On effective close-loop control of longitudinal ventilation in road tunnels in case of fire

P Altenburger, I Riess, R Brandt
HBI Haerter AG, Switzerland

ABSTRACT

The following controller types for effective closed-loop control of longitudinal airflow velocity in road tunnels in case of fire have been investigated and optimised:
- PI-/PID-controller (proportional-integral-derivative controller)
- MPC-controller (model predictive controller)

In general, for the control of the longitudinal velocity in road tunnels, classic controllers as PI/PID-controllers are used. The control parameters are usually determined by "trial and error". However, if the control parameters are not optimised adequately, there is a risk of slow control and oscillating. Only with optimised control parameters, a fast and robust control can be guaranteed.

A modern controller, which is becoming increasingly important in control theory, is the MPC-controller.

The two controller types have been optimised and compared according to several criteria.

ABBREVIATIONS

D	Derivative	PID	PID-controller
DT	Dead time	PT1	1st order low pass
I	Integral	PT2	2nd order low pass
JF	Jet fans	PT3	3rd order low pass
MPC	MPC-controller	SP	Setpoint
P	Proportional	T	Tunnel
PI	PI-controller	Veh	Vehicles

1 INTRODUCTION

Many road tunnels which exceed a certain length are equipped with mechanical ventilation. Usually jet fans are used for the control of the longitudinal airflow. In case of fire, the ventilation has to support the self-rescue of the tunnel users by fast control of the smoke.

Depending on the guideline of the country, in some cases the airflow in the tunnel has to be close-loop controlled (e.g. bidirectional traffic or unidirectional traffic with congestion). However, it is usually not specified how quickly the required airflow condition must be achieved nor what type of controller has to be used.

The self-rescue takes place in the first few minutes after a fire starts. Therefore the airflow conditions are critical in the first few minutes. As a consequence, it is very important that the airflow control achieves its goal as quickly as possible.

In general, for the control of the longitudinal airflow velocity in road tunnels, classic PI/PID-controllers are used. The control parameters are usually determined by "trial and error" because it can be done fast and easy. In the guidelines, it is mostly not specified, how the control parameters have to be chosen. However, the speed of the control depends crucially on the optimal choice of the control parameters.

If the control parameters of the PI/PID-controllers are not optimised adequately, there is a risk of slow control and oscillating of the jet fans and airflow velocity. Only with optimised control parameters, a fast and robust control can be guaranteed.

A modern controller, which is becoming increasingly important in control theory, is the MPC-controller (Model Predictive Control).

In this study, both controllers (MPC-controller, PI/PID-controllers) are examined and optimised for the control of the longitudinal airflow in road tunnels in case of fire. The optimised controllers are then compared.

For the PI/PID-controller, the control parameters according to Ziegler/Nichols step response method (4) are derived.

For the control with the MPC-controller, the parameters were chosen according to literature about MPC-controllers (2).

In order to find the optimal control parameters for both controller types, the controlled system has to be modelled with linear basic transfer elements.

2 OUTCOMES

The two controller types have been tested by controlling the longitudinal airflow velocity in a sample tunnel equipped with jet fans from 0 m/s (start conditions) to 1 m/s or to 3 m/s.

The two controller types have been compared according to quantified control criteria, such as rise-time, overshoot, settling-time and stability of the controlled airflow velocity. Also, qualitative criteria have been assessed, including complexity, number of specific parameters required, availability of simulation tools and availability of algorithms for standard control equipment.

The MPC-controller beats the PI/PID-controller in control speed. However, in general, the use of PI-controller with Anti-Windup is still recommended. On the basis of the simple structure, the availability, the low number of parameters and the stability of the controller, the advantages of the PI-controller are superior to the MPC-controller. Because of the limited ventilation capacity, the use of Anti-Windup is imperative. The Anti-Windup limits the integration of the PI-controller, if the limit of jet fans is reached (1).

For fast control, sufficient ventilation capacity is beneficial. The requested number of jet fans during dynamic control may significantly exceed the required number of jet fans in steady state. However, the tunnel ventilation is usually designed for steady state conditions. As a consequence, in a worst-case scenario, the control may be slowed down and the desired airflow velocity may be achieved later, because of the limited jet fan capacity.

3 MODELING

With the modelling of the system, the main relationships of the control-loop can be defined. In the following, the system "longitudinal ventilation" (tunnel without smoke extraction) is considered.

In the control-loop of the system "longitudinal ventilation", the following models are considered:

- Time delay when starting multiple jet fans (jet fans must be turned on staggered or ramped due to electric current spikes)
- Jet fan dynamics
- Tunnel air dynamics
- Airflow velocity measurement (filtering of the measured signals)

The control loop of the system "longitudinal ventilation" includes the following state variables:

- Number of required jet fans: n_{JF_req}
- Number of required jet fans, taking into account the time delay when starting multiple jet fans: $n_{JF\_req\_ramp}$
- Number of operating jet fans in the tunnel: n_{JF}
- Airflow velocity in the tunnel: v
- Measured airflow velocity in the tunnel: v_{meas}
- Required airflow velocity in the tunnel: $v_{setpoint}$

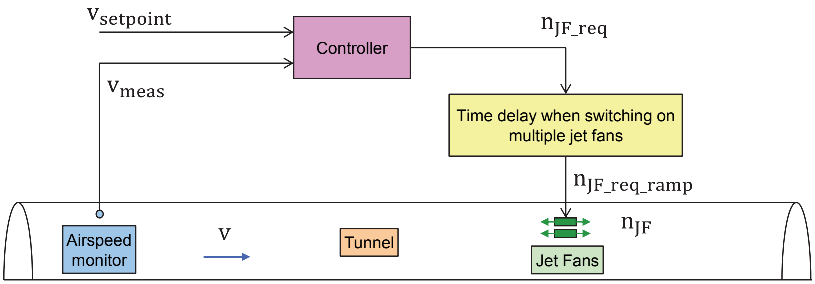


Figure 1 Control loop of the system "longitudinal ventilation"

The relationships between the different state variables are described by the following models.

3.1 Model of time delay (ramp) when starting multiple jet fans

If jet fans without starting aids are driven directly (DOL), the starting of several fans are usually executed with a time delay (delay time T_{JF_D}) of a few seconds to avoid electric current spikes in the electrical plant. For a small number of jet fans, the delay time can be ignored. For multiple jet fans, however, the time delay must be taken into account in the model. The starting of multiple jet fans is modelled as a ramp.

For the ramp, the following equation applies:

$n_{JF\_req\_ramp} = \begin{cases} \frac{1}{T_{JF\_D}} \cdot t, & t < n_{JF\_req} \cdot T_{JF\_D} \\ n_{JF\_req}, & t \geq n_{JF\_req} \cdot T_{JF\_D} \end{cases}$		3-1
n_{JF_req}	Number of required jet fans	[-]
$n_{JF\_req\_ramp}$	Number of required jet fans, taking into account the ramping when starting multiple jet fans	[-]
T_{JF_D}	Delay time between starting of jet fans	[s]

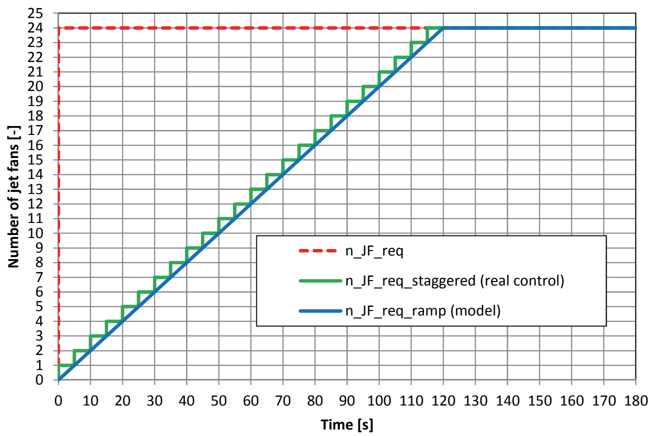


Figure 2 Time delay (ramping) when starting multiple jet fans

3.2 Model of jet fan dynamics

If a stopped jet fan is started, the impeller has to be accelerated first. As a consequence, the impact of the jet fan on the tunnel air has a time delay compared to the activation of the jet fan. The time delay of the jet fan impact is modelled as a 1st order low pass. The following differential equation applies:

$\frac{dn_{JF}}{dt} = \frac{1}{\tau_{JF}} \cdot (n_{JF\_req} - n_{JF})$		3-2
n_{JF_req}	Number of required jet fans	[-]
n_{JF}	Number of operating jet fans	[-]
τ_{JF}	Time constant of the jet fans	[s]

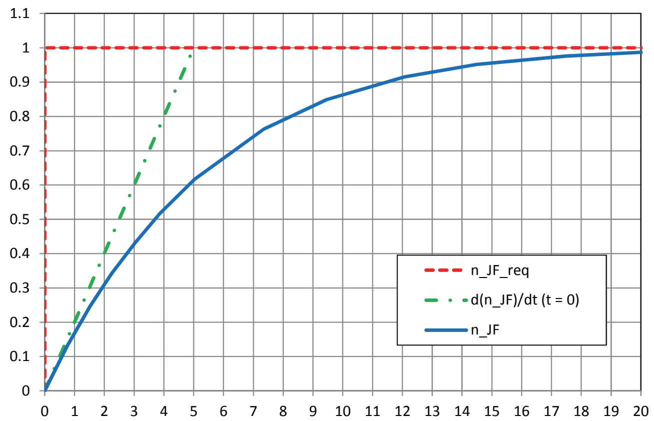


Figure 3 Dynamics of jet fans

3.3 Model of tunnel air dynamics

In the tunnel, several pressures are acting which either accelerate or slow down the airflow velocity in the tunnel. Neglecting all external disturbing pressures and assuming standing vehicles (traffic jam), the following differential equation applies:

$$\underbrace{\frac{dv}{dt}L\rho}_{\Delta p_{mom}} = \underbrace{-\frac{1}{2}\rho\left(\kappa_{PL} + \frac{\lambda \cdot L}{D_{hyd}} + \kappa_{PR} + \frac{n_{Veh}cw_{Veh}A_{Veh}}{A_T}\right)v\lvert v\rvert}_{\Delta p_{Geom+Veh}} + \underbrace{\frac{\rho A_{JF}(v_{JF} - v)v_{JF}}{k_{JF}A_T}}_{\Delta p_{JF}}n_{JF}$$	3-3

Δp_{mom}	Pressure due to momentum change	[Pa]
$\Delta p_{Geom+Veh}$	Pressure due to geometry und vehicles	[Pa]
Δp_{JF}	Pressure due to operating jet fans	[Pa]
v	Airflow velocity in the tunnel	[m/s]
ρ	Density of air	[kg m^{-3}]
L	Length of the tunnel	[m]
κ_{PL}	Inflow/outflow loss coefficient of left portal	[-]
κ_{PR}	Inflow/outflow loss coefficient of right portal	[-]
λ	Friction coefficient of the tunnel	[-]
D_{hyd}	Hydraulic diameter of the tunnel	[m]
n_{Veh}	Number of vehicles in the tunnel	[-]
cw_{Veh}	Resistance coefficient of the vehicles	[-]
A_{Veh}	Cross sectional area of the vehicles	[m^2]
A_T	Cross sectional area of the tunnel	[m^2]
n_{JF}	Number of operating jet fans	[-]
A_{JF}	Cross sectional area of the jet fans	[m^2]
v_{JF}	Outlet velocity of the jet fans	[m s^{-1}]
k_{JF}	Installation factor of the jet fans	[-]

The outlet velocity of the jet fans v_{JF} is usually many times larger than the airflow velocity v in the tunnel. Therefore for the pressure due to the operating jet fans, a simplified equation can be assumed:

$\Delta p_{JF} \approx \frac{\rho \cdot A_{JF} \cdot v_{JF}^2}{k_{JF} \cdot A_T} \cdot n_{JF}$	3-4

With the simplified model of pressure generation by jet fans the differential equation can be simplified:

$\frac{dv}{dt} = -a_T \cdot v \cdot \|v\| + b_T \cdot n_{JF}$		3-5
a_T	"Resistance constant" of the tunnel	$[m^{-1}]$
b_T	"Impact constant" of a jet fan in the tunnel	$[m\ s^{-2}]$

This leads to the following two constants, which describe the tunnel system:

$a_T = \frac{\left(\kappa_{PL} + \frac{\lambda \cdot L}{D_{hyd}} + \kappa_{PR} + \frac{n_{Veh} cw_{Veh} A_{Veh}}{A_T}\right)}{2 \cdot L}$	3-6
$b_T = \frac{A_{JF} \cdot v_{JF}^2}{L \cdot k_{JF} \cdot A_T}$	3-7

3.4 Model of airflow velocity measurement filtering

The measured airflow velocity is usually filtered to suppress short-term fluctuations of the measured signal. As filter, a 1st order low pass is used. The following differential equation applies:

$\frac{dv_{meas}}{dt} = \frac{1}{\tau_{meas}} \cdot (v - v_{meas})$		3-8
v_{meas}	Measured airflow velocity in tunnel	[m/s]
v	Airflow velocity in tunnel	[m/s]
τ_{meas}	Time constant of the measurement filter	[s]

4 LINEAR APPROXIMATION MODELS

The controlled system, in particular the model of the tunnel is non-linear. However, a linear model of the controlled system is required for the MPC-controller. For the PI/PID-control with the control parameters according to Ziegler/Nichols, the controlled system has to be approximated to a 1st order low-pass with dead time, which is a linear model as well.

In the following, several linear approximation models are developed for the differential equations for the dynamics of the tunnel, the jet fan dynamics, and the airspeed measurement.

4.1 Linear approximation model of the time delay when starting multiple jet fans

The delay caused by the jet fan ramping can be approximated to a 1st order low pass. The time constant is assumed as half of the maximum ramp duration.

$\tau_{Ramp} \approx 0.5 \cdot n_{JF\_max} \cdot T_{JF\_D}$		4-1
τ_{Ramp}	Time constant of the time delay when starting multiple jet fans	[s]
n_{JF_max}	Maximum number of jet fans in the tunnel	[-]
T_{JF_D}	Delay time between starting of jet fans	[s]

Alternatively, the delay of the jet fan ramping can be described as a dead time. The dead time can be derived by combining the ramp model and the tunnel model (tunnel as 1st order low pass). The dead time is calculated by the following formula:

$T_{Ramp\_DT} = \dfrac{\tau_T - (T_{Ramp} + \tau_T) \cdot e^{-\frac{T_{Ramp}}{\tau_T}}}{\left(1 - e^{-\frac{T_{Ramp}}{\tau_T}}\right)}$		4-2
T_{Ramp_DT}	Dead time by the delay of the jet fan ramping	[s]
τ_T	Time constant of the tunnel	[s]
T_{Ramp}	Duration of the jet fan ramping	[s]

4.2 Linear approximation model of the tunnel air dynamics

The tunnel air dynamics is described by a non-linear differential equation. The tunnel air dynamics model may be approximated to a 1st order low pass (PT1-element). This results in the following differential equation:

$\dfrac{dv}{dt} \approx -\dfrac{1}{\tau_{T\_PT1}} \cdot v(t) + \dfrac{K_{T\_PT1}}{\tau_{T\_PT1}} \cdot n_{JF}(t)$	4-3

For the amplification of the 1st order low pass, the following equation applies:

$K_{T\_PT1} = \sqrt{\dfrac{b_T}{n_{JF\_max} \cdot a_T}}$	4-4

For the time constant τ_T of the tunnel, the following equation applies:

$\tau_{T\_PT1} = \dfrac{1}{\sqrt{a_T b_T n_{JF\_max}}}$	4-5

4.3 Linear approximation model of the jet fan dynamics

The jet fans dynamics is modelled by a 1st order low pass, which is already a linear model (see equation 3-2). Alternatively, the model can be described as a dead time. For the modelling, the dead time of the jet fans is equated to the time constant of the jet fans:

$T_{JF\_DT} \approx \tau_{JF}$		4-6
T_{JF_DT}	Dead time of the jet fan dynamics	[s]
τ_{JF}	Time constant of the jet fans	[s]

4.4 Linear approximation model of the airflow velocity measurement (filtering of the measured airflow velocity signals)

The airflow velocity measurement is modelled by a 1st order low pass, which is already a linear model (see equation 3-8). Alternatively, the model can be described as a dead time. For the modelling, the dead time of the airflow velocity measurement is equated to the time constant of the airflow velocity measurement:

$T_{meas\_DT} \approx \tau_{meas}$		4-7
T_{meas_DT}	Dead time of the measurement filter	[s]
τ_{meas}	Time constant of the measurement filter	[s]

4.5 Combination of the linear approximation models

The control loop consisting of jet fans, tunnel and airflow velocity measurement can be described by combination of the individual linear models.

The following linear approximation models are suitable for describing the dynamics of the system “longitudinal ventilation” (jet fan dynamics, jet fan ramping, tunnel dynamic and airflow velocity measurement):

- System as a 1st order low-pass with dead time
  (Tunnel as 1st order low pass, jet fans, jet fan ramping and measurement as dead time)
- System as a 2nd order low pass
  (Tunnel as 1st order low pass, jet fans, jet fan ramping and measurement combined as 1st order low pass)
- System as a 3rd order low pass
  (Tunnel, jet fans and measurement each as 1st order low pass)
- System as a 4rd order low pass
  (Tunnel, jet fans, jet fan ramping and measurement each as 1st order low pass)

5 PI/PID-CONTROL

Figure 4 shows the structure of an ideal PID-controller with anti-windup. In order to have a PI-controller only, the D-part (dashed) is omitted.

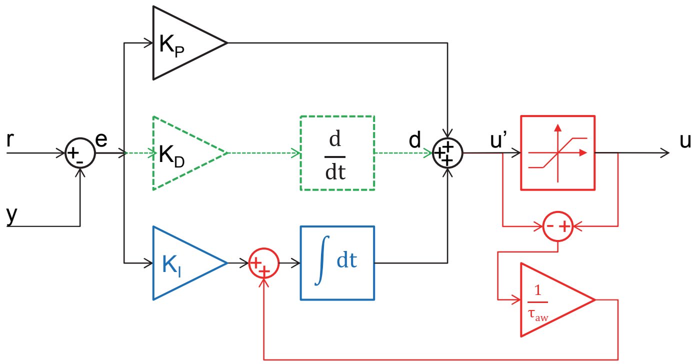


Figure 4 Structure of an ideal PID-controller with anti-windup

For the control of the system “longitudinal ventilation” with a PI/PID-controller, the control parameters according to Ziegler/Nichols step response method are derived. In order to derive these, the controlled system has to be approximated to a 1st order low-pass with dead time (PT1-DT element). With the step response of the controlled system, the following parameters can be determined:

- Static gain K
- Time constant τ
- Dead time T_{DT}

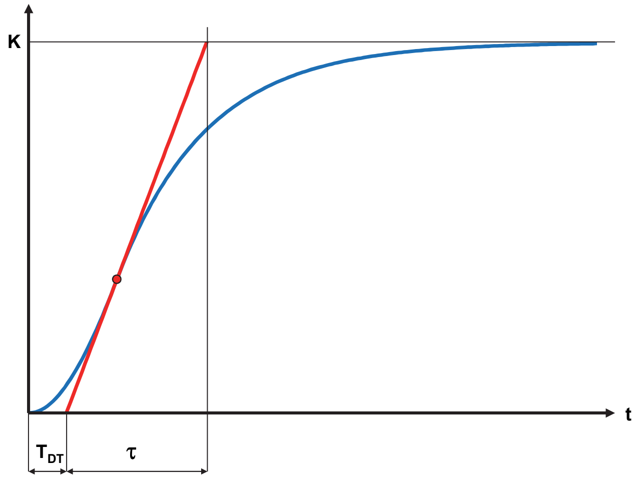


Figure 5 Step response with tangent in the turning point

With these parameters, the control parameters according to Ziegler/Nichols (4) can be derived (see Table 1).

Table 1 Control parameters according to Ziegler/Nichols

Controller	$\mathbf{K_p}$	$\mathbf{T_i}$	$\mathbf{T_d}$
P-controller	$K_{P\_P} = 1 \cdot \frac{\tau}{K \cdot T_{DT}}$		
PI-controller	$K_{PI\_P} = 0.9 \cdot \frac{\tau}{K \cdot T_{DT}}$	$T_{PI\_I} = 3.33 \cdot T_{DT}$	
PID-controller	$K_{PID\_P} = 1.2 \cdot \frac{\tau}{K \cdot T_{DT}}$	$T_{PID\_I} = 2 \cdot T_{DT}$	$T_{PID\_D} = 0.5 \cdot T_{DT}$

With:		
K_{P_P}	Amplification of the P-controller	[s/m]
K_{PI_P}	Amplification of the PI-controller	[s/m]
K_{PID_P}	Amplification of the PID-controller	[s/m]
T_{PI_I}	Time constant of the I-part of the PI-controller	[s]
T_{PID_I}	Time constant of the I-part of the PID-controller	[s]
T_{PID_D}	Time constant of the D-part of the PID-controller	[s]

The parameters K, τ and T_{DT} can be derived from the system models (see section 4):

- The amplification of the 1st order low pass was already described in equation 4-4
- The time constant τ_T of the tunnel was already described in equation 4-5
- The dead time of the system is the sum of all dead times in the system

$T_{DT} = T_{Ramp\_DT} + T_{JF\_DT} + T_{meas\_DT}$		5-1
T_{DT}	Dead time of the approximated system	[s]
T_{Ramp_DT}	Dead time by the delay of the jet fan ramping	[s]
T_{JF_DT}	Dead time of the jet fan dynamics	[s]
T_{meas_DT}	Dead time of the measurement filter	[s]

This leads to the following table:

Controller	$\mathbf{K_p}$	$\mathbf{T_i}$	$\mathbf{T_d}$
P-controller	$K_{P\_P} = 1 \cdot \frac{1}{b_T \cdot T_{DT}}$		
PI-controller	$K_{PI\_P} = 0.9 \cdot \frac{1}{b_T \cdot T_{DT}}$	$T_{PI\_I} = 3.33 \cdot T_{DT}$	
PID-controller	$K_{PID\_P} = 1.2 \cdot \frac{1}{b_T \cdot T_{DT}}$	$T_{PID\_I} = 2 \cdot T_{DT}$	$T_{PID\_D} = 0.5 \cdot T_{DT}$

b_T	"Impact constant" of a jet fan in the tunnel	[m/s^2]
T_{DT}	Total dead time of the controlled system	[s]

The dead time of the system can also be measured or simulated in the tunnel by a step response test:
- At the time $t < 0$, all jet fans are turned off
- At the time $t = 0$, all SV are turned on
- For the time $t > 0$, the resulting profile of the airflow velocity is measured

For the anti-windup, the following time constant has been found suitable (1):

$T_{PID\_aw} = T_{PI\_aw} = 5\ s$		5-2
T_{PI_aw}	Time constant of the anti-windup	[s]

6 MPC-CONTROL

An MPC-controller contains a complete model of the process dynamics with all relationships between the state variables. With the help of the internal model, the MPC-controller can "look to the future", i.e. can make predictions within a given time horizon.

The internal model of the MPC-controller must be described by a linear model of the system which includes the tunnel, the jet fans as well as the filtering of the airflow velocity measurement.

The following linear approximation models for the internal model were analysed:
- System as a 2nd order low pass
- System as a 3rd order low pass

The MPC-controller needs additional control parameters, such as:
- Sampling time t_S (time steps of controller)
- Model horizon n_M (number of time steps for model horizon)
- control horizon n_C (number of time steps for control horizon)
- prediction n_P (number of time steps for model prediction)
- weighting matrix Q (importance of the controlled variables)
- weighting matrix R (penalizing of big changes of the manipulating variables)

For the control with the MPC-controller, the following parameters were chosen according to (2):

Table 2 Chosen parameters for MPC-controller

MPC-control Parameter	Value
t_S	5 s
n_M	320
n_C	20
n_P	340
Q	1
R	0

7 CHARACTERISTIC VALUES OF A CONTROLLER

The quality of a close-loop controller can be quantified with the following characteristic values (see Figure 6):

- Dead time: T_{DT}
- Rise time from start of the control to 90% of the setpoint: T_{R90}
- Settling time from the start of the control to ±10% around the setpoint: T_{S10}
- Overshoot from the setpoint: D_y
- Permanent control deviation: e∞

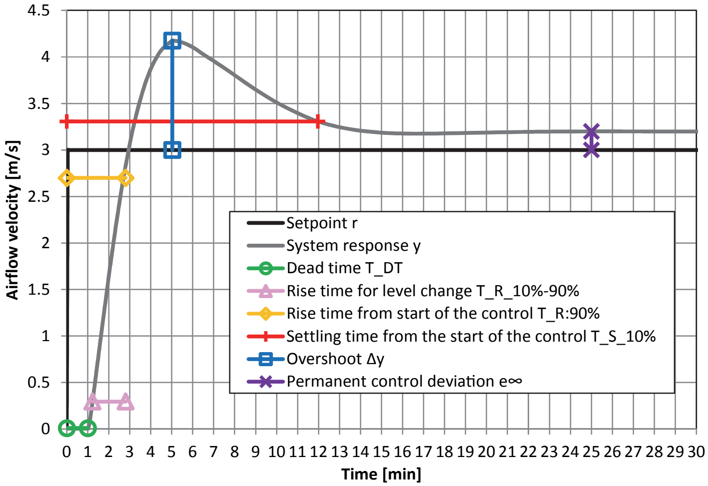


Figure 6 Characteristic values of a control response

8 COMPARISON OF THE TWO CONTROLLERS IN A SAMPLE TUNNEL

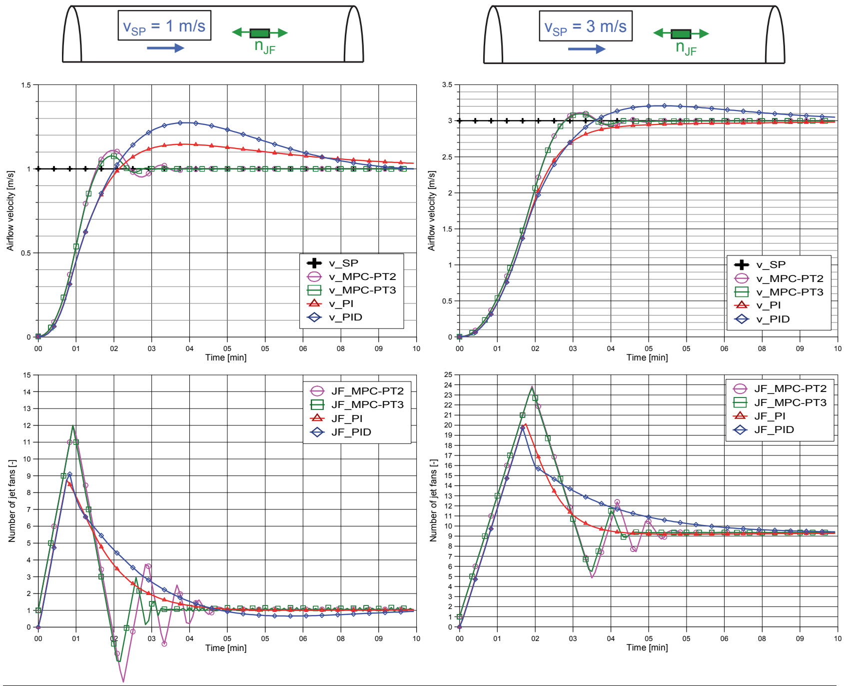
The two controller types were tested on a sample tunnel, simulated with MATLAB (3).

Table 3 shows the geometry and the jet fan data of the sample tunnel.

Table 3 Tunnel geometry and jet fan data of the sample tunnel

Tunnel data	Tunnel length	4'200 m
	Cross sectional area	46.8 m^2
	Hydraulic diameter	6.7 m
Jet fan data	Number of installed jet fans	24
	Impeller diameter	630 mm
	Cross sectional area of the jet fan	0.312 m^2
	Static thrust	460 N
	Outlet velocity at static thrust	35.07 m/s

Figure 7 shows various controllers applied on the system “longitudinal ventilation”. The airflow velocity is controlled to a desired airflow velocity (setpoint) of 1 m/s and 3 m/s.



Abbreviations:	
v_SP:	Desired airflow velocity in the tunnel
v:	Actual airflow velocity in the tunnel
JF:	Number of jet fans
MPC_PT2:	Control with MPC-controller, internal model 2nd order low pass
MPC_PT3:	Control with MPC-controller, internal model 3rd order low pass
PI:	Control with PI-controller
PID:	Control with PID-controller

Figure 7 Comparison of PI-, PID- and MPC-control when controlling the system “longitudinal ventilation” to 1 m/s

Table 4 shows rise time, overshoot and settling time for the control of the system “longitudinal ventilation” to 1 m/s and 3 m/s.

Table 4 Characteristic values, control to 1 m/s and 3 m/s

Airflow velocity	**Controller type**	**Rise time $T_{R90\%}$**	**Overshoot Δv**	**Settling time $T_{S10\%}$**
1 m/s	PI	≈ 1.8 min	≈ 0.15 m/s (≈ 15%)	≈ 5 min
	PID	≈ 1.8 min	≈ 0.28 m/s (≈ 28%)	≈ 6 min
	MPC (PT2)	≈ 1.4 min	≈ 0.11 m/s (≈ 11%)	≈ 2.2 min
	MPC (PT3)	≈ 1.4 min	≈ 0.08 m/s (≈ 8%)	≈ 1.4 min
3 m/s	PI	≈ 2.9 min	≈ 0 m/s (≈ 0%)	≈ 2.9 min
	PID	≈ 2.9 min	≈ 0.2 m/s (≈ 6%)	≈ 2.9 min
	MPC (PT2)	≈ 2.4 min	≈ 0.1 m/s (≈ 3%)	≈ 2.4 min
	MPC (PT3)	≈ 2.4 min	≈ 0.1 m/s (≈ 3%)	≈ 2.4 min

9 CONCLUSIONS

The comparison between the different controllers shows:

MPC-controller:
- The MPC-controller is faster than the PI/PID-controllers.
- The MPC-controller with a 3rd order low pass tunnel model is faster than the MPC-controller with a 2nd order low pass tunnel model
- The MPC-controller is relatively complex, as many parameters have to be determined
- Standard simulation software usually does not consist of an MPC-controller

PI- and PID-controller:
- The PI-/PID-controllers are not as fast as the MPC-controller
    - Slightly slower rise time as MPC-controller
    - Slightly larger overshoot as MPC-controller
    - Longer settling time than MPC-controller
- Almost any simulation software includes standard PI- and PID-controllers. And if not, they can easily be modelled with mathematical blocks.
- The inclusion of the D component in a PID controller can lead to problems with real input signals.
- The PI-controller is superior to the PID-controller, as it has only benefits
    - Smaller overshoots
    - Only 2 parameters

10 RECOMMENDATIONS

For the control of the longitudinal airflow in the event of fire, it is recommended to use a standard PI-controller with anti-windup. Due to the simple structure, the small number of parameters and the good control performance, it is superior to the MPC-controller. Due to the limited number of jet fans in tunnels, an anti-windup is essential.

Practical aspects speak against the use of MPC-controllers. The availability of MPC-blocks in simulation software and PLC software is not always given. In addition, the complexity of the MPC-controller leads to new uncertainties and associated risks.

Crucial for a fast control, regardless of the controller, is that sufficient jet fan capacity is available. The number of required jet fans for an ideal control by far exceeds the number of required jet fans at steady state. The number of installed jet fans is usually designed for a steady state. In the worst case scenario, the control may be slowed down (the desired airflow velocity is achieved later) due to the limited number of jet fans.

In the simulations, it was assumed that jet fans can be switched in fractional numbers. For tunnels in which the jet fans are driven with frequency converters, this is realistic. For tunnels in which the jet fans are driven directly, the jet fans numbers have to be integers. Depending on whether few large jet fans or many small jet fans are installed, the accuracy of the control can be limited. Especially if large jet fans are used, the quality of the control can be improved significantly if at least some of the jet fans are operated with frequency converters.

11 APPLICATION IN TUNNEL PROJECTS

The control of the longitudinal airflow with a PI-controller with anti-windup and with the control parameters according to Ziegler/Nichols step response method was successfully implemented in the following tunnels:

- Cassanawald (Switzerland, 1200 m, bidirectional traffic, longitudinal ventilation)
- Chlus (Switzerland, 800 m, bidirectional traffic, longitudinal ventilation)
- Viamala (Switzerland, 765 m, bidirectional traffic, longitudinal ventilation)

12 REFERENCES

(1) HBI Haerter AG: "Regelung der Luftströmung in Strassentunneln im Brandfall", Forschungsauftrag Bundesamt für Strassen (ASTRA), 2013, report number 1409
(2) R. Dittmar, B.-M. Preiffer: "Modellbasierte prädiktive Regelung", 2004
(3) Software: MATLAB R2011b; MathWorks
(4) W. Beitz, K.-H. Grote: "Dubbel: Taschenbuch für den Maschinenbau", 20. Auflage, Teil X, Springer 2001