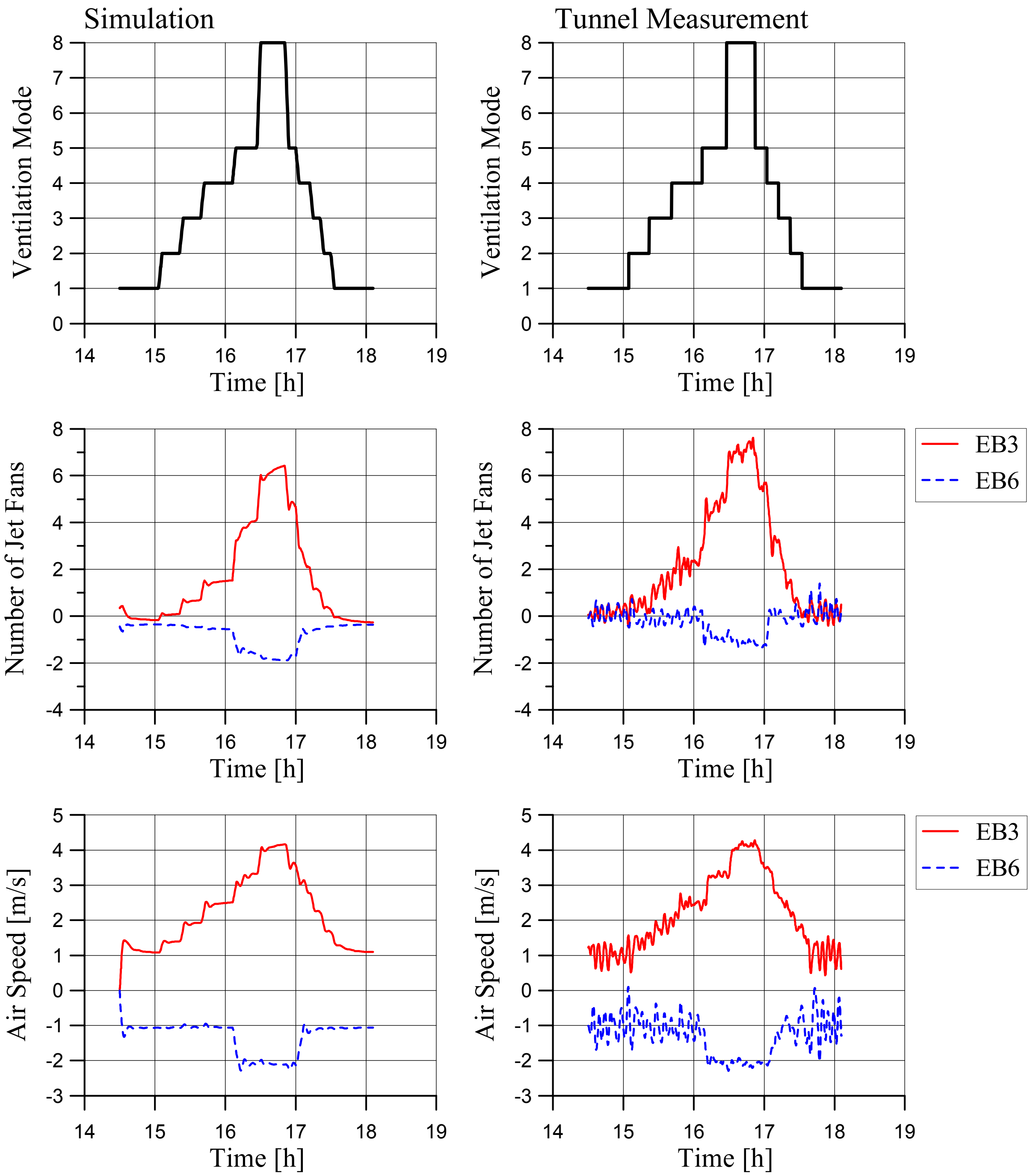

Figure 6 Comparison HIL tunnel simulator vs. measurements

Dynamic testing of the control code can either be done in the office or on site. It makes sense to continue testing on site as soon as the equipment in the tunnel is available. Discrepancies between the desired operation and the simulation results can be communicated to the control system supplier. Alterations can be agreed and implemented.

3.4 Commissioning

Due to extensive testing of the control system prior to installation, only a minimum time is required for commissioning tests on site. The features that remain to be tested on site include the air quality and air flow monitors as well as communication between the control system and the ventilation equipment, such as jet fan selection from a particular group. Only minor adjustments to the control parameters are required on site, depending on the accuracy of the aerodynamic model (Figure 6).

In this particular project, it would not have been possible to debug the control code, optimise the system parameters and run all required tests within the time frame available between the installation in the tunnel and the tunnel opening. It is expected that in any project of similar complexity, a HIL tunnel simulator would be the only measure to finalise the control system in time.

4 TIME SCHEDULE

Testing the ventilation control system is a rather slow process as the control parameters have to be tested in real time simulations. The time scales of a typical tunnel ventilation system range from 10 to 30 minutes. Each test scenario runs for eight to twelve hours, so several transitions from one ventilation mode to another may be tested. Simulator tests may run at night-time in order to allow a comprehensive analysis of recorded data during the day.

The required amount of testing, of course, depends on the quality of the control code as well as the pre-selection of control parameters. Usually, control parameters are adapted rather easily, but for changes to the code, the control system supplier has to be involved.

Table 1 gives a possible time schedule for the project. The control code has to be available at least four months prior to tunnel opening. The interface between the control system and the simulator has to be defined six months prior to tunnel opening. It is preferable for the simulator tests if a basic HMI is available at an early stage of the control code tests.

Table 1 Time schedule

Time from tunnel opening	Action
- 6 months	decision whether or not the tunnel simulator should be applied for HIL tests of the control system code
- 4 months	tunnel simulator set up for communication with PLC and HMI (if available) begin of tests on control code
- 2 months	control code debugged and optimised begin installation of control system hardware in the tunnel
-1 month	begin of tests on the ventilation system in the tunnel (optional: fine tuning of the tunnel simulator according to aerodynamic measurements in the tunnel) commissioning tests
- 1 week	end of tests on the ventilation system
+ 0	tunnel opening
+ 1 to 2 weeks	fine tuning of control parameters according to actual traffic in the tunnel

One drawback of the tunnel simulator application is the shifted time schedule of project delivery. Especially the time schedule of the control system supplier has to be shifted in a way that allows for completion of the control code prior to testing. In the time schedule of a conventional project, the control code has to be finalised only a short time before the installation of the hardware in the tunnel. Thus, a decision about the application of the tunnel simulator made only six months before tunnel opening might already be too late for the control system supplier.

5 CONCLUSIONS

- The ventilation control system of a complex tunnel network has been tested prior to installation in the tunnel. Any reduction of tests and optimisations in the completed tunnel allow an earlier project completion.
- Once the tunnel is open to traffic, there is only minor fine-tuning required – without interference to normal operation. The risk of breach of technical requirements such as continuous portal air inflow or maintaining in-tunnel air quality is greatly reduced.
- The control system is operating in an optimised way from day one of the tunnel operation.
- The decision about whether or not a HIL test of control code should be carried out should be made as early as possible in the project.
- As the tunnel simulator represents an additional investment, the costs have to be weighed against potential savings and reduced technical risks during commissioning. The benefits of the simulator clearly increase with the complexity of the ventilation system and the ventilation control system.
- At a later stage, the simulator may be used as a training tool for the tunnel operator by running a separate, but identical ventilation control system (either in a PLC or on a computer) connected to the tunnel simulator.

REFERENCES

(1) IDA Road Tunnel Ventilation, EQUA Simulation AB