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Model Predictive Fuzzy Control of Longitudinal Ventilation System in a Road Tunnel

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Professional paper

In this paper we describe a control method for longitudinal ventilation of road tunnels. The method consists of two main elements: a) prediction of a number of jet fans and b) fuzzy control of pollutant levels. Based on measurements of traffic intensity and weather conditions and by knowing tunnel parameters, production of CO, NOx and small particles (soot) is predicted. Estimated values of pollutants are then used for calculation of fresh air volume demand, i.e. required air flow is determined. One dimensional force equation is used for estimation of a number of jet fans that would produce a thrust force sufficient to provide calculated air flow. In the same time a fuzzy controller compares measured and requested levels of pollutants and adjusts a predicted number of jet fans in order to keep the pollutant levels within predefined boundaries. The proposed method is tested by simulation and obtained results are compared with a method which was previosly used in the ventilation system of the tunnel Ucka. Finally, the field results from the proposed control method implementation in the tunel Ucka are presented.

Key words: fuzzy control, predictive control, road tunnel ventilation

1 INTRODUCTION

Vehicles passing through a tunnel produce various types of poison gasses as well as soot, especially in the case of heavy vehicles with diesel engines [1]. With new legislations and demands from tunnel users who are concerned for their health and safety, more and more sophisticated equipment needs to be installed in the tunnel: video cameras, refined traffic-sensing devices, more reliable fire detection system and high-sensitive pollution sensors [2]. High standards for air quality and the need for good visibility require a advanced ventilation system for management and control of pollution. Two objectives, opposite in nature, have to be fulfilled simultaneously by the ventilation system: a) the system should keep visibility (opacity, OP) on a required level and make certain that pollutants remain within admissible margins and b) energy (costs) used for objective a) should be minimal. Under some circumstances it is difficult to meet both objectives concurrently by using simple control algorithms, hence, recently the procedures that combine artificial intelligence and predictive control are implemented for system supervision [3, 4, 5]. Usually, together with these new algorithms, longitudinal ventilation is used, mostly due to its acceptable cost.

In this paper we introduce a control scheme that relies on the fuzzy logic and includes feedforward loop based on traffic and weather data. The developed concept is intended to replace the one currently used in tunnel Ucka, Croatia. First we describe the principle of a model predictive fuzzy controller, followed by a detailed explanation of tunnel air-flow prediction and estimation of a required number of jet fans. Then, the structure of fuzzy algorithm is described. At the end we present and comment simulation and field results obtained with the new concept and compared with the currently running control system.

2 THE STRUCTURE OF A MODEL PREDICTIVE FUZZY CONTROLLER

The structure of a model predictive fuzzy controller is shown in the Figure 1. As can be seen, the structure consists of predictive, fuzzy and jet-fans controllers, pollutants measurement and a reference generation module.

Since the tunnel ventilation system simultaneously takes care of three different pollutants (CO, NOx and soot), the *reference generation* module determines an actual set point of the control system. The pollutant which differs the most from its required level, overtakes the set point. The operator is allowed to override the automatic generation of the system set point.

The task of the *predictive controller* is to determine required air flow which depends on a traffic type, traffic intensity and weather conditions. Based on that prediction, an estimation of a number of jet fans, $\hat{n}_{F\_est}$, which would produce a thrust force

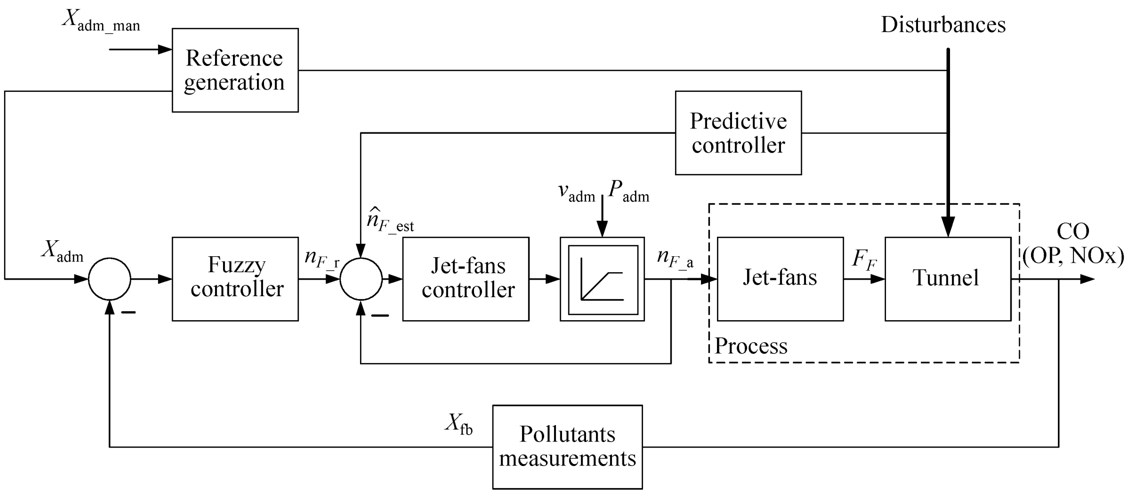

Fig. 1 A structure of the model predictive fuzzy controller

sufficient to provide calculated air flow, is carried out. Since the tunnel model, which is the part of the predictive controller, describes a real tunnel only to some extent, the *fuzzy controller* compares the required level of pollutant, X_{adm}, with the measured value, X_{fb}, and adjusts the jet-fans prediction in order to keep the pollution close to the predefined level. The fuzzy controller output, n_{F_r}, and predictive controller output, $\hat{n}_{F\_\text{est}}$, are fed into the *jet-fans controller*. Their sum is compared with current a number of active jet-fans, n_{F_a}. In case

$$n_{F\_\text{r}} + \hat{n}_{F\_\text{est}} > n_{F\_\text{a}},$$

the controller sends a request for a jet-fan switch--on; in case

$$n_{F\_\text{r}} + \hat{n}_{F\_\text{est}} < n_{F\_\text{a}}$$

the controller sends a request for a jet-fan switch--off. As the energy consumption of the ventilation system is significant, care must be taken when switch-on requests are sent to jet-fans. In addition, air velocity within the tunnel should not rise above an adequate level. These two restrictions, consumed energy and an air velocity, limit a number of currently active jet fans.

2.1 Air flow prediction

The first step in air flow prediction is calculation of amounts of CO, NOx and small, visibility-reducing particles produced by traffic. These amounts depend on several parameters such as the speed and the type of vehicles, a tunnel length, a tunnel altitude, etc. A total CO produced by vehicles in the tunnel can be calculated as:

$$Q_{\text{CO\_est}} = q_{\text{CO}} \cdot N \cdot L \cdot k_{\text{aCO}} \cdot k_{\text{gCO}} \cdot k_{\text{sCO}} \, \frac{p_0}{p} \cdot \frac{T}{T_0}. \quad (1)$$

where: q_{CO} – CO produced by a vehicle, m^3/veh/km, N – number of vehicles per hour, veh/h, L – tunnel length, km, k_{aCO}, k_{gCO}, k_{sCO} – correction factors for altitude, gradient and speed, respectively, p_0 – normal pressure (1013 hPa), p – atmospheric pressure, hPa, T_0 – normal temperature (273 K), T – atmospheric temperature, K.

Productions of other two pollutants, NOx and small particles, are determined by following relations:

$$Q_{\text{NOx\_est}} = q_{\text{NOx}} \cdot (N_{\text{L}} + 10 \cdot N_{\text{H}}) \cdot L \cdot k_{\text{gNOx}}, \quad (2)$$

$$M_{\text{P\_est}} = m_p \cdot (N_{\text{H}} + 0.08 \cdot N_L) \cdot L \cdot k_{\text{ap}} \cdot k_{\text{gp}} \quad (3)$$

where: q_{NOx} – NOx produced by a vehicle, m^3/veh/km, N_{L} – number of light vehicles per hour, veh/h, N_{H} – number of heavy vehicles per hour, veh/h, k_{gNOx} – correction factor for gradient, m_p – mass of particles produced by a heavy vehicle, mg/veh/km, k_{ap}, k_{gp} – correction factors for altitude and gradient, respectively.

Once pollutants productions are known, the predictive controller determines a required air velocity as:

$$v_{\text{a\_est}} = \frac{Q_{\text{a\_est}}}{A_T}, \quad (4)$$

where A_{T} is the tunnel cross section in square meters. The fresh air flow, $Q_{\text{a\_est}}$, is calculated as

$$Q_{\text{a\_est}} = \max\left(\frac{M_{p\_\text{est}}}{M_{p\_\text{adm}}}, \frac{Q_{\text{CO\_est}} \cdot 10^6}{CO_{\text{adm}}}, \frac{Q_{\text{NOx\_est}} \cdot 10^6}{NOx_{\text{adm}}} \right),$$

with M_{p_adm} as admissible concentration of small particles, mg/m^3, CO_{adm} as admissible concentration of carbon monoxide, ppm, and NOx_{adm} as admissible concentration of nitrogenous gases, ppm.

2.2 Prediction of a number of jet fans

In order to predict a number of jet fans required to provide a pressure rise which would establish an estimated air velocity, all forces that impact air mass within the tunnel should be taken into account. The *piston effect force*, F_{pist}, caused by a vehicle drag, has the largest influence on the air flow. Although not so significant, forces caused by a *tunnel wall friction*, F_{f}, *portal pressure difference*, F_{p}, and *inlet portal losses*, F_{in}, must be integrated into the calculation for an accurate estimation of *jet fans force*, F_{jet}. When these forces are in balance, i.e. the sum of all five forces is zero, the air mass within the tunnel has a constant velocity.

The piston effect force for heavy and light vehicles can be calculated as

$$F_{\mathrm{pist\_H}} = N_{\mathrm{H}} \cdot C_{\mathrm{dH}} \cdot A_{\mathrm{H}} \cdot \frac{\rho_{\mathrm{a}}}{2} \cdot \left| v_{\mathrm{H}} - v_{\mathrm{a\_est}} \right| \cdot (v_{\mathrm{H}} - v_{\mathrm{a\_est}})$$
$$F_{\mathrm{pist\_L}} = N_{\mathrm{L}} \cdot C_{\mathrm{dL}} \cdot A_{\mathrm{L}} \cdot \frac{\rho_{\mathrm{a}}}{2} \cdot \left| v_{\mathrm{L}} - v_{\mathrm{a\_est}} \right| \cdot (v_{\mathrm{L}} - v_{\mathrm{a\_est}}) \tag{5}$$

where: C_{dH} – heavy vehicle drag coefficient, A_{H} – heavy vehicle frontal area, m^2, v_{H} – heavy vehicle velocity, km/h, C_{dL} – light vehicle drag coefficient, A_{L} – light vehicle frontal area, m^2, v_{L} – light vehicle velocity, km/h, ρ_{a} – air density, kg/m^3.

The force caused by a static pressure difference on the tunnel portals is equal to

$$F_p = A_T \cdot (p_{\mathrm{in}} - p_{\mathrm{out}}) \tag{6}$$

where p_{in} and p_{out} are the inlet portal and outlet portal pressures.

The wall friction force which is obtained from the following equation

$$F_{\mathrm{wf}} = -k_{\mathrm{wf}} \cdot A_T \cdot \frac{\rho_{\mathrm{a}}}{2} \cdot \frac{L}{D} \cdot v_{\mathrm{a\_est}}^2 \tag{7}$$

is always opposed to the direction of tunnel air flow, as well as it is the force caused by flow separation at the inlet portal

$$F_{\mathrm{in}} = -k_{\mathrm{in}} \cdot A_T \cdot \frac{\rho_{\mathrm{a}}}{2} \cdot v_{\mathrm{a\_est}}^2 \tag{8}$$

where: k_{wf} – wall friction coefficient, D – tunnel hydraulic diameter, m^2, k_{in} – inlet loss coefficient. As we stated earlier, the goal of the predictive controller is determination of a number of jet fans which establishes the tunnel air velocity equal to $v_{\mathrm{a\_est}}$. Having calculated all forces that induce movement of the air within the tunnel, predictive controller estimates the number of jet fans as

$$n_{F\_\mathrm{est}} = \frac{\Sigma F}{k_F \cdot A_F \cdot \rho_{\mathrm{a}} \cdot \left| v_F \right| \cdot (v_F - v_{\mathrm{a\_est}})} \tag{9}$$

where: k_F – pressure-rise coefficient of a jet fan, A_F – discharging area of a jet fan, m^2, v_F – discharging speed of a jet fan, m/s, and

$$\Sigma F = F_{\mathrm{pist\_H}} + F_{\mathrm{pist\_L}} + F_{\mathrm{p}} + F_{\mathrm{wf}} + F_{\mathrm{in}}.$$

Due to the difficulties with determination of tunnel parameters k_{wf} and k_{in} and due to the dynamic change of drag coefficients C_{dH} and C_{dL} with respect to the number and the type of vehicles, one-dimensional force equation describes the tunnel air mass motion with a limited accuracy. An improvement can be achieved by using heuristically obtained look-up tables for a drag coefficients determination. For a precise estimation of tunnel parameters a set of on-site experiments and simulations should be conducted [6, 7].

The other way to overcome the problem of inaccurate estimation is the usage of a *forgetting factor*, K_{JF}, in the form of a simple filter

$$\hat{n}_{F\_\mathrm{est}}(k) = K_{\mathrm{JF}} \cdot \hat{n}_{F\_\mathrm{est}}(k-1) + (1 - K_{\mathrm{JF}}) \cdot n_{F\_\mathrm{est}}(k). \tag{10}$$

In case that parameters and coefficients present in estimation equations are accurate, forgetting factor K_{JF} should be set close to 0. On the other hand, if exact values are not known, K_{JF} should be just about 1. In that way, influence of the predictive controller on the final number of active jet fans can be controlled by only one parameter, K_{JF}.

2.3 Fuzzy controller

Prior to the description of the fuzzy controller we briefly exemplify details of the pollution control system currently used in the tunnel Ucka. The tunnel, 5 028 meters long, is bidirectional with one lane in each direction (Istra<=>Kvarner). There are 24 fan groups installed for each direction (three jet fans form a fan group). The nominal jet fan power is 80 kW with output air velocity of 30 m/s. The control algorithm of the old ventilation system is based only on pollutants measurements. Although distant stations for weather observation and loops for measurement of traffic parameters exist, data collected by this equipment is not considered by the control algorithm (they are used only for monitoring and statistics). The switching of fan groups is led by pollutant thresholds and predefined states.

Since the number of thresholds and states, as well as control actions, is determined heuristically, the quality of ventilation depends on the operator's experience. At the beginning of a shift, the operator loads his/her procedure into the tables depending on the traffic parameters and weather conditions. According to given Tables 1 and 2, the control algorithm works as follows: thresholds for carbon monoxide are defined as $\mathrm{Tr}_1 = 7$ ppm, $\mathrm{Tr}_2 = 8$ ppm, $\mathrm{Tr}_3 = 9$ ppm, $\mathrm{Tr}_4 = 10$ ppm and $\mathrm{Tr}_5 = 12$ ppm. Then, CO is in state St_0 if its measured value is less than Tr_1, i.e. CO < 7 ppm. If $\mathrm{Tr}_1 < \mathrm{CO} < \mathrm{Tr}_2$ then carbon monoxide is in the state St_1, and so on. From Table 1 we read that while CO is in state St_1 the control algorithm switches off 2 fan groups every 15 minutes. If CO is in state St_3 the control algorithm switches on 1 fan group every 10 minutes. Table 2 contains actions when states change. For example, transition from St_1 to St_2, i.e. positive transition Tr_2, activates 2 fan groups, whereas changeover from St_2 to St_1 (negative transition) does not influence jet fans. On the other hand, threshold Tr_5 activates the action only in the case of a negative transition (switches off 1 fan group).

Table 1 **Actions triggered on states**

state	St_0	St_1	St_2	St_3	St_4	St_5
# fan groups	all	2	2	1	1	1
action	off	off	off	on	off	on
T/min	0	15	15	10	30	5

Table 2 **Actions triggered on tresholds**

treshold	Tr_1	Tr_2	Tr_3	Tr_4	Tr_5
# fan groups	all	2	2	2	1
action	off	on	off	on	off

Such a presentation of a control algorithm is very difficult to comprehend. The number of parameters (thresholds, states, actions, ...) is large and it is very difficult to correlate their values with required control quality and system dynamics. Tabular approach cannot cope with a rapid change of traffic and/or weather conditions as adaptation to new circumstances is done manually by the operator (assuming that the operator recognizes a new situation and has prepared a control table for it). Since the algorithm considers only direction of change (increase or decrease of CO) without taking into account the amount of change, the time response of ventilation system is rather slow and energy consuming. Furthermore, the assenting influence of natural ventilation is not incorporated into the algorithm, thus the number of active jet fans, in case of a high level of CO and favorable pressure difference and traffic, is kept high for a much longer period than necessary. The first step in the improvement of current control algorithm is in its extension with the predictive controller, whereas the second step is the substitution and enhancement of thresholds and states tables by the fuzzy controller.

In order to take into account the dynamics of CO transition, the fuzzy controller has two inputs, pollutant deviation from a set point, e_{CO}, and deviation rate of change, Δe_{CO}. One output, Δn_{F_r}, in the form of five singleton fuzzy sets is defined. Since the tunnel ventilation process has the astatic character, the final output is formed as

$$n_{F\_\mathrm{r}}(k) = n_{F\_\mathrm{r}}(k-1) + \Delta n_{F\_\mathrm{r}}(k). \tag{11}$$

Each input has 5 fuzzy sets (NL, NS, Z, PS, PL) defined over its universe of discourse, as shown in Figure 2.

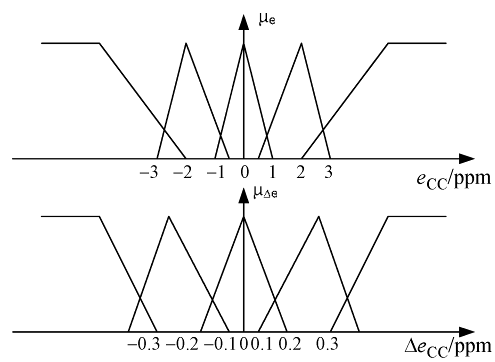

Fig. 2 Membership functions of the fuzzy controller inputs

The controller rules are shown in Table 3.

Table 3 **Fuzzy controller rules**

	NLE	NSE	ZE	PSE	PLE
NLDE	3	3	1	1	0
NSDE	3	1	1	0	−1
ZDE	1	1	0	−1	−1
PSDE	1	0	−1	−1	−3
PLDE	0	−1	−1	−3	−3

The fuzzy control algorithm, which uses *min* operator for implication and center of gravity principle (COG) for output calculation, is executed every 30 s.

3. SIMULATION RESULTS

The tunnel Ucka ventilation system, controlled by the model predictive fuzzy controller, has been simulated and the results are compared with those obtained with the tabular controller.

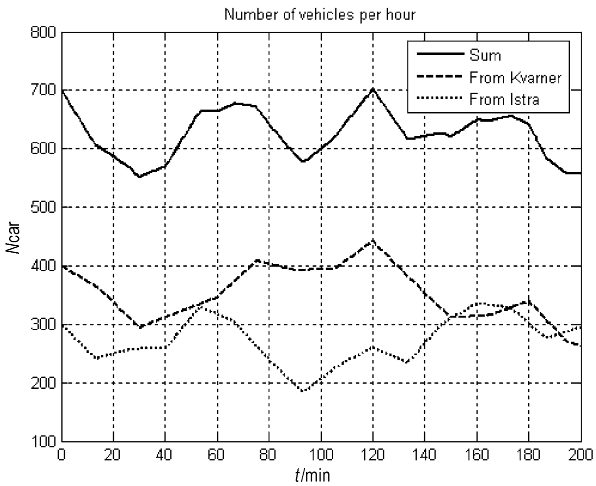

Fig. 3 The traffic intensity in the tunnel during simulation

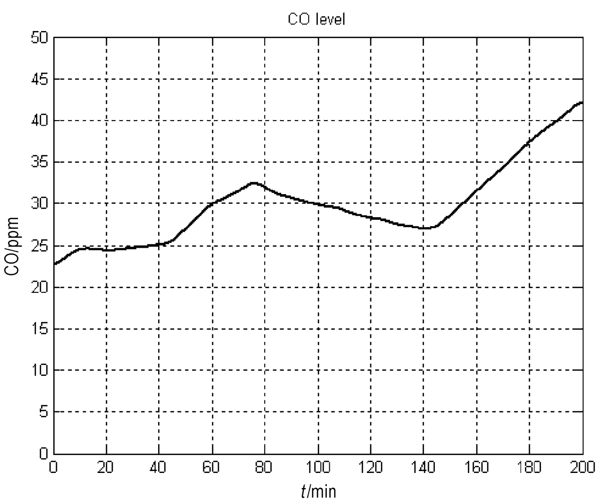

Fig. 4 The CO level in the case of a natural ventilation

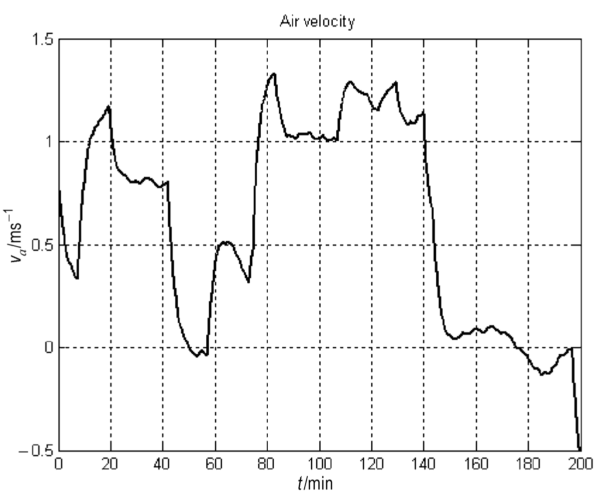

Fig. 5 The air velocity in the case of a natural ventilation

Figure 3 shows the number of vehicles in the tunnel in both directions. The traffic intensity is changing randomly with an average value around 300 veh/h and slightly higher concentration from the Kvarner portal.

Figures 4 and 5 show the CO concentration and air velocity, respectively, in case the control system is not active, i.e. CO is diluted only by natural ventilation.

The results obtained with the longitudinal ventilation system controlled by the tabular controller are shown in Figures 6–8, while Figures 9–11 present the results in the case of the model predictive fuzzy control of the tunnel ventilation.

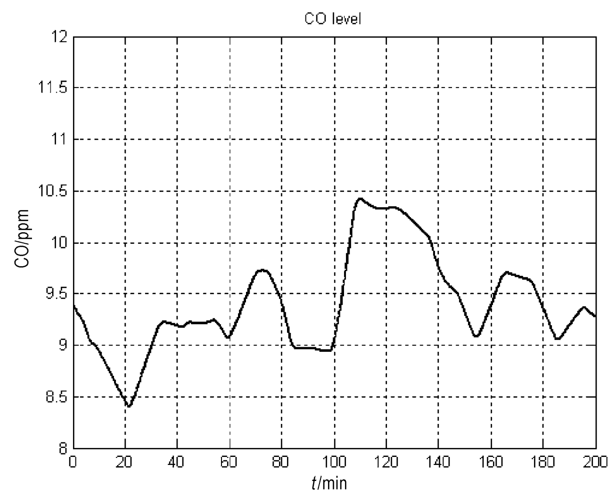

Fig. 6 The CO level in the case of using the tabular controller

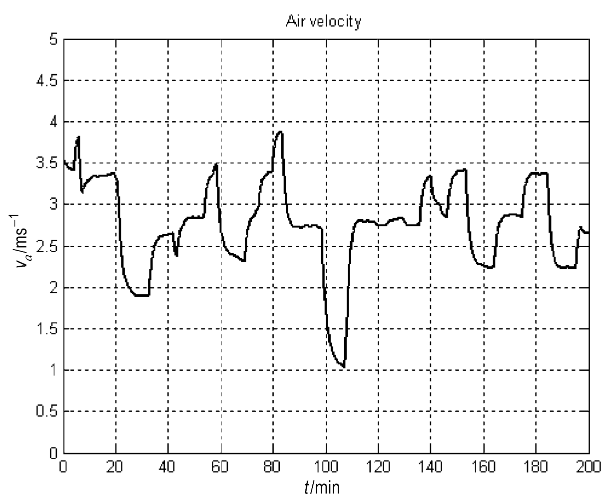

Fig. 7 The air velocity in the case of the tabular controller

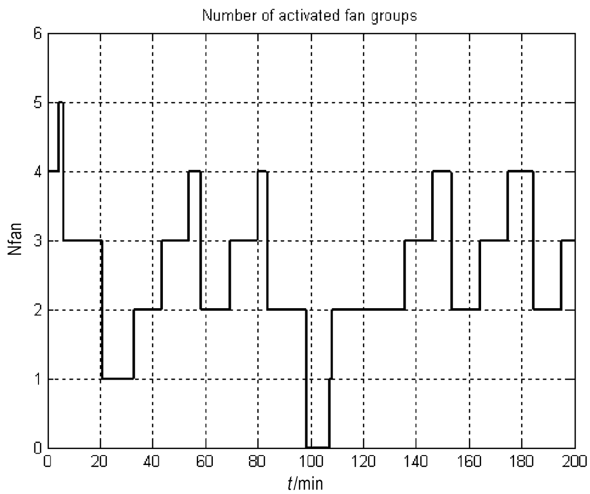

Fig. 8 The number of active fan groups in the case of using the tabular controller

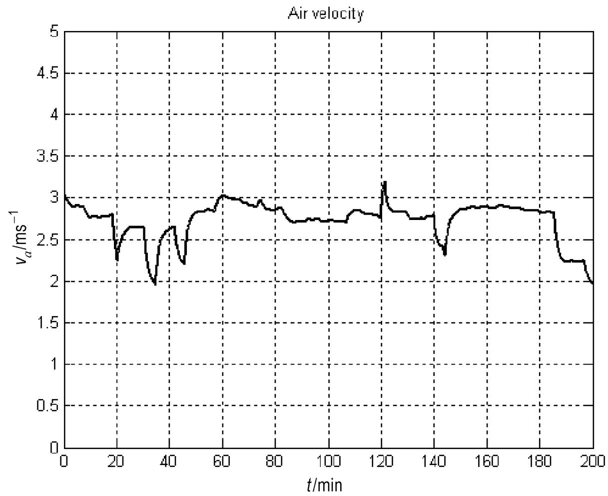

Fig. 10 The air velocity in the case of using the model predictive fuzzy controller

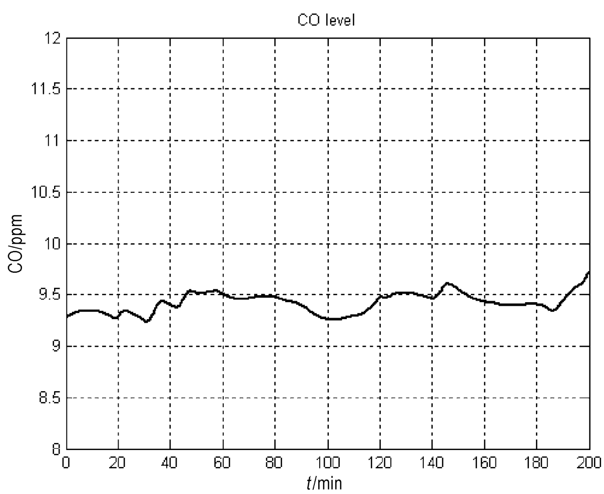

Fig. 9 The CO level in the case of using the model predictive fuzzy controller

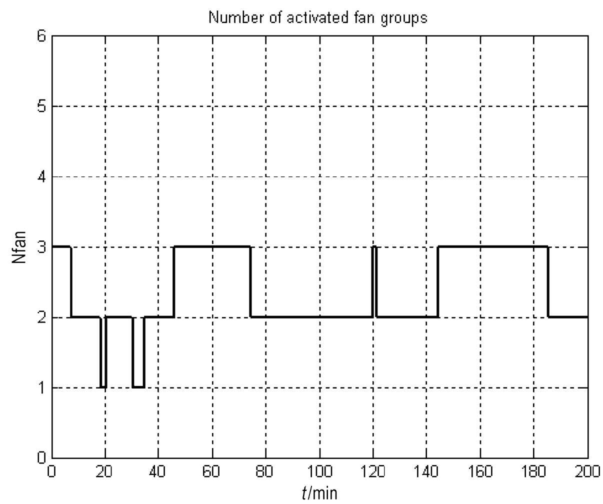

Fig. 11 The number of active fan groups in the case of using the model predictive fuzzy controller

It can be seen that in both cases the CO concentration is considerably reduced. The value of CO with inactive ventilation system soars over 40 ppm, whereas tabular and model predictive fuzzy controllers keep that value around 9–10 ppm. The average CO concentration is 9.4 ppm for both controllers, but differences in CO level dynamics are noticeable (Figures 6 and 9). The model predictive fuzzy controller reacts instantly to any changes in traffic or weather conditions, before these changes significantly effect the CO concentration. The installed power of each fan group is 80 kW. During 200 minutes, which was the period of simulation, jet fans, in the case of the tabular controller, have consumed 645 kWh. In the same time, energy used by the fan groups controlled with the model predictive fuzzy controller, was 615 kWh, which is around 5 % less than in the first case. When comparing dynamics of activated jet fans (Figures 8 and 11) one can see that jet fans are switched on and off twice more often in the case of the tabular controller, significantly increasing the stress on the supply power grid, because the fan current drain peaks when it is being switched on.

4 FIELD RESULTS

The new control scheme has been implemented on industrial PC that is installed in tunnel Ucka control center. Preliminary field results are presented herein. Average concentration of CO in manual control mode during daylight is depicted in Figure 12.

In time T0 all jet fans have been switched off. As it was expected CO concentration started to increase. Then in T39 (39 min) 4 jet fan groups have been switched on, and after 24 minutes operator started additional 4 jet fan groups (T63). From Figure 12 it can be seen that CO concentration has gradually decreased in the next 20 minutes. Figure 13 shows the tunnel air velocity during the daylight experiment. Significant decrease in the air velocity can be noticed in case all jet fans are switched off.

The similar experiment has been conducted during the night, when traffic intensity is very low. Obtained results are shown in Figures 14 and 15. One phenomenon comprised in the mathematical model can be clearly seen, that is, nonlinear correlation between the air velocity and the number of active jet fans. Influence that one jet fan group has on the air velocity decreases with the number of active jet fans. Also, it is evident that CO concentration cannot be reduced below certain value (1.5 ppm). Actually, increase of the air velocity in that case produce counter effect, since dust is raised from the pavement. The propagation of CO through the tunnel is shown in Figure 16 (five CO sensors, evenly distributed).

The tunnel parameters have been determined from the experimental results and included in the model.

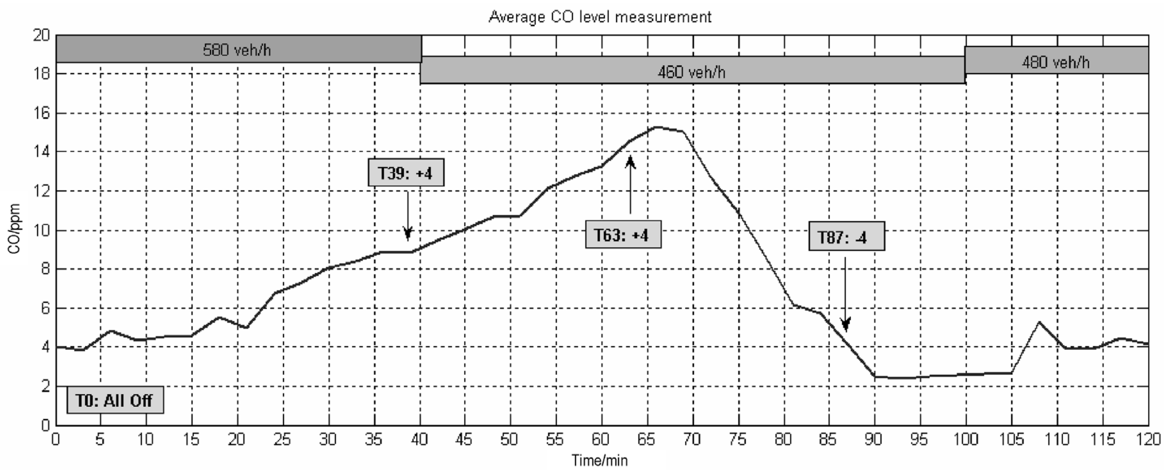

Fig. 12 The CO level in manual control mode (field results-daylight)

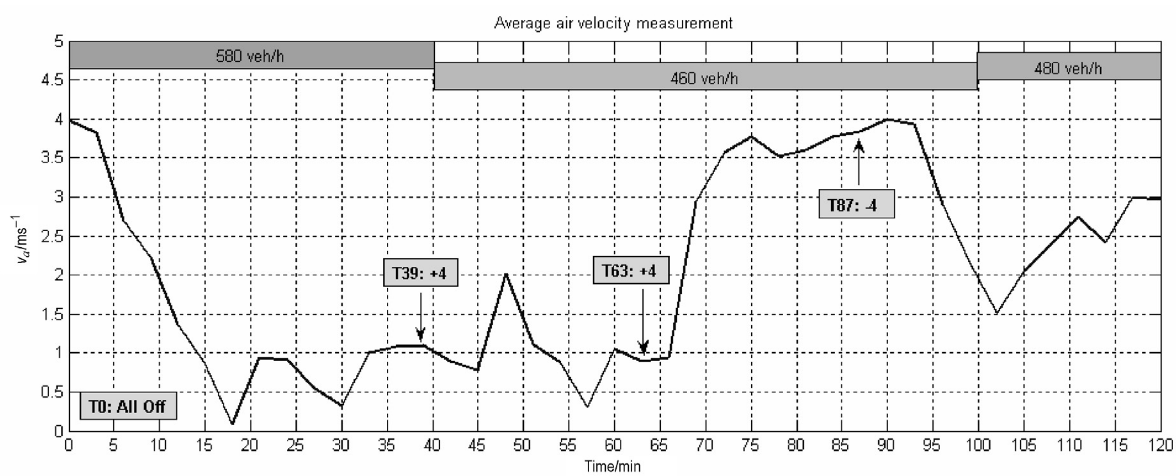

Fig. 13 The air velocity in manual control mode (field results-daylight)

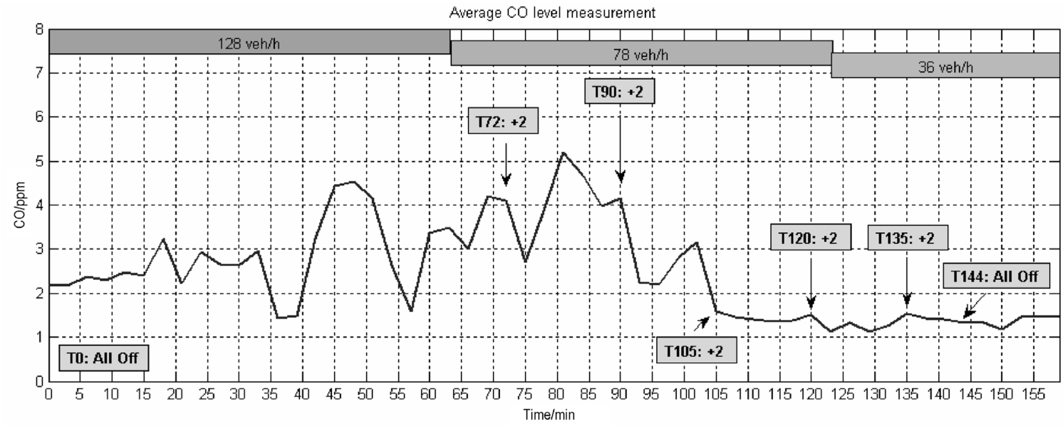

Fig. 14 The CO level in manual control mode (field results-night)

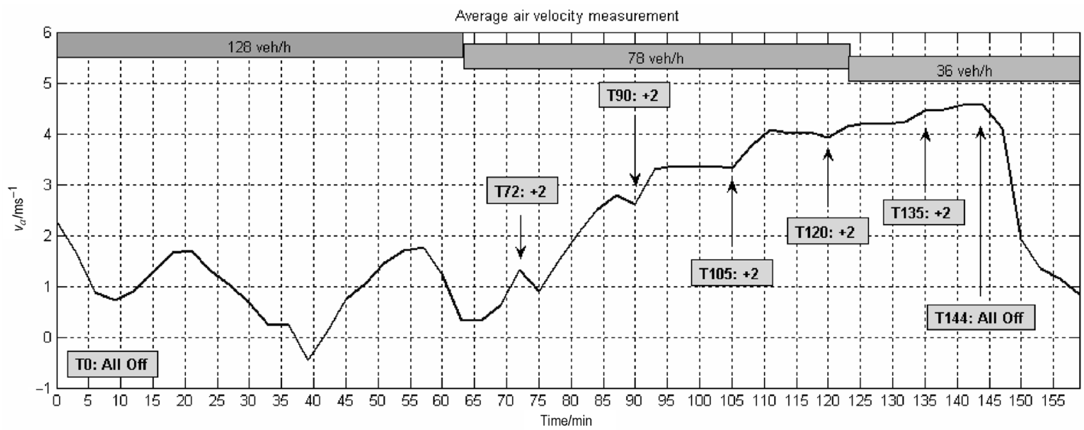

Fig. 15 The air velocity in manual control mode (field results-night)

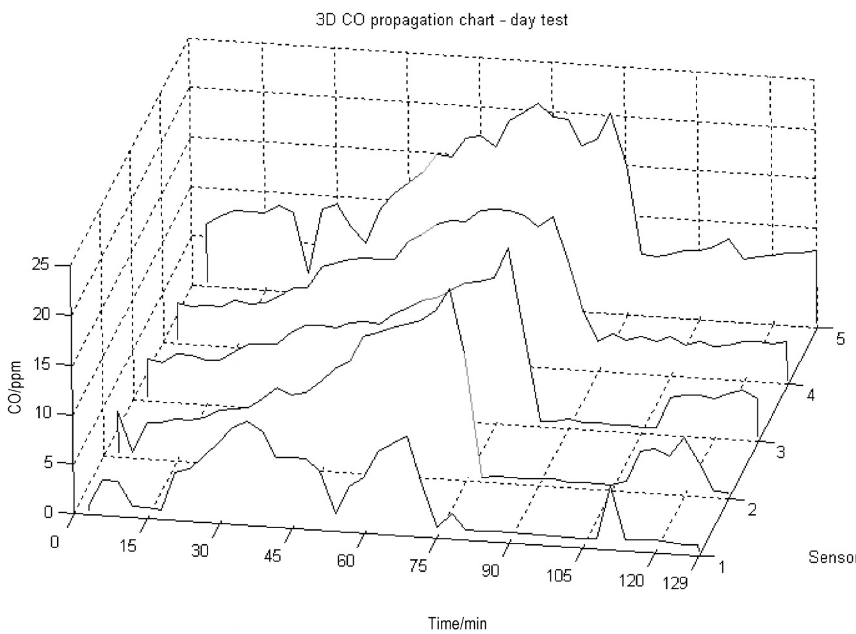

Fig. 16 Propagation of CO through the tunnel (field results-daylight)

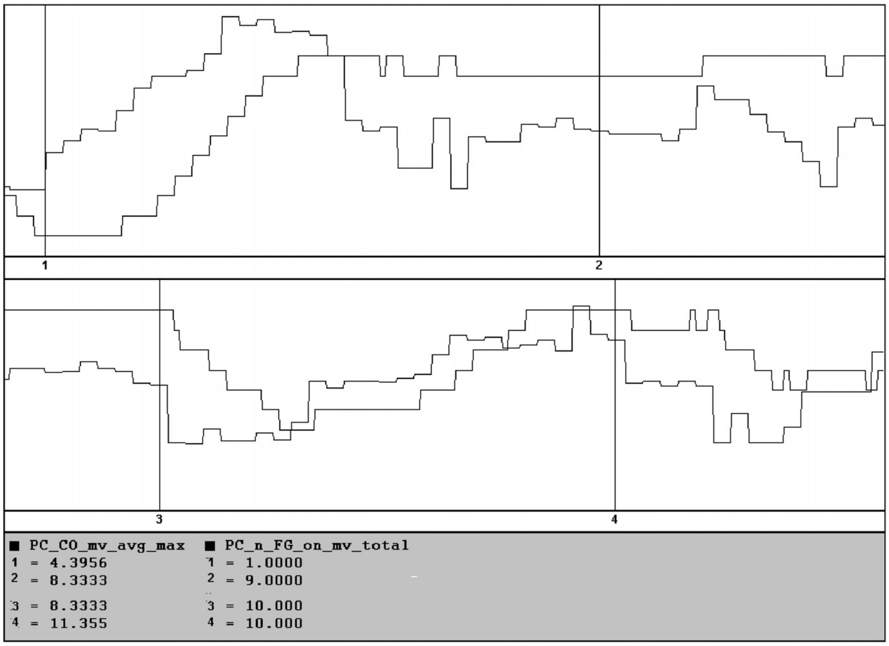

Fig. 17 CO level (black) vs. number of active fan groups (gray) – field results

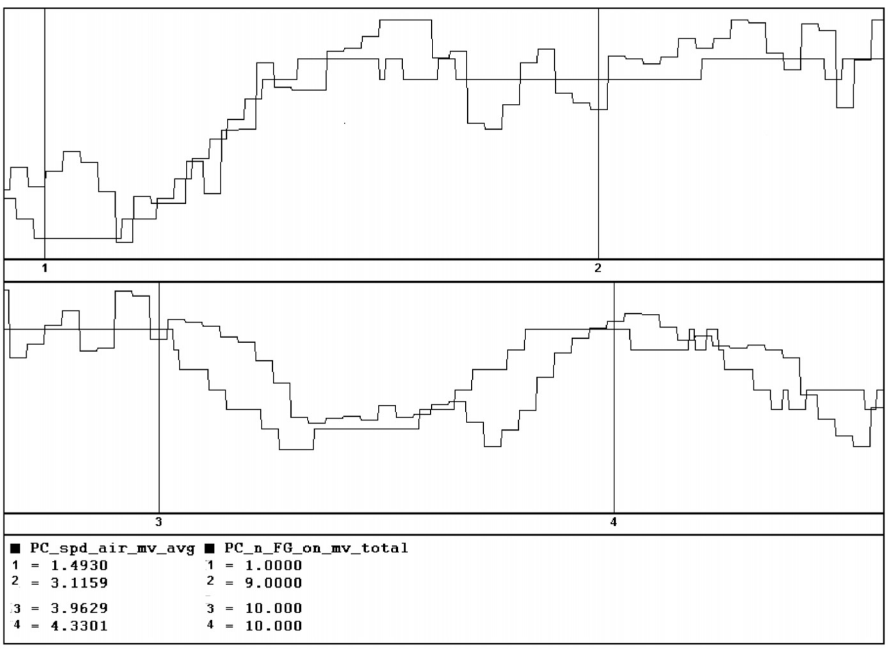

Fig. 18 Tunnel air velocity (black) vs. number of active fan groups (gray) – field results

Figures 17 and 18 present field results from tunnel Ucka obtained with the model predictive fuzzy control of the ventilation system. Figure 17 shows CO level measurement along with the number of active fan groups. It may be seen that the ventilation control system responds quickly to changes in CO level due to varying traffic conditions and keeps the CO concentration at around 8.5 ppm with 9 active fan groups, in average. The close link between tunnel air speed velocity and the number of active fan groups may be clearly seen at figure 18. Average air speed during the experiment was around 3.5 m/s.

5 CONCLUSIONS

A model predictive fuzzy control algorithm for a longitudinal ventilation system in a road tunnel is described. Based on traffic and weather data, predictive controller estimates fresh air requirements and calculates the number of jet fans needed to generate a thrust force sufficient to provide calculated air flow. Due to difficulties with determination of exact values of the tunnel and vehicles parameters, prediction of pollution and estimation of required air flow are uncertain, hence, fuzzy controller is integrated into the system in order to provide steady state accuracy.

The proposed scheme is tested by simulation and results show that time response of the ventilation is much faster compared with the system controlled by conventional controller. In the same time energy consumption is reduced around 5 % for simulated situation.

The field result obtained upon implementation of the proposed control method in a real road tunnel verify the simulated behaviour and expected ventilation system performance.

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Upravljanje sustavom longitudinalne ventilacije cestovnog tunela zasnovano na neizrazitoj logici s prediktivnim modelom. U ovom članku opisana je metoda upravljanja sustavom longitudinalne ventilacije cestovnih tunela. Metoda se sastoji od dvije glavne cjeline: a) predikcije potrebnog broja aktivnih ventilatora; i b) neizrazitog upravljanja razinom zagađenja zraka u tunelu. Na osnovi mjerenja vremenskih uvjeta i intenziteta prometa kroz tunel, te poznatih parametara tunela, obavlja se predikcija proizvodnje ugljičnog monoksida, dušikovih oksida i krutih čestica iz ispuha vozila. Te procijenjene količine zagađenja se u nastavku koriste za proračun zahtjeva za svježim zrakom, tj. potrebne brzine strujanja zraka kroz tunel. Broj ventilatora s ukupnim potiskom dovoljnim da se postigne to strujanje određuje se iz ravnoteže sila koje djeluju na zračnu masu u tunelu. Istodobno, neizraziti regulator uspoređuje mjerene i zadane vrijednosti zagađenja, te podešava proračunati broj ventilatora kako bi održao stupanj onečišćenja zraka unutar dopuštenih granica. Predložena metoda upravljanja ispitana je simulacijom uz usporedbu s metodom upravljanja koja je dosad korištena u tunelu Učka, a potom su dani rezultati stvarne implementacije predstavljene metode upravljanja na tunelu Učka.

Ključne riječi: neizrazito upravljanje, prediktivno upravljanje, ventilacija tunela

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