Development of tunnel simulation software aiming at optimization of tunnel control operations

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ABSTRACT

For the tunnel “Schwarzer Berg” of the German motorway A 70 a simulator was developed. The functional requirements of the project amounted to the constant training of the tunnel operators along with the testing of the ventilation’s automatic control system. For the second part an additional simulator was developed internally in order to verify the first one’s output. A total of 210 fire emergencies were modelled and the reactions of the ventilation system were thoroughly reviewed. Analysis demonstrated the need for optimization of the ventilation control system. The project illustrates the advantages offered by modelling of complex control systems in terms of control optimization, personnel training in addition to cost and time savings during refurbishments.

KEYWORD: simulation, personnel training, tunnel ventilation, tunnel safety

OBJECT DESCRIPTION

In the following the tunnel main characteristics will be discussed, namely its geometry, traffic information and the ventilation control strategy.

Geometry

The tunnel “Schwarzer Berg” constitutes part of the German motorway A 70 that connects the cities of Würzburg and Bamberg. The tunnel has an east-west orientation and comprises two tubes, each carrying two lanes of traffic. The length of the north and south tube is measured at 738 and 722 m respectively. The longitudinal gradient amounts to 1 % from to East to West throughout the length of the tunnel.

Traffic

The tunnel “Schwarzer Berg” carries unidirectional traffic. In case of maintenance in one tube the adjacent one can be operated under bidirectional traffic. Annual average daily traffic is predicted to amount to 30,000 vehicles for the year 2015. Heavy vehicles amount to 25 % of total traffic.

Description of ventilation system

Both the north and the south tube are equipped with a longitudinal ventilation system. The ventilation system comprises, rather unusually, two types of ventilators for each tube. No frequency converter is installed to any of the ventilators.

The ventilation system of the north tube consists of a total of 8 ventilators. Specifically six 710 mm diameter ventilators each producing 640 N of thrust are installed, together with two 1,120 m diameter ventilators each producing 1,300 N of thrust.

In the south tube six 630 mm diameter ventilators each producing 405 N of thrust are installed, along with two 1,250 mm diameter ventilators each capable of producing 2,000 N of thrust.

Control strategy - Design

The air quality in tunnel “Schwarzer Berg” is constantly monitored and should the need arise the ventilation system is activated in order to keep pollutant concentrations below predefined limits. The current report focuses nevertheless on the simulation of emergencies. The aspects of air quality in tunnel under normal operation will not be discussed.

Fire management in tunnel can be separated into two discrete phases, namely the “self-rescue” and the “fire-fighting” one. The ventilation system aims, during the self-rescue phase, at protecting the road users from the heat and smoke generated. To this end, the control strategy comprises three steps:

- Setting a target tunnel air speed.
- Initialising the ventilation system.
- Controlling the tunnel air speed.

The minimum air speed required in the affected tube depends on the traffic conditions and, in case of bidirectional traffic, on the fire position in the tube. In tunnel “Schwarzer Berg” for flowing and congested unidirectional traffic the target air speed is +2,5 m/s and +1,5 m/s respectively. In case of bidirectional traffic the air flow is always directed towards the nearest portal at a speed of ±1 m/s. A positive air speed indicates a flow from the tunnel entrance to the tunnel exit, as they are defined when the tunnel operates under unidirectional traffic. The target wind speeds for the ventilation system are summarised in Table 1.

Table 1 Air flow direction and speed in case of fire.

Traffic mode	Target air speed (m/s)	Tolerance (m/s)
Unidirectional, flowing	+2,5	-0, +3
Unidirectional, congested	+1,5	±0,5
Bidirectional	±1,0	±0,5

Following the fire detection the ventilation system is initialised and set to its so called “basic setting”, at which the ventilators at the tunnel section where the fire is located are disabled and the status of the remaining is predefined depending on the traffic mode.

For the control operation, due to the different thrust provided by the two ventilator types, the concept of “equivalent ventilator” is introduced.

The number of ventilators that needs to be switched on or off is given always in terms of “equivalent ventilators”. For the north tube a 640 N thrust ventilator corresponds to one “equivalent ventilator” and a 1,300 N thrust ventilator corresponds to two “equivalent ventilators”. The definition of the “equivalent ventilator” is analogous for the south tube; a 405 N and a 2,000 N thrust ventilator correspond to one and five “equivalent ventilators” respectively. The definition of the “equivalent ventilator” is summarised in Table 2.

Table 2 Definition of “equivalent ventilator”.

North tube		
1 ventilator with 640 N thrust 1 ventilator with 1,300 N thrust	corresponds to	1 equivalent ventilator 2 equivalent ventilators
South tube		
1 ventilator with 405 N thrust 1 ventilator with 2,000 N thrust	corresponds to	1 equivalent ventilator 5 equivalent ventilators

The number of ventilators that needs to be switched on or off is determined by the difference of the current air speed from the target one, according to “control tables”. An example of a “control table” in case of fire in the south tube operating under unidirectional flowing traffic is shown in Table 3.

Table 3 Example of "control table": south tube, unidirectional flowing traffic.

Target air speed = +2,5 m/s			
Measured air speed u (m/s)			ΔN_{EV}[a]
	u ≥	+3,5	-4
+3,5	> u ≥	+3,3	-3
+3,3	> u ≥	+3,0	-2
+3,0	> u ≥	+2,7	-1
+2,7	> u ≥	+2,3	0
+2,3	> u ≥	+2,0	+1
+2,0	> u ≥	+1,6	+2
+1,6	> u ≥	+1,0	+3
+1,0	> u		+4

[a] Number of equivalent ventilators that needs to be switched on or off.

The total of ventilators that needs to be switched on or off is determined from the "control tables" in terms of "equivalent ventilators" (ΔN_{EV}). For instance, in case of fire in the south tube under unidirectional flowing traffic, if the air speed would lie between +2,7 and +3,0 m/s one "equivalent ventilator" would have to be turned off (see Table 3). This translates as switching off a 405 N ventilator, or switching off a 2,000 N ventilator and switching on four 405 N ones.

The "control tables" were generated during the design stage of the ventilation system. They constitute the backbone of the automatic control system of the tunnel "Schwarzer Berg".

DESCRIPTION OF SIMULATORS, TEST SCENARIOS

Tunnel "Schwarzer Berg" simulator (simulator-1)

The simulator built for the tunnel "Schwarzer Berg" models not only the ventilation system already described (vide infra) but the entire safety infrastructure (pollution control, lighting, video etc.) as well. This report focuses nevertheless on the ventilation system.

The ventilation subsystem of the simulator was composed of two modules, the aerodynamic and the ventilation control one. The aerodynamic module would simulate the temporal development of physical parameters, such as fire intensity, portal pressure, air velocity, smoke expansion, piston effect, aerodynamic drag etc. along with their interactions. The mathematical modelling of the aerodynamic module was developed internally and was used by both simulators. The control module of the simulator-1 was an exact copy of the control system installed in tunnel "Schwarzer Berg".

Test simulator (simulator-2)

A second simulator was developed for verification purposes. Foremost, the implementation of the mathematical modelling to software in simulator-1 was to be validated. In addition, the control strategy was independent of the one installed in the tunnel and used by simulator-1. The control strategy of simulator-2 was established that it operated properly through rigorous testing. The rationale for the separate control module was to verify the reactions of the automatic control system of the tunnel "Schwarzer Berg". The infrastructure unrelated to the ventilation (pollution control, lighting, video etc.) was not however modelled in simulator-2.

Simulator-2 - simplifications

A number of simplifications were implemented in the control module of simulator-2 intending to reduce its complexity. The starting current of the jet fans was not modelled, so any number of ventilators could be started simultaneously. Furthermore the ventilator start-up time and the ventilator shut-off delay were not modelled. As a result ventilators in simulator-2 would perform at maximum capacity the moment they were started, and they could also be reversed instantaneously. Occasionally occurring time delays (usually in the range of 1-2 seconds) due to program cycles and operating system loads, observed in real systems, were also not modelled. Finally one of the design goals of the tunnel's ventilation control was the minimising of the switching operations, enabling the highest possible availability of the system. This restriction was not included in the control module of simulator-2. It was expected therefore that the output of the simulators would not be identical. Nevertheless any disparities should be attributable to the simplifications of simulator-2's control module.

The relations between the tunnel and the simulators are presented in Figure 1.

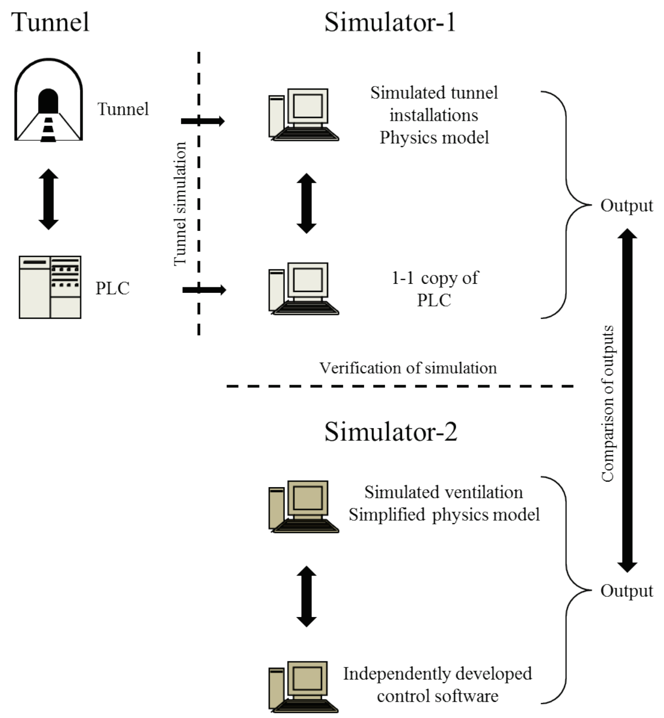

Figure 1 Relations between the simulators and the tunnel.

Test scenarios
Through the variation of atmospheric conditions, traffic situation, fire intensity, fire location as well as the ventilation system status before the fire detection, a great assortment of fire emergencies could be simulated. A total of 210 fire scenarios were modelled. Only the self-rescue phase was considered.

For every scenario the aerodynamic conditions before the fire because of traffic, wind and the ventilation system were determined. After the fire had started, each scenario was simulated for 15 minutes. Detection time was constant for every scenario at 2 minutes after fire had erupted. At that time the control system closes the tunnel to traffic and sets the ventilation system into fire mode. The physical parameters of the simulation, such as air speed, smoke expansion, thermal output, traffic etc. were calculated every 1 second.

RESULTS

Aerodynamic module
Foremost the implementation of the mathematical modelling was checked. No disparities were detected.

Control module
Analysis of the scenarios demonstrated that on several account the reactions of the automatic control of the tunnel “Schwarzer Berg” was not the expected ones. First, a scenario where no problems were

found will be presented (scenario #41), in order to outline the evaluation process. Afterwards the issues identified will be addressed.

Scenario #41

An example of a scenario where no issues were detected is scenario #41. Its parameters are:

- Tube: north
- Traffic: unidirectional, congested
- Portal pressure: -7 Pa
- Fire location: 54 m from exit portal
- Fire intensity: 30 MW, output increases linearly over 10 minutes
- Ventilation: active before fire eruption

The air speed and ventilator performance are illustrated in Figure 2. The ventilation system is active before the fire erupts. At time t_0 = 0 s the fire starts. At time t_1 = 120 s the fire is detected and the ventilation enters its "basic setting", with only ventilators #1, #2 and #7 being active.

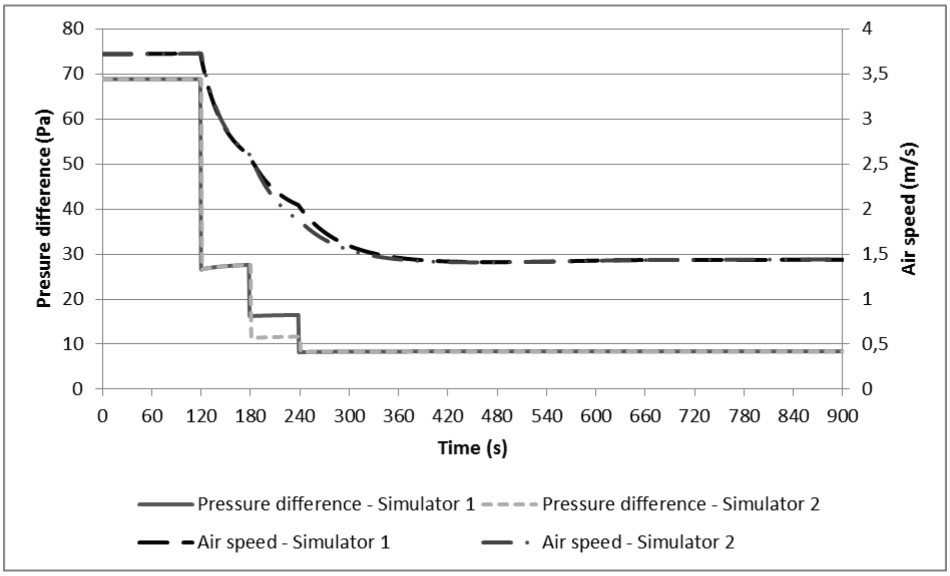

Figure 2 Ventilator performance and air speed – Scenario #41.

The switching orders are summarised in Table 4. At t_2 = 180 s, 60 seconds after the fire detection, the measured air speed of +2,6 m/s is compared to the target one, which for congested traffic is +1,5 m/s and a switching order of ΔN_{EV} = -2 is issued. Simulator-1 then deactivates ventilator #7, which corresponds to 2 "equivalent ventilators" while simulator-2 deactivates ventilators #1 and #2, each corresponding to 1 "equivalent ventilator", since it is not bound to minimise switching orders. Because the thrust ratio provided by the different ventilator types is not exactly 2:1, a small difference in pressure and air speed can be seen between 180 and 240 seconds.

Table 4: Switching order – scenario #41.

	Simulator-1					Simulator-2				
Time (s)	ΔN_{EV}	#1 (1 e.v.)	#2 (1 e.v.)	#7 (2 e.v.)	ΔN_{EXEC}[a]	ΔN_{EV}	#1 (1 e.v.)	#2 (1 e.v.)	#7 (2 e.v.)	ΔN_{EXEC}
120	-	⇒[b]	⇒	⇒	-	-	⇒	⇒	⇒	-
180	-2	⇒	⇒	×[c]	-2	-2	×	×	⇒	-2
240	-1	×	⇒	×	-1	-1	×	⇒	×	-1

[a] Switching order executed.
[b] Ventilator is ON.
[c] Ventilator is OFF.

At t_3 = 240 s the air speed is measured again and a switching order of ΔN_{EV} = -1 is issued. Simulator-1 deactivates ventilator #1 while simulator-2 deactivates ventilator #7 and reactivates ventilator #2. Because no start-up time is modelled in simulator-2, no performance difference is detected. At t_4 = 300 s and for the rest of the simulation the air speed matches the target air speed and no further switching orders are issued.

Scenario #135

In the following, the sum of the switching orders variable ($\sum\Delta N_{EV}$) shall be discussed. This variable is used in the software implementation of the control strategy of tunnel "Schwarzer Berg". In some scenarios it was observed that if the absolute value of the sum of consecutive switching orders was larger than a certain value (specifically 8), the ventilation system would not execute subsequent switching orders. As example, the switching sequence of scenario #135 will be presented. Its parameters are:

- Tube: south
- Traffic: unidirectional, congested
- Portal pressure: 0 Pa
- Fire location: middle of tube
- Fire intensity: 5 MW, output increases linearly over 10 minutes
- Ventilation: active before fire eruption

The air speed and ventilator performance are illustrated in Figure 3.

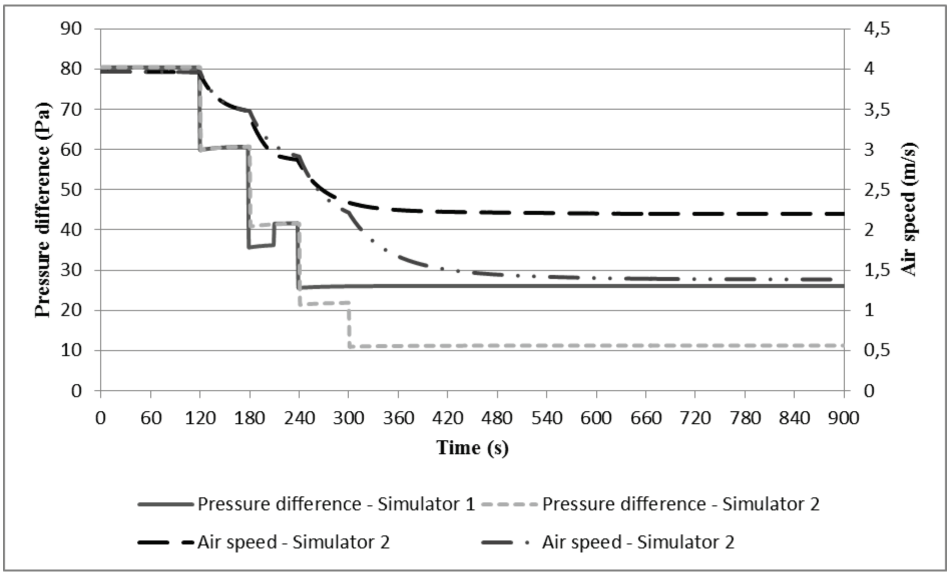

Figure 3 Ventilator performance and air speed – Scenario #135.

Before the detection of the fire all ventilators are active. For the south tube this translates to 16 equivalent ventilators. After the fire has been detected (t_1 = 120 s) the ventilation is set to its "basic setting" where, for this fire location, ventilators #3, #4, #5 and #6 are switched off.

At t_2 = 180 s and at t_3 = 240 s switching orders of ΔN_{EV} = -4 are issued and the absolute values of the $\sum\Delta N_{EV}$ variable equals 8. At t_4 = 240 s yet another switch off order is issued but the control system of simulator-1 does not react, although there are still 4 equivalent ventilators running. As a result the air speed remains for the rest of the simulation above the target speed in a congested traffic scenario of +1,5 m/s. This could prompt the disruption of the smoke layer stratification.

It should be noted that the system would not respond to further "switch off" orders but it would execute "switch on" ones.

The control system of ventilator-2 responds as expected and in approximately 4 minutes after the fire has been detected the air speed in the tube has reached its target value. The switching sequence is presented in Table 5. A total of 24 scenarios were found to be affected by this issue.

Table 5 Switching sequence – scenario #135.

	Simulator-1				**Simulator-2**		
Time (s)	ΔN_{EV}	ΔN_{EXEC}	$\sum\Delta N_{EV}$	# of equivalent ventilators active	ΔN_{EV}	ΔN_{EXEC}	# of equivalent ventilators active
< 120	-	-	-	16	-	-	16
120	-	-	0	12	-	-	12
180	-4	-4	-4	8	-4	-4	8
240	-4	-4	-8	4	-4	-4	4
300	-2	0	-8	4	-2	-2	2

Scenario #93

When examining Figure 3 a drop of ventilator performance can be observed for simulator-1 between 180 and 210 seconds. This relates an overcorrection issue that was observed in several scenarios and will be discussed in detail below. As example scenario #93 will be presented:

- Tube: south
- Traffic: unidirectional, flowing
- Portal pressure: 7 Pa
- Fire location: 200 m from exit portal
- Fire intensity: 5 MW, output increases linearly over 10 minutes
- Ventilation: inactive before fire eruption

Table 6 Switching order – scenario #93 – simulator-1.

Time (s)	ΔN_{EV}	#1 (1 e.v.)	#2 (1 e.v.)	#3 (1 e.v.)	#4 (1 e.v.)	#7 (5 e.v.)	#8 (5 e.v.)	ΔN_{EXEC}
< 120	-	×	×	×	×	×	×	-
120	-	⇒	⇒	⇒	⇒	×	⇒	-
180	-4	×	⇒	×	×	×	×	-8
210	+5	×	⇒	×	×	⇒	×	+5
240	-4	⇒	×	×	×	×	×	-5
$\sum\Delta N_{EV}$ = -8								$\sum\Delta N_{EXEC}$ = -8

Before the fire the ventilation is deactivated. At fire detection the ventilation assumes its "basic setting" and ventilators #1through #4 and #8 are activated. At the first control step a switching order of ΔN_{EV} = -4 is issued. However the system deactivates units #1, #3, #4 and #8 for a total of -8 equivalent ventilators. A corrective action is undertaken 30 seconds later through the activation of ventilator #7. Nevertheless the sum of the executed deactivations at that point is $\sum\Delta N_{EXEC}$ = -3 instead of the ordered $\sum\Delta N_{EV}$ = -4. The final corrective action occurs at the next control step, at which instead of the ordered ΔN_{EV} = -4 the system deactivates 5 equivalent ventilators. The ventilator output of simulator-1 as well that of simulator-2 are illustrated in Figure 4.

The overcorrections during control steps lead to lower availability of the ventilators and in some scenarios delayed the process of reaching the target air speed. A total of 38 scenarios were affected. In Figure 4 at t = 120 s the lack of starting current modelling in simulator-2 can observed. Furthermore the effect of reaching the maximum $\sum\Delta N_{EV}$ can also be seen at t = 300 s.

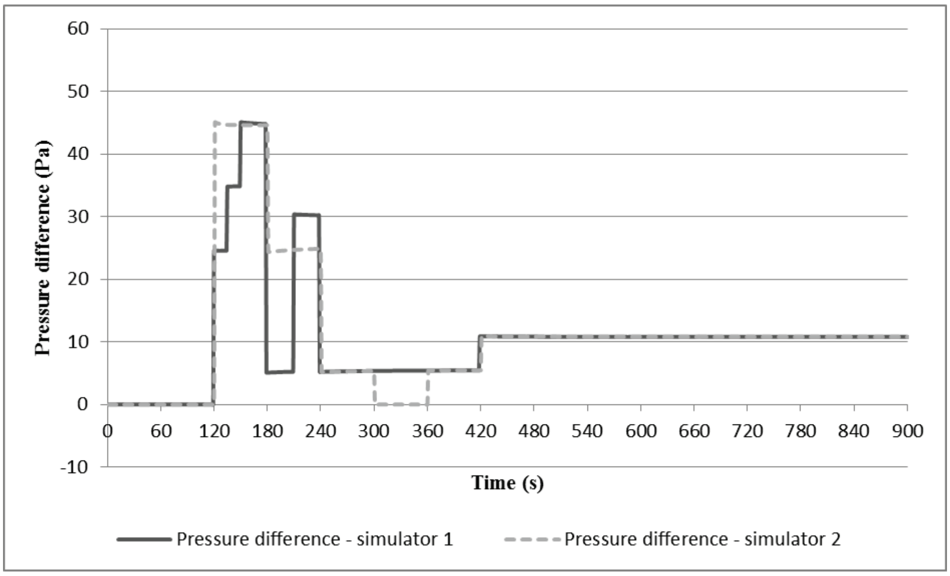

Figure 4 Ventilator performance – Scenario #93.

Scenario #100
The control system of the tunnel "Schwarzer Berg" would not adhere in some cases to the minimisation of switching operations requirement. The parameters of scenario #100 are:

- Tube: south
- Traffic: unidirectional, flowing
- Portal pressure: 7 Pa
- Fire location: 94 m from entry portal
- Fire intensity: 30 MW, output increases linearly over 10 minutes
- Ventilation: inactive before fire eruption

Table 7 Switching order – scenario #100 – simulator-1.

Time (s)	ΔN_{EV}	#2 (1 e.v.)	#3 (1 e.v.)	#4 (1 e.v.)	#5 (1 e.v.)	#6 (1 e.v.)	#8 (5 e.v.)	ΔN_{EXEC}
< 120	-	×	×	×	×	×	×	-
120	-	×	⇒	⇒	⇒	⇒	⇒	-
180	-2	×	×	×	⇒	⇒	⇒	-2
240	-4	⇒	⇒	⇒	×	×	×	-4

The switching sequence is presented in Table 7. At t = 240 s a switching order of ΔN_{EV} = -4 is issued. The system correctly deactivates ventilator #8 and activates ventilator #2 without any overcorrections. In the process however the system also needlessly deactivates ventilators #5 and #6 and activates units #3 and #4. In a total of 15 scenarios this reaction was observed.

Scenario #156
Under some circumstances the automatic system would erroneously deactivate the ventilation system; an extremely dangerous reaction. An example of this behaviour is illustrated in Figure 5. The parameters of scenario #156 are listed below:

- Tube: south
- Traffic: bidirectional, flowing
- Portal pressure: 7 Pa
- Fire location: 300 m from entry 0
- Fire intensity: 30 MW, output increases linearly over 10 minutes
- Ventilation: inactive before fire eruption

In case of bidirectional traffic the air flow is directed at a speed of 1 m/s (±0,5 m/s tolerance) towards the nearest portal. In this scenario the nearest portal is the entry portal, therefore the air speed as well as the ventilator induced pressure difference are reported as negative.

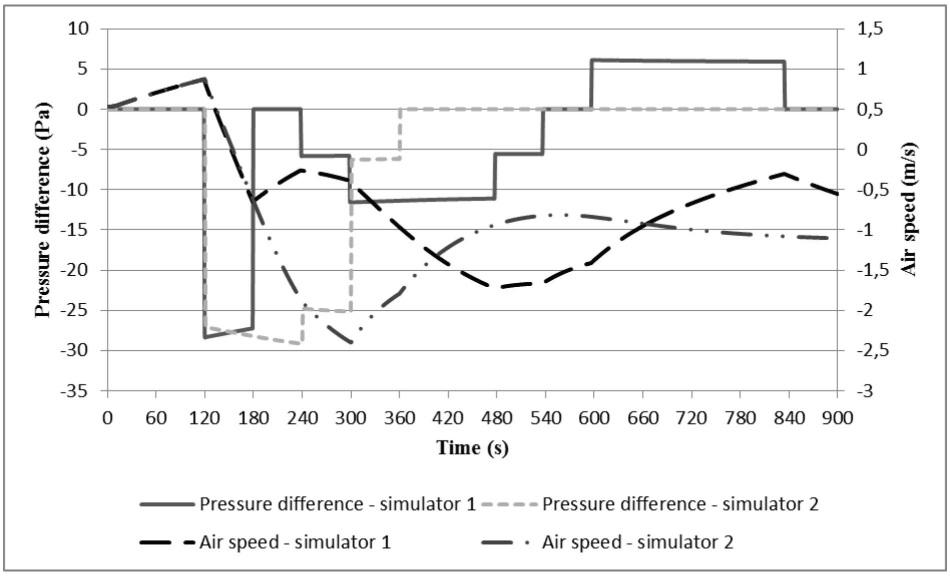

Figure 5 Ventilator performance and air speed – Scenario #156.

The ventilation is set to its "basic mode" as soon as the fire is detected. At t = 180 s however the control system of simulator-1 inappropriately deactivates the entire system, although the measured air speed at the time ($u_{t = 180}$ = -0,6 m/s) lies within tolerance levels. The control sequence continues however and the system reacts properly to the next control steps.

Shutting down the ventilation system interferes with the ability of the ventilation to set the air speed to the predefined target. In case of simulator-2 the system the target air speed is reached approximately 4 minutes after the fire is detected. The control system of simulator-1 however struggles with oscillation (see Figure 5). In total 7 scenarios were affected by this behaviour.

EVALUATION

Summary of results

Simulator-2 was developed specifically to provide an efficient method to verify the output of the tunnel "Schwarzer Berg" simulator (simulator-1).

The results demonstrated that the aerodynamic model was accurately implemented.

In regard to the reactions of the automatic system, in a number of test scenarios erroneous actions were observed. Herein only the most serious issues detected were reported affecting a total of 84 scenarios. In the rest 12 scenarios the control system errors observed were of minor importance and did not affected the conditions in the tunnel. A detailed review is provided below.

Ventilation automatic control system of tunnel "Schwarzer Berg"

In 96 out of 210 fire scenarios the control system undertook unexpected reactions. Those reactions were not detected from the fire tests before the system was deployed in the tunnel. In 24 of these scenarios, or 11 % of all cases modelled, the control system's aberrations had a strong influence on the expected conditions in the tunnel and could, under real conditions, increase the risk the road users were subjected to. The most serious issues discovered are summarised below:

- **The system would not process more than 8 of the same switching orders.**
  It was observed that the automatic system would ignore switching orders that affected more than 8 equivalent ventilators. In these cases the air speed would remain outside the tolerance

levels which could disrupt the smoke layer stratification.

- **The control system would often overcorrect.**
  In a number of scenarios the system would overcorrect during switching operations. This interfered with the ability of the ventilation system to control the conditions in the tunnel.
- **The system frequently would not adhere to the minimisation of switching operations.**
  Occasionally the automatic control would unnecessarily switch off a number of units and at the same switch on an equal number of equivalent ones. This negatively affected the availability of the ventilation system because of the delays involved in starting up and shutting down ventilators.
- **Ventilation system shut down.**
  In a relatively small number of cases the control system erroneously deactivated the ventilation system. Although the control process was not halted and the system was activated again during the next control step, the conditions in the tunnel were seriously affected.

As a result, it was recommended to replace the control system of the tunnel “Schwarzer Berg” in order to ensure the appropriate ventilation reactions during an emergency. The replacement of the control system is planned for 2014. Additionally fire tests are projected in order to examine and, if necessary, improve the accuracy of the aerodynamic model.

Simulator advantages

The simulator acts as a powerful training instrument for the tunnel operators. The operators are provided with an exact reproduction of the interface situated in the tunnel control room. They are given therefore the ability to familiarise themselves with all the systems of the tunnel and observe their effects in the conditions in it.

Furthermore the simulator is an extremely useful tool for preparing the operators for emergencies. Operators can create fire scenarios and observe how the air speed, traffic flow, smoke expansion etc. develop with time and as a function of the reaction system reactions. The operators can manually intervene in a simulated emergency and determine the effects their actions have on the outcome. This facilitates the continuous training of the tunnel operators, which is of pivotal importance in an emergency situation.

The simulator also provides an excellent test bed for the performance of the automatic control system. It is inconceivable, because of cost and time constrains, to perform the number of fire tests required in order to examine the reactions of the automatic system under every reasonable scenario. Bugs or implementation errors in the control software could therefore remain undetected until a catastrophe actually occurs.

Not only can the simulator assist with the optimisation in the already installed systems, but it can also accelerate any refurbishments and upgrades. New systems can be beforehand simulated and their performance can be refined before their deployment. Downtime is therefore minimised and additional costs of unforeseen complications are eliminated.

Cost

The cost for the tunnel “Schwarzer Berg” simulator was approximately €200k. In comparison, the infrastructure cost for the tunnel was estimated at €4,0m. The simulator represents a 5 % increase of the infrastructure capital costs in this case, where the tunnel is relatively short and the ventilation investment costs are among the lowest possible. For longer tunnels or for tunnels with sophisticated ventilation the cost of the simulator is expected to represent an even smaller increase of the infrastructure capital cost.

For tunnels with complicated ventilation systems or for tunnels where operator intervention is expected in an emergency, the cost could be justified by the advantages offered by the simulation software.