Longitudinal Ventilation Control System in Road Tunnels

Jasna Horvat, Nedjeljko Peric, Member, *IEEE*, Ivan Petrovic, Member, *IEEE,* Renata Jelušić

Abstract—In this paper types of ventilation of road tunnels are described. Using fundamental fluid mechanics airflow in the tunnel is analysed. Mathematical graphical tool Grafcet is presented and used to describe ventilation control algorithm. Proposed algorithm is rather simple but easy to use. It has been verified in Ucka Tunnel (Croatia) and brief analysis of one day of normal regime operation is given.
Index Terms-- Road Tunnel Ventilation System, Grafcet, Ventilation Control in Road Tunnels

I. Introduction

Technical problems that appear during design and building of a tunnel are not exclusively in construction field but also relate to the limiting factors of tunnel exploitation. Safe use of road tunnels implies both air quality management and fire control.

Crucial factors [1,2], when deciding about the ventilation system, are the economic performance and the safety analysis for normal operation and the operation in case of fire in the tunnel. Taking into account traffic direction (unidirectional, bi-directional, maximum traffic volume, etc.), tunnel situation (length, ascent, cross-section, escape routs, etc.), environmental laws and fire safety considerations, an assessment can be performed and the ventilation system can be chosen.

The simplest is "naturally ventilated" tunnel, defined as a tunnel that is not equipped with fans for the mechanical control of airflow in the traffic zone. Some kind of natural ventilation exists in any tunnel. In fact a mix of factors such as atmospheric and traffic conditions always induce an airflow. Natural ventilation of a tunnel is, in some cases, satisfactory even for quite long tunnels (up to 2000 m for unidirectional traffic), but it is not possible to solve the problem of smoke control in the case of fire in the tunnel and thus this kind of ventilation is usually used only for tunnels up to 500 m.

Mechanical ventilation is used in all cases where natural ventilation does not satisfy, such as in long tunnels, tunnels with higher traffic volume etc. It implies usage of fans that provide sufficient amount of fresh air. Basically, each ventilation system is designed to provide acceptable air quality under normal regime at all traffic situations. In the case of fire it must ensure safety for the tunnel users as well as facilitate fire-fighting and emergency operations.
There are three basic types of mechanical ventilation: longitudinal, transverse and semi-transverse system. It is also possible to combine mechanical ventilation with air cleaning, which is rather new technology and is only starting to be used.

Basic characteristic of longitudinal ventilation is that it creates a uniform longitudinal flow of air all along the tunnel. The fans are mounted on the ceiling of the tunnel, above the traffic area. In such systems, the clean air enters the tunnel from one portal and gets gradually polluted with substances emitted by vehicles, thus reaching the tunnel exit with a higher concentration of pollution. Airflow velocity is constant through the tunnel, while the concentration of toxic substances increases in the direction of the airflow linearly. The main advantage of this type of ventilation is that the costs both for installing and for maintaining are relatively low. It is particularly suitable for tunnels carrying one-way traffic, where the piston effect assists the airflow. In the case of fire inside the tunnel the only feasible way to evacuate smoke is by pushing it through the tunnel to the portal. This inevitably results in appearance of smoke in the traffic area, at least on one side of the fire and is the most important drawback of longitudinal tunnel ventilation systems.

In mechanical ventilation systems other than longitudinal, the fresh air is supplied and/or extracted through purpose built ducts along the tunnel.

In tunnels with transverse ventilation system there are two ducts and air flows from one of the ducts through slots or ports into the traffic section while polluted air is withdrawn through the other duct. The ducts may be above or below the roadway but usually fresh air is input near the roadway and the vitiated air is exhausted along the tunnel ceiling. In ideal case there is no longitudinal airflow. In the case of fire in the tunnel smoke is exhausted through the ducts from the site of fire and thus localised. The transverse system is the most expensive method of tunnel ventilation in both

J. Horvat and R. Jelusic are with Koncar – Power Plant and Electric Traction Engineering Inc.
N. Peric and I. Petrovic are with The Department of Control and Computer Engineering in Automation, Faculty of Electric Engineering and Computing, Univ. of Zagreb, Unska 3, Zagreb, Croatia

construction and operating cost. It is normally used only in long tunnels for which no other system is adequate.

In semi-transverse ventilation system, fresh air is added equally along the tunnel through out of an air supply duct, but there is no air extraction. The fresh air is supplied transversely while the polluted air flows longitudinally to the two ports. In the case of fire smoke can be extracted through the duct out of the tunnel. The main disadvantage of such ventilation system is that it is not possible to control the longitudinal airflow.
In this paper the basic aerodynamic assumptions required for the analysis of road tunnels airflow are given. Thereafter mathematical graphical tool Grafcet used for describing discrete-event systems is explained. The longitudinal ventilation automation algorithm presented in this paper is defined according to the data that corresponds to the Ucka Tunnel (Croatia) and is described by using Grafcet.

II. AERODYNAMIC ANALYSIS OF AIRFLOW IN ROAD TUNNELS

The unifying basis for analysis of the tunnel environment air quality is the fluid mechanics of the airflow in tunnel interior and through any ventilation system. Air is a good Newtonian fluid and can be well represented as an Ideal Gas for road tunnel interior and exterior conditions. For practical purposes, road tunnel transient compressible effects are negligible just as increase in the total tunnel air mass due to vehicle combustion. Airflow in road tunnel is essentially one-dimensional axial flow due to the nature of the tunnel geometry. The road tunnel is essentially a large constant cross section duct with vehicles. The axial airflow is highly turbulent due both to a large Reynolds number and to the turbulence promoting effects of the vehicles and ventilation flows. This results in relatively uniform axial velocity distribution over the tunnel cross section. For the practical analysis of road tunnel mechanics it is required also to assume quasi-steady state conditions. Although local air speeds can fluctuate rapidly with time, the longer term velocity means are rather stable and respond slowly to changes in the driving forces such as traffic rates, mechanical ventilation rates and exterior wind forces.

The basic equations [3] describing airflow in road tunnels are the conservation equations for mass, momentum and energy. In accordance with the given assumptions, the flow can be described as incompressible, one-dimensional and steady state.

A. The Tunnel Continuity Equation

The conservation of mass for tunnel air is illustrated in Equation 1 and expressed by the continuity equation:

$$\frac{d\overline{v}}{dx} = \frac{q_i - q_e}{A} = Q_i - Q_e \,. \qquad (1)$$

This equation states that change of tunnel cross-section average axial velocity equals difference of volumetric rate per unit axial length and tunnel effective cross-sectional area for influx and efflux.

B. The Tunnel Force Balance

Steady state conservation of momentum for an inertial control volume requires that the net flow rate of momentum through the surfaces of the volume be equal to the sum of all forces acting on the volume

$$\overline{\rho} \cdot A \cdot \left(\overline{v}_L^2 - \overline{v}_0^2\right) = \int_0^L \left(\dot{M}_i - \dot{M}_e\right) \cdot dx + A \cdot \left(p_o - p_L\right) -$$
$$- g \cdot A \cdot \int_0^L \rho_x \cdot \sin\left(\Theta_R\right) \cdot dx + \int_0^L f_{Pist} \cdot dx + \int_0^L f_{JF} \cdot dx -$$
$$- \int_0^L f_{Frict} \cdot dx. \qquad (2)$$

Equation 2 illustrates integration of the principal forces and flows over the entire tunnel length and represents the conservation of momentum equation for the entire tunnel interior air volume. This equation expresses the balance of forces, which is required for dynamic equilibrium and which results in axial airflow through tunnel. All terms of equation have the units of force and the left-hand side expression is the axial force required over tunnel length to accelerate the tunnel air from entrance speed to exit speed.

First expression on right hand side represents axial component of the forces exerted upon the tunnel air by ventilation influx less forces required to remove the ventilation efflux from the tunnel volume. The flow of ventilation air through ports and openings in the tunnel interior can have significant effect on the longitudinal airflow that is highly dependent on the angle of ventilation port.

The second term is the net axial component of the external forces acting on the tunnel entrance and exit. It is simply the product of the tunnel cross sectional area and the difference between portal static pressures. There are five external effects which contribute to the difference in portal static pressure and they are portal entrance and exit losses, dynamic and static pressure conversions, the chimney effect, atmospheric pressure difference and the action of local winds at the portals.

The last four terms are the total axial forces over the tunnel length due to the acceleration of the gravity on the tunnel air mass, the piston effect of vehicles, the thrust of jet fans, and the effects of tunnel interior friction and flow losses.

The gravity force is the net axial component of the force due to the tunnel air mass and depends highly on the slope of the tunnel.

The piston effect force is the sum of the axial forces exerted by all vehicles in the tunnel on the tunnel air. Its influence depends on speed and blockage ratios of the vehicle in the tunnel and thus on percentage of heavy-duty vehicles in the tunnel. Furthermore this force is determined by number of vehicles in the tunnel and weather traffic is unidirectional or bi-directional.

In order to determine the effective force exerted on the tunnel air by fans, the type of fan and its power should be considered as well as its position in cross-section of the tunnel, number of fans and longitudinal distance between them.

Tunnel interior friction and flow losses force always acts opposite to the local airflow direction. Internal flow losses are principally viscous friction due to the tunnel interior surfaces and dynamic head losses due to obstructions in the tunnel airflow, but also include losses due to other effects such as cross section changes and longitudinal curvature.

C. *The Tunnel Energy Equation*

The general principle of conservation of energy is a restatement of the first law of thermodynamics. For steady state control volume conditions, the energy input rate and internal generation rate must balance the energy output rate. Mass flows into or out of control volume carry stored energy in a variety of forms including kinetic, potential and internal. Energy also flows into and out of the control volume by work, heat or other energy transfers with the surrounding environment.

The conservation of energy for an entire tunnel length is illustrated in Equation 3:

$$\begin{aligned}
&\int_0^L \dot{e}_{Veh}\cdot dx+\int_0^L \dot{e}_{Jet}\cdot dx+\int_0^L \dot{e}_{Equip}\cdot dx = \\
&= A\cdot\left[\rho_L\cdot\bar{v}_L\cdot\left(h_L+\frac{\bar{v}_L^2}{2}+g\cdot z_L\right)-\rho_0\cdot\bar{v}_0\cdot\left(h_0+\frac{\bar{v}_0^2}{2}+g\cdot z_0\right)\right]+ \\
&+\int_0^L\left[\rho_e\cdot q_e\cdot\left(h_e+\frac{q_e^2}{2\cdot a_e^2}+g\cdot z_e\right)-\rho_i\cdot q_i\cdot\left(h_i+\frac{q_i^2}{2\cdot a_i^2}+g\cdot z_i\right)\right]\cdot dx \\
&+\int_0^L \dot{e}_{H.T.}\cdot dx. \qquad (3)
\end{aligned}$$

The expressions on left hand side can be identified as rate of energy transfer from vehicles to the tunnel air over the entire tunnel length under steady state conditions, energy addition rate to the tunnel air due to jet fans and the total energy transfer rate to the tunnel air that results from lighting and other equipment in the tunnel interior. Most of the energy content of the fuel burned by vehicles will end up as energy added to the tunnel air not only from the heated exhaust gasses but also mechanical and rolling friction, dissipated air motion due to drag and heat rejected from the cooling systems. Fan motors are located inside the air flow and it can be expected that essentially all heat generated due to fan motor inefficiency as well as the useful fan work will be transferred to the tunnel air. Therefore, the overall jet fan energy transfer rate to the tunnel air is essentially the electric power supplied to the fans.

The first expression on the right hand side is the net rate of energy removal from the tunnel air by the axial fluid flows at the tunnel portals, the second expression is the net rate of energy removal from the tunnel volume over the tunnel length due to the tunnel fluid effluxes and influxes through the ventilation systems and finally the last term is the net rate of energy removal from the tunnel air volume due to heat transfer interactions with the tunnel interior surfaces and to thermal radiation exchanges with the external environment at the portals.

After examining described equations it can be stated that the airflow air in the tunnel is complex phenomenon which depends on many factors and numerous coefficients that are hard to measure and are changing with time. The ventilation control algorithm proposed in this paper is made on assumption that the tunnel is discrete-event system and modeled by Grafcet.

III. GRAFCET

Grafcet is a mathematical graphical tool, drawing its inspiration from Petri's nets and its aim is describing discrete-event systems taking in account sequential behavior and concurrency. Discrete-event system is a system with a discrete state space and a state evolution that is determined by events. Its behavior may depend on two kinds of information coming from its environment: conditions and events. The first kind of information relates to the state of the environment of discrete-event system and the other kind of information relates to a change in the state of environment. The state of discrete-event system can always be defined by Boolean values. An event has no duration, whereas the value of a Boolean variable lasts some time. The relations between conditions and events are given by formal definitions and properties of algebra of events.

A Grafcet is a graph having two types of nodes: steps and transitions (Fig. 1). Directed arcs connect the two. Step is represented by square and it may have two states. It may be either active (this is represented by a token in a step) or inactive. The steps, which should be active when the system is started, are represented by a double square and are known as initial steps. Actions are associated with the steps, and these are the outputs of the Grafcet. They can be either level actions modeled by a Boolean variable with a finite duration or impulse actions with infinitely short duration.

The transitions symbol is a bar that is preceded or/and followed by a double bar if multiple steps precede it or if it involves activating multiple steps when transition is fired. Receptivity R_i is associated with each transition (i). The receptivity is a function of the grafcet input variables, the internal state or time. It can be both state and event.

Directed links are represented as a line that connects steps and transitions.

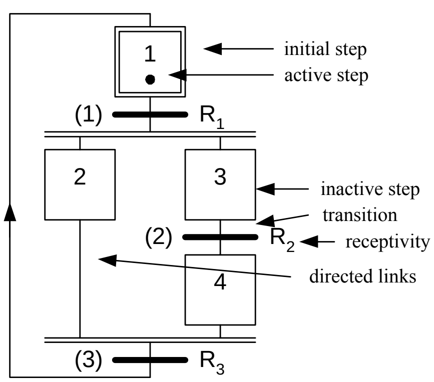

Fig. 1. Basic elements of Grafcet.

An active step contains one and only one token, and an inactive step does not contain any tokens. All active steps at any given moment define the situation at that moment. A situation corresponds to a system state. The evolution of the situation is achieved by firing of transitions. The inputs of the system are associated with the transitions and the outputs are associated with steps. A transition is firable if both following conditions are met:

1. All the steps preceding the transition are active (the transition is said to be enabled).
2. The receptivity of the transition is true.

All firable transitions are immediately fired. If there are several simultaneously firable transitions they are simultaneously fired. If a step must be simultaneously activated and deactivated it remains active.

The interpretation of a grafcet model must be unambiguous.

Macrosteps and macroactions are the abbreviations of an ordinary grafcet model, which are useful when building a grafcet in hierarchical manner.

The aim of the macrostep is to facilitate the description of complex systems. The macrosteps makes it possible to lighten the graphical representation of a grafcet by detailing certain parts, called macrostep extensions, separately. It is represented by a square divided into three parts by two horizontal lines.

When describing complex systems, the size of grafcet model may increase so that they become difficult to work out and thus to understand, correct and update. Using macroactions hierarchy is obtained and it is much easier to describe complex systems. A macroaction may be a level or an impulse action. It is produced by one grafcet and has effect on the behavior of an other grafcet.

IV. VENTILATION CONTROL ALGORITHM

The ventilation control algorithm presented in this paper [1] is based on data from 5062 m long Ucka Tunnel in Croatia with longitudinal ventilation system. In this paper only basis for normal operating regime is described.

A. *Input Data*

Necessary input data for the ventilation control algorithm are primarily meteorological data measured on five stations in the tunnel and two stations, one on each portal. Concentration of carbon monoxide, opacity and air flow velocity are measured on the measuring stations in the tunnel while temperature and air pressure are measured at portals. The algorithm uses time average values of these measurements and maximum spatial value of carbon monoxide, opacity and velocity of airflow. Maximum spatial value of carbon monoxide and opacity are used to determine the state of pollution in the tunnel and this is leading input value for the algorithm.
Apart from meteorological data, the algorithm also uses electrical utility, state of fans and communication input data to be able to determine availability of each of 24 group of three fans for each direction. Also, traffic input data as well as data from fire alarm stations are used.

B. *Basis of Ventilation Control Algorithm*

A tunnel system engineer defines optional number of thresholds (T_1, T_2, .. ,T_N) and then carbon monoxide concentration and opacity threshold values for each threshold. State of pollution is defined as a zone between two thresholds (ST_1, ST_2, ..). The Table 1 shows all parameters and actions for each state and threshold.
For each threshold, action (turning on or off groups of fans) can be defined as well as number of groups of fans. If action is turning on it will be carried out only when the threshold is crossed from lower to higher pollution state. Also, if the action is “OFF” the groups of fans will be turned off only when the threshold is crossed from higher to lower state of pollution.

Similar, in each pollution state certain number of groups of fans can be turned on or off in predefined period of time.

In higher states it is possible to ban change of ventilation direction as well as activate first or second alarm or initiate closing of the tunnel.

When turning on or off one group of fans ventilation control algorithm is set to choose the one with the lowest working hours taking into total account energy consumption and availability of each group of fans.

Table 1. Parameters and actions of ventilation control algorithm.

		ST 0	T 1	ST 1	T 2	ST 2	T 3	ST 3	T 4	...
CO threshold value			xxx		xxx		xxx		xxx	
OP threshold value			xxx		xxx		xxx		xxx	
Action on threshold	Action (ON/OFF)		ON/OFF		ON/OFF		ON/OFF		ON/OFF	
	No. of groups of fans		0/1/2/SVI		0/1/2/SVI		0/1/2/SVI		0/1/2/SVI	
Action in state	Action (ON/OFF)	ON/OFF		ON/OFF		ON/OFF		ON/OFF		ON/OFF
	No. of groups of fans	0/1/2		0/1/2		0/1/2		0/1/2		0/1/2
	Period (min)	xxx		xxx		xxx		xxx		xxx
Change of direction banned										NO/YES
Alarm 1										NO/YES
Alarm 2										NO/YES
Closing of the tunnel										NO/YES

	Alarm 1	Alarm 2 + closing of the tunnel
V treshold value	xxx	xxx

Apart from basic part of ventilation control algorithm described by Table 1, the algorithm can also recognize better ventilation direction when ventilation is turned on for the first time, the need of changing the ventilation direction and appearance of fog on one of the portals.

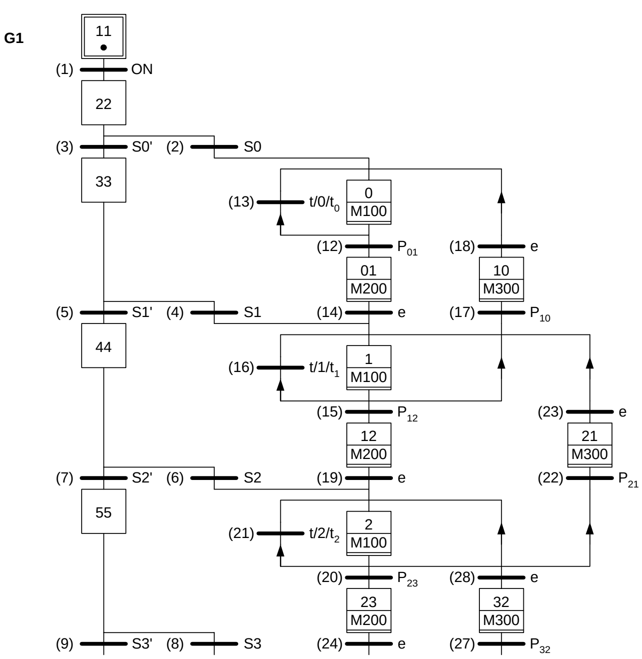

Fig. 2. Part of grafcet model of basic ventilation algorithm.

In Figure 2 part of basic ventilation control algorithm described using Grafcet is shown. Initial step 11 is active until the automatic ventilation control is turned on and transition (1) is fired. Using transitions (2), (3), (4),.. the current pollution state is determined and the one of the macrosteps 1, 2, 3,.. which represent certain pollution state is activated. If the state of pollution remains unchanged this macrostep will be activated periodically. If a threshold is overstepped to a lower state, one of macrosteps 10, 21, 32,.. is activated and the actions are carried out. Similar, if a threshold is crossed to a higher state one of macrosteps 01, 12, 32,.. is activated and actions defined for that situation are activated.

It can be seen that certain macrosteps have the same extensions. Extension M100 represents action in a certain pollution state, extension M200 represents action, which occur if threshold to higher state is overstepped, while extension M300 represents action if threshold is overstepped towards lower state.

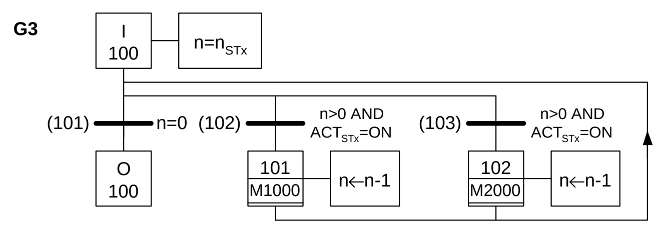

Fig. 3. Grafcet model of action in a state.

Action that periodically occurs in each state is described by grafcet model shown in Figure 3. This grafcet model is rather simple. After it has determined, using transitions (102) and (103), if at least one group of fans needs to be turned on or off, steps 101 or 102 are activated. Extension M1000 represents turning on of one group of fans and is used every time one group needs to be turned on. On the other hand, extension M2000 stands for turning off of one group of fans.

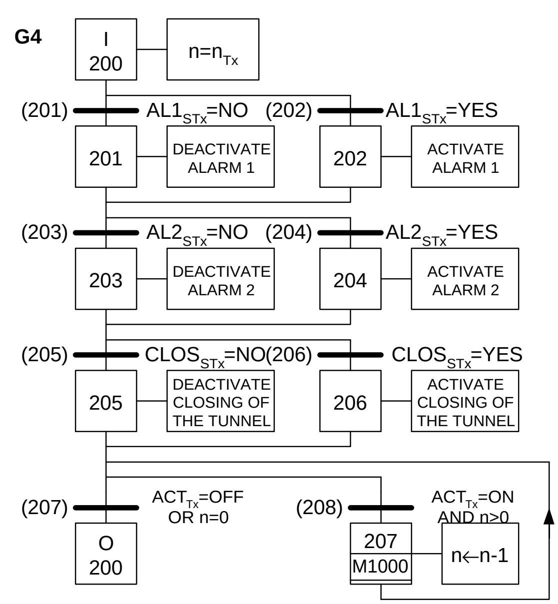

Fig. 4. Grafcet model of action when crossing threshold from lower to higher state of pollution.

Figure 4 describes an action that occurs when threshold is crossed from lower to higher state. Using a few transitions it is determined if alarm 1 or 2 needs to be activated or if the tunnel should be closed. Finally, by repetitive activation of step 207, one by one group of fans is turned on.

Grafcet model of an action that occurs when threshold is overstepped from higher state to the lower resembles to shown grafcet model.

On the lowest hierarchical level of presented ventilation control algorithm is grafcet model that represents turning on or off of one group of fans. This grafcet model is rather complex and depends highly on data of specific tunnel so it will not be shown in this paper.

C. *Verification of ventilation control algorithm*

Verification of presented ventilation control algorithm is based on analysis of system behavior during one day of automatic ventilation control in normal ventilation regime.

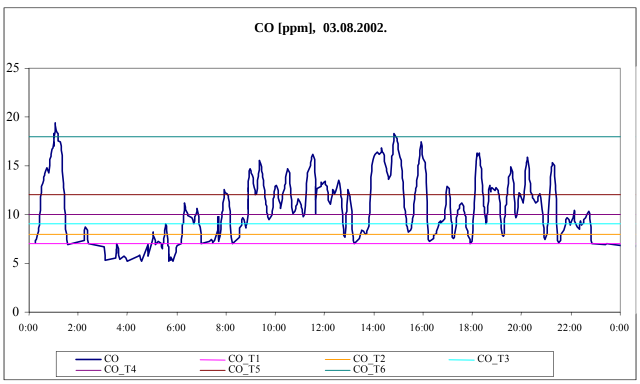

Fig. 5. Measured value of carbon monoxide concentration and first six thresholds of carbon monoxide.

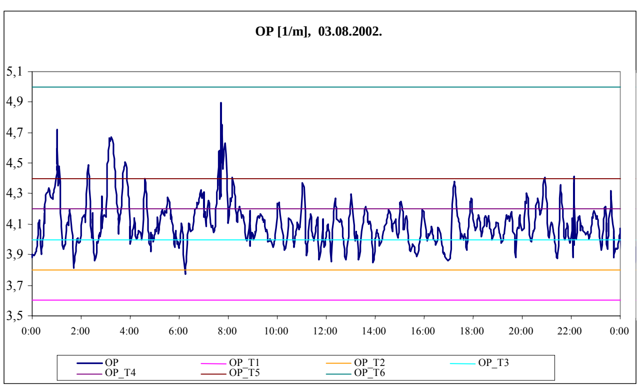

Fig. 6. Measured value of opacity and first six thresholds of opacity.

In Figures 5 and 6 it can be seen that the concentration of carbon monoxide and opacity hardly ever cross sixth threshold.

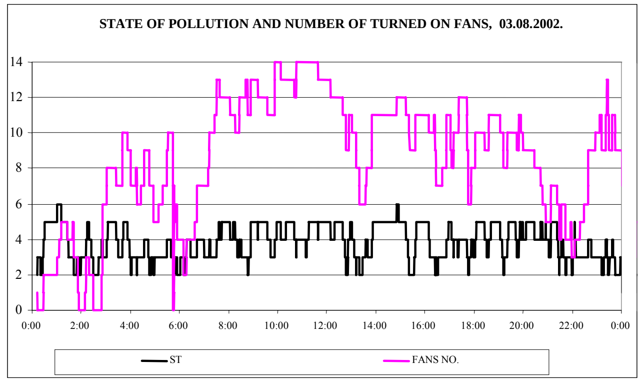

Fig. 7. Number of turned on fans and state of pollution.

In Figure 7 it is shown how state of pollution stays rather stable and the number of fan groups that are turned on.

V. CONCLUSION

Ventilation system of road tunnels is expensive and for the passengers safety vital equipment of the tunnel. This justifies interest in researching and improving of such systems. Grafcet, mathematical tool for describing discrete-event systems, was found very useful when describing control algorithm since it enables hierarchical structure by using macrosteps and macroactions. The ventilation algorithm presented in this paper is very flexible and economical jet simple and understandable.

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