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Model-based airflow controller design for fire ventilation in road tunnels

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ABSTRACT

This paper describes a new approach to design the proportional-integral-derivative (PID) controller of the longitudinal airflow velocity in road tunnels for fire situations. Our work shows clearly that the use of a proper model provides valid data for model-based tuning of tunnel controllers, which is demonstrated by real tunnel tests. The design uses the simplified mathematical model of airflow dynamics based on Bernoulli and continuity equations, which describe the airflow dynamics in one dimension. Optimizing controller parameters on site is very time consuming and this problem increases in the case of complex tunnels with several entrance and exit ramps, which typically have occurrences of traffic congestion. Our approach is based on the design of the controller through simulations, which use the mathematical model of airflow velocity in the tunnel. This approach spares a lot of work and time with the controller tuning within tunnel tests. Moreover, it can discover potential problems, which can occur during real instances of fire in the tunnel. The additional advantage of this approach is a possibility to simulate a scenario of errors and failures of some devices, which are important for reliable control of longitudinal airflow velocity. Although this approach is focused primarily on complex road tunnels, due to their complexity and significant time savings with the controller tuning, it can be also used for simpler tunnels with no ramps (usually highway tunnels) where the design of the airflow controller is not as complex compared to the case of road tunnels. This paper also includes a case study of the airflow controller design for the Blanka tunnel complex in Prague, Czech Republic, which is the largest city tunnel in Central Europe.

1. Introduction

After the following series of tragic events in tunnels such as; the Mont Blanc Tunnel – 39 fatalities, the Tauern Road Tunnel – 12 fatalities, the St. Gotthard Tunnel – 11 fatalities and the Gleinalm Tunnel – 5 fatalities, more specific guidances and recommendations for the fire ventilation strategies have been published, e.g. (World Road Association, 2011; CETU, 2003). In summary, reliable control of longitudinal airflow velocity is essential for effective smoke propagation. In the first minutes of a fire event, especially in city tunnels with frequent congestions, it is important to maintain low airflow velocities in the traffic direction to support evacuation. After initial moments of evacuation, conditions for fire-fighters need to be maintained, in order to enable fire-fighting operations. It is achieved through increased longitudinal airflow velocity, in order to push all the smoke downstream of a fire.

In practice, the major parts of industrial processes are controlled by PLC (Parr, 1998). The situation is the same in road tunnels, because ventilation, lighting, drainage and other technological systems are controlled by PLC. The PID controller is the most popular feedback controller in practice, as it is easy for implementation in PLC and, if it is properly tuned, can fulfil most requirements on the control of industrial processes. Moreover, it has a satisfactory response against disturbances and measurement noise. In road tunnels, there can occur several disturbance effects in the case of fire such as; pressure loss caused by fire and device failures (jet fans, sensors).

This paper is divided into six sections, which are structured as follows: In Section 2, the derivation and analysis of the 1D mathematical model of airflow velocity including the modelling of fire

Abbreviations: PID, proportional-integral derivative controller; PLC, programmable logic controller; CFD, Computational Fluid Dynamics; CETU, Centre d'etudes des tunnels; PIARC, Permanent International Association of Road Congresses; CCTV, Closed-circuit television; SIMC, Skogestad Internal Model Control.

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dynamics is presented. Section 3 explains the principle of the PID controller for the longitudinal airflow velocity. Section 4 is the case study and gives results from tunnel testing, which took place in the Blanka tunnel complex before opening of the tunnel to traffic. This section also includes a comparison of simulation and real measured data. The final two sections are conclusions and acknowledgements, respectively.

2. Mathematical model of airflow velocity

Our idea is to design the PID controller based on the mathematical model of airflow velocity. The controller performance is influenced by the quality of the mathematical model. For this reason, it is necessary to put significant effort into the development of the airflow dynamics model.

There are two basic approaches to model the airflow dynamics in road tunnels. The first uses the Navier-Stokes equations and the second is based on the Bernoulli and continuity equations. Although the Navier-Stokes equations are non-linear partial differential equations and the airflow dynamics can be described by these equations in three dimensions, they are very computationally time demanding and not suitable for the design of the PID controller.

In recent years, there have been several research groups dealing with the simplified airflow velocity models. One of the most important of them, the research group led by Mizuno, has been dealing with methods of airflow velocity modelling since the 1980s. They have published several important papers, in which they describe the derivation of mathematical models of airflow velocity (Ohashi, 1982; Mizuno, 1991). They verified their approach on two Japanese highway tunnels – the Kan-etsu tunnel (10.965 km) and the Ena-san tunnel (8.625 km). Another group led by a Swede Bring used a similar approach to model the airflow dynamics in one dimension and verified the approach on the real data from the city tunnel in Central Stockholm "Söderledstunneln" in 1997 (Bring et al., 1997). Both mentioned groups were focused on highway tunnels with no entrance and exit ramps. Whereas the Bring's group used the steady-state model of airflow velocity, the Mizuno's group derived the dynamic mathematical model of airflow velocity, which is suitable for a design of the PID controller for airflow velocity. They used the Newton's law of motion for the derivation. In the following, we show the another approach to derive the dynamic mathematical model of airflow velocity through the extended Bernoulli and continuity equation.

2.1. Extended Bernoulli equation for highway tunnel

The Extended Bernoulli equation can be used for the mathematical description of airflow velocity in a tunnel tube. We start with the simplest case of a road tunnel, longitudinally ventilated with uni-directional traffic without any ramps; depicted in Fig. 1.

The Bernoulli equation for an ideal liquid can be written for two points in the tunnel tube as follows (Fox et al., 2011):

$$p_1 - p_2 + \frac{1}{2}\rho({v_1}^2 - v_2^2) = 0 \tag{1}$$

where p_1, p_2 (Pa) represent the static pressure at two given points in the tunnel tube, v_1, v_2 (m s^{-1}) denote the airflow velocities at two given points of the tunnel tube and ρ (kg m^{-3}) is the air density.

Until now, we have supposed an ideal liquid (air in our case), which is incompressible ($\rho = \text{constant}$) and frictionless and we have also supposed the steady-state airflow ($\frac{\partial v}{\partial t} = 0$). Although the real liquid is compressible, we consider the incompressible flow in the following text, since the assumptions for incompressible flows are valid for Mach numbers considerably lower than 1 (Drikakis and Rider, 2005), which is valid for the airflow velocity

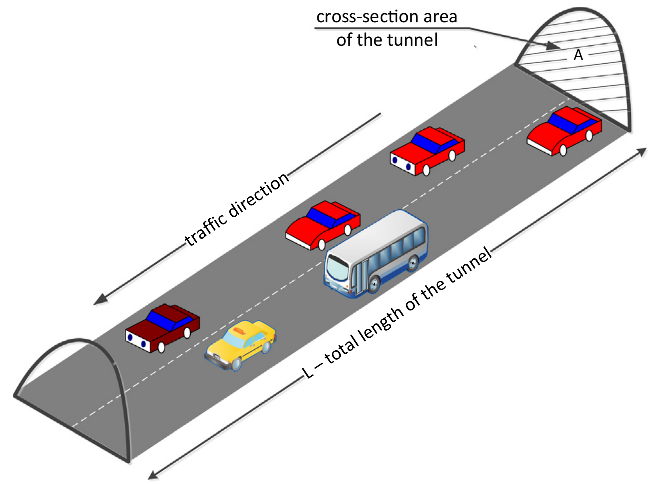

Fig. 1. The most common layout of a road tunnel without ramps.

in road tunnels where the Mach number does not achieve values higher than 0.03.

The Bernoulli equation has to be extended for the real flow and for the design of the airflow velocity controller. If we take air friction, influence of other pressure changes in the tunnel and unsteady flow of air into account, we can extend Eq. (1) in the following way (Fox et al., 2011; White, 2009)

$$p_1 - p_2 + \frac{1}{2}\rho \cdot ({v_1}^2 - v_2^2) - \rho \int_0^{\mathrm{L}} \frac{\partial v(s,t)}{\partial t}\mathrm{d}s + \Delta p(t) = 0 \tag{2}$$

where L (m) is the total length of the tunnel tube, $\rho \int_0^{\mathrm{L}} \frac{\partial v}{\partial t}\mathrm{d}s$ represents the pressure change caused by unsteady flow and Δp (Pa) denotes the total pressure change in the tunnel caused by pressure losses and pressure gains, respectively.

We assume that the airflow velocity along the whole tunnel tube is constant and is only the function of time; $v(s,t) = v(t)$, i.e. $v_1 = v_2$. Furthermore, we assume that the static pressure p_1 is equal to the static pressure p_2, i.e. $p_1 = p_2$, since we consider the same atmospheric conditions such as, temperature and atmospheric pressure, along the whole tunnel. Under these assumptions, Eq. (2) is simplified to

$$-\rho \int_0^{\mathrm{L}} \frac{\partial v(t)}{\partial t}\mathrm{d}s + \Delta p(t) = 0 \tag{3}$$

Since $v(t)$ is only the function of time, Eq. (3) can be simplified after calculating the integral as follows

$$-\rho \mathrm{L}\frac{\mathrm{d}v(t)}{\mathrm{d}t} + \Delta p(t) = 0 \tag{4}$$

The term $\frac{\mathrm{d}v(t)}{\mathrm{d}t}$ is sometimes called local acceleration and is denoted as $a(t)$. The final expression of the Bernoulli equation is following

$$-\rho \mathrm{L}a(t) + \Delta p(t) = 0 \tag{5}$$

In road tunnels, there are many factors, which influence the total pressure change Δp. Pressure losses are usually divided into major losses (air friction) and minor losses (entry of air in the tunnel, air outlet from the tunnel, change of geometry, etc.). All pressure changes, which are taken into account in our mathematical model, can be expressed as

$$\Delta p(t) = \Delta p_{fric}(t) + \Delta p_{area}(t) + \Delta p_{fire}(t) + \Delta p_{pist}(t) + \Delta p_{JF}(t) + \Delta p_{stack}(t) + \Delta p_{wind}(t) \tag{6}$$

where Δp_{fric} (Pa) denotes the pressure loss caused by air friction, Δp_{area} (Pa) are local area losses, Δp_{fire} (Pa) is the pressure change