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Optimization-based control of ventilation in a road tunnel complex

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ABSTRACT

This paper introduces a novel approach for controlling the operational ventilation in complex road tunnels. Basically, the control structure is feed-forward with an adaptive logic. The feed-forward part includes the static optimization which uses the mathematical model of airflow dynamics. The adaptive logic is based on the recursive least squares with exponential forgetting, which compensates deviations between the mathematical model and real measured data, and thus provides a feedback. During the standard operation of road tunnels, requirements to maintain indoor air quality (IAQ) and protect the surrounding area of a tunnel from pollution, are necessary. Moreover, reducing electricity costs is desirable, as the ventilation in road tunnels forms a significant part of electricity costs. The control scheme has been validated through the long-term evaluation of operation in the Blanka tunnel complex in Prague, Czech Republic, which is the largest city tunnel in Central Europe. The experimental validation of the proposed control scheme is the main contribution of the paper.

1. Introduction

In recent years, the transport sector has become a major source of environmentally hazardous emissions (Achour et al., 2011), placing complex demands on the IAQ and ambient environment of road tunnels, especially in urban areas. The operational ventilation of a road tunnel needs to keep pollutant concentrations inside the tunnel below defined limit values. Pollutant concentrations include nitrogen oxides (NO_x), carbon monoxide (CO), or opacity due to particulate matter (PM). As a result of improved combustion and catalyst technology in cars, CO is no longer a predominant consideration in the design of the tunnel ventilation. Instead, the operational ventilation is now primarily focused on NO_x and opacity (Longley, 2014).

Protecting the ambient environment of a tunnel is a complex issue, especially in urban tunnels where (PIARC, 2008):

- traffic creates significant levels of pollution,
- the environment is sensitive (e.g. there is a high concentration of buildings within close proximity to exit portals of the tunnel),
- air quality standards are strict.

Several techniques exist for reducing the impact of traffic on the ambient environment of a tunnel. These include strategic planning (to avoid planning a tunnel route through a highly populated area), pollutant removal technology (filters), regulation of traffic (time regulation, allowance of certain type of vehicles, etc.) and dispersion techniques (forced ventilation or dilution of pollutant concentrations) (PIARC, 2008).

Furthermore, ventilation in road tunnels forms a significant part of operational costs. In summary, the following goals are important for successful ventilation in road tunnels:

- maintenance of IAQ,
- protection of ambient environment,
- reduction of operational costs.

This paper introduces a novel approach for controlling the operational ventilation in complex road tunnels based on a nonlinear model of airflow dynamics. The advantages of this approach can be summarized in the following:

- applicability to complex road tunnels (with entrance and exit ramps) and not only to highway tunnels,
- ability to control the semi-transverse system of ventilation including both jet fans and ventilation machine rooms,

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- ability to fulfill many requirements on the air quality and work with many control input variables,
- robustness against control input failures,
- energy efficiency of the operation.

The control structure is feed-forward with an adaptive logic. The feed-forward control is implemented via the static optimization and the adaptive logic is represented by the recursive least-squares algorithm with exponential forgetting.

Similar structures have been applied to many control systems in recent years. Nielsen et al. (2017) provided the experimental validation of an adaptive feed-forward control of exhaust recirculation in large diesel engines. The feed-forward controller is represented by a model inversion and the adaptive logic is implemented by a nonlinear parameter estimator.

Gang et al. (2013) designed and validated experimentally an adaptive feed-forward compensation logic of an electro-hydraulic shaking table. They designed a hybrid controller with an error compensator based on the inverse transfer function.

In recent years, there have been several projects focused on the operational ventilation control in road tunnels. Some of these projects have applied fuzzy logic control (FLC) for the maintenance of pollutant concentrations inside the tunnel. Chen et al. (1998) developed the FLC and verified it through computer simulations. Karakas (2003) developed FLC for operational ventilation and compared it with the proportional–integral–derivative (PID) controller.

Hrbček & Šimák (2011), Tan et al. (2012) used the Model-based predictive control (MPC) approach to maintain IAQ. When compared with traditional control strategies (e.g. PID), MPC has numerous advantages such as constraints management or the ability to predict future process variable trends. However, the typical MPC algorithm requires knowledge of the process dynamics. The dynamic model in the explicit form can be found for tunnels without ramps which are usually highway tunnels. Obtaining the dynamic model for complex road tunnels with connected ramps is difficult. Moreover, typical MPC algorithms assume simplified linear models which are unsatisfactory for models of airflow dynamics in road tunnels.

Ferkl & Meinsma (2007) established an optimal ventilation control strategy for highway tunnels based on a steady-state model of the tunnel. This optimal control strategy is achieved through the linear programming.

Although all aforementioned works use different control strategies, they do not provide any experimental validation of simulation models and proposed control strategies.

Euler-Rolle et al. (2017) designed a dynamic feed-forward control strategy of jet fans through the feedback linearization. The big advantage of this work is a demonstration of the control strategy by its application to an Austrian highway tunnel. They extended this control strategy by a non-linear observation and disturbance rejection of pressure drops which cannot be easily modeled, e.g. stack effect or wind effect on tunnel portals (Fuhrmann et al., 2017). Although this strategy is innovative, it is limited to highway tunnels without ramps and with the longitudinal ventilation.

In summary, the standard control approach, such as the PID or a rule-based control is not applicable to this complex nonlinear system, as it is a multiple-input multiple-output (MIMO) system which cannot be easily decoupled. The MPC usually requires the linear dynamic model, which is not suitable for road tunnels. Moreover, MPC could have problems with computational load due to the tens of state variables and nonlinear process dynamics. The FLC has been validated only on simulation models and has not provided satisfactory results in the real operation of road tunnels.

This paper is structured as follows: Section 2 introduces the Blanka tunnel complex including the ventilation system. Section 3 summarizes the design procedure of the control structure. Section 4 introduces a simplified mathematical model of airflow dynamics. The control structure design is described in Section 5. A validation of the proposed control structure is stated in Sections 6 and 7.

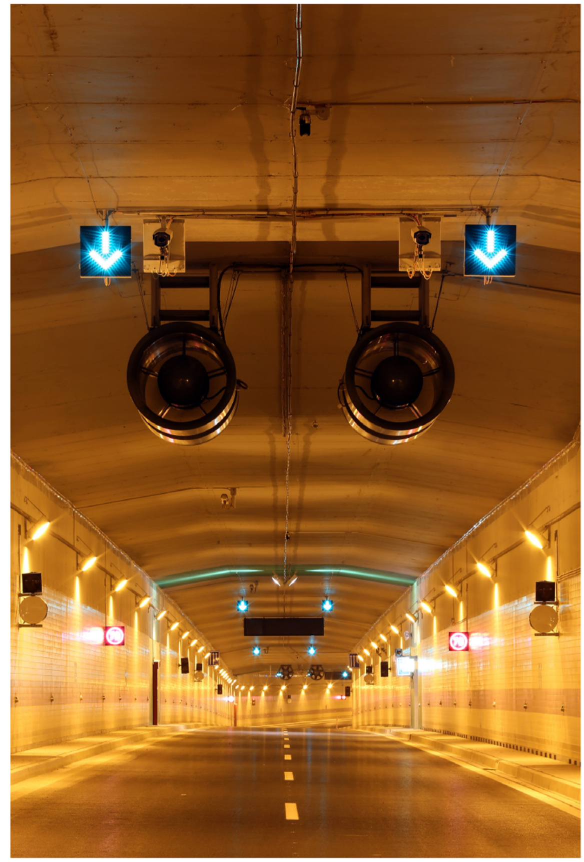

Fig. 1. A couple of jet fans located at the ceiling of the tunnel (Satra, s.r.o.; Karlíček, 2016).

2. Case study: The Blanka tunnel complex in Prague

2.1. Basic information

At 5.5 km in length, the Blanka tunnel complex is one of the largest underground structures in the Czech Republic. The tunnel was opened to traffic in September 2015 and now (July 2017) is in a trial operation.[1] The average traffic intensity in the tunnel is more than 70.000 vehicles per day. It comprises a northern and southern tunnel tube supporting uni-directional traffic. Besides the two main portals, Malovanka and Troja, exit and entry ramps are in each tube at two locations called Prašný most and U Vorlíků. A schematic illustration of the Blanka tunnel complex is shown in Fig. A.16.

2.2. Ventilation system

2.2.1. Jet fans

For longitudinal airflow velocity control, a total of 88 jet fans (JF) is installed in both tubes under the ceiling of the tunnel, see Fig. 1. Most of the jet fans are controlled by soft starters with on/off regulation. The jet fans are fully reversible, enabling them to increase or decrease airflow velocity. In support of the operational ventilation control, the jet fans are divided into 29 groups. To enable the continuous regulation of speed, almost each group contains one jet fan with a variable speed drive. Fig. A.16 depicts locations of each group within the tunnel.

[1] The trial operation means that the tunnel is open for traffic, but there are minor adjustments of tunnel technologies (ventilation, lighting, . . .) based on the real operation including a system setting, algorithms tuning, etc.