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Tunnelling and Underground Space Technology 21 (2006) 315
Tunnelling and Underground Space Technology incorporating Trenchless Technology Research
www.elsevier.com/locate/tust

Static controller for ventilation of highway tunnels

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There are many large highway tunnels constructed all around the world. The operation of such tunnels has to meet several requirements, e.g. energy consumption optimization, minimal influence on the surrounding environment, lifetime conservation, minimal maintenance costs, portal protection from exhaust, etc. As the tunnel system is typically very complex (consists of a large number of fans, sensors, several ventilation shafts, etc.), a controller designed according to modern control design methods could be very efficient.

The task of the controller is to keep the exhaust limits inside the tunnel below desired limits, with low energy consumption. We have decided to neglect the fairly complicated tunnel dynamics, and to design a static controller.

First of all, we will find a static pollution level in one section M of a one-directional highway tunnel. The measured air flux Q can be split and we can write down the following equation:

$$p_M = \frac{k_M n_M s_M}{\sum_{i=1}^{M} a_i f_i + Q^*}, \tag{1}$$

where p_M is the desired pollution level, k_M is an average exhaust production of one vehicle per second, n_M is the number of vehicles inside the tunnel, s_M is the position of the pollution sensor, S_{area} is the tunnel cross-section area, a_i is a fan contribution coefficient, f_i is the fan power and Q^* is the air flux not caused by the fans.

In Eq. (1), we want to set some fan powers f_i according to some desired pollution level p_M. But we want to control the entire tunnel, i.e. all the sections together. As there can be large amounts of interdependencies between the inputs and outputs of the tunnel system, the easiest solution is to formulate the problem of control as an optimization problem. Given Q^* and k_i, n_i, s_i there corresponds to each p a unique sum of air flux values, that is, a mapping P exists such that $\sum a_i f_i = P(p_i)$. So requiring p_i to be in some interval $[0, p_{i,\max}]$ translates into requiring $\sum a_i f_i$ to be in some appropriate interval $[Q_{\min}, Q_{\max}]$. The latter involves our control variables f_i and hence the following linear program, which aims to achieve $p_i \in [0, p_{i,\max}]$ with minimal power, is a possible solution to our problem:

$$\min_{f_i} \sum_i |f_i| : \quad f_i \in [0, 100], \quad \sum a_i f_i \in [Q_{\min}, Q_{\max}]. \tag{2}$$

Note that this is a standard linear program – one of the basic optimization problems – and it can be solved by any of the wide variety of available solvers. Its advantage is flexibility, as more constrains can be imposed. For example, we can achieve the portal protection from exhaust by introducing a further constrain in the form of $Q_{\text{portal}} < 0$.

Keywords: Highway tunnel; Ventilation control; Exhaust control; Optimization

doi:10.1016/j.tust.2005.12.031