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A NEW VENTILATION METHOD FOR THE KAN-ETSU ROAD TUNNEL

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Summary

The Kan-etsu tunnel is the longest road tunnel now under construction. It forms part of the Kan-etsu highway crossing central Japan. The unique feature of this tunnel is that in spite of its considerable length it is fitted with a longitudinal ventilation system. This is the first time for a longitudinal system to have been used on a tunnel of this length and in-depth investigations have been carried out to study the statics of the system completed with vertical duct units and electrostatic dust collectors. To reach a conclusive assessment allowing the system to be adopted, it is also necessary to determine the dynamics of the system. For this purpose, our numerical simulation program has been developed as a means of modelling the non-steady state distribution of the pollutants occurring in the tunnel. The results of the simulation experiments and calculations have facilitated a clear understanding of the dynamics of ventilation and yielded valuable insights into the relative merits of the various control systems available.

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NOMENCLATURE

A_b = Area of the nozzle

A_e = Area equivalent of vehicle drag

A_j = Area of the jet fans

D = Coefficient of diffusion

D_r = Characteristic diameter of the tunnel section

E_j = Booster fan energy

E_v = Ventilator energy

F_f = Friction loss force

F_j = Booster fan driving force

F_p = Piston driving force of the vehicles

F_t = Total outside force acting on the air

F_v = Ventilator driving force

F_w = Natural wind driving force

G_1–G_6 = Correction gain

L_r = Total length of the tunnel

M = Mass of air in the tunnel

N_j = Number of boosters in operation

Q_b = Ventilator flow

Q_r = Flow in the tunnel

T = Time interval

V_j = Velocity at the exit of the booster fan

V_r = Velocity of air flow in the tunnel

V_t = Velocity of a vehicle

V_w = Natural wind velocity

c = Concentration of smoke or carbon monoxide

n^+, n^- = Number of vehicles up and down the tunnel respectively

l = Length of section

q = Emission of pollutants from vehicles

t = Time

x = Longitudinal coordinate in the tunnel

β = Angle of the nozzle

ζ = Loss coefficient at the entrance

λ = Friction loss coefficient of pipe

ρ = Air density

Suffix & prefix

i = Section number

in = entrance of each section

out = exit of each section

* = normal value

Δ = deviation from normal value

1. INTRODUCTION

The Japanese National Highway network for transportation between cities is steadily increasing in complexity and length to keep up with the development of Japanese industry and society. The total length of the highway will reach 3,200km by the end of fiscal year 1981.

Because Japan has a small land area and is mountainous, there are of necessity many tunnels. The Kan-etsu tunnel (scheduled to be open for public service in 1984) is part of the Kan-etsu highway which runs across the middle of Japan. It will be the longest road tunnel in Japan when completed.

A notable feature of this tunnel is its use of a ventilation system to dilute harmful gases emitted from vehicles. This system employs longitudinal ventilation with vertical ducts and dust collectors to provide energy savings in view of the critical energy situation which has existed since the oil crisis of 1973. This will be the world's first use of the longitudinal ventilation system for such a long tunnel. To verify the capability of this system, we have performed experiments using dust collectors in an actual tunnel, model experiments of flow analysis at the branch of a vertical duct, and measurement and analysis of natural winds throughout the year using a nearby railway tunnel as a model. Based on these preliminary studies, we have developed a numerical simulation program for a digital computer. It is utilized to obtain the optimal control system which allows the minimum consumption of power to set the ventilators using both traffic and pollution data.

2. FEATURES OF THE KAN-ETSU ROAD TUNNEL

The Kan-etsu tunnel crosses the Tanigawa mountain range between Tokyo and Niigata, as part of the Kan-etsu highway, 300km in total length. The tunnel is attracting worldwide attention from the standpoints of both its length and equipment. The first stage of tunnel construction is to consist of two lanes out of a total of four. This choice was made based on economy in view of the volume of traffic. The Niigata-bound lanes will be open at first in 1984 to opposing traffic. The second construction phase for the Tokyo-bound lanes is not finally scheduled as of yet.

This tunnel has a total length of 10,885m with the inclinations of 1.0% and 0.5%. It has two vertical ducts and six dust collector stations as shown in Fig. 1. The cross section is shown in Fig. 3 with the area of 61.5m^2 and a characteristic diameter of 7.9m.

For the ventilation of the Kan-etsu tunnel, a longitudinal ventilation system has been adopted to achieve economy in construction, and economy in installation and running costs. This system requires the installation of two vertical ducts and six dust collector stations. These were found to function satisfactorily and are described elsewhere. (Ref. 1) While later research concluded that the number of dust collector stations could be reduced to five, the discussion in this paper assumes the former specification. 128 booster fans will also be installed to drive the air flow. The layout of the ventilation equipment is illustrated in Fig. 1. The ventilation rate necessary for the designed traffic conditions was calculated statically, as shown in Fig. 2.

Fig. 2 shows the distribution of smoke and CO concentrations under the designed operation conditions, see Table 1. Using the longitudinal system, these values increase linearly in the direction of the air flow. Smoke is reduced at dust collectors and the vertical ducts, while CO is reduced at vertical ducts only. The efficiency of the dust collectors is estimated to be at least 80%.

3. VENTILATION SIMULATION METHOD

3.1 Purpose of the ventilation simulation.

A variety of investigations concerning the performance of longitudinal ventilation systems with vertical ducts using dust collectors had been made for the Kan-etsu teunnel. However, it was felt that further detailed investigation of the unsteady characteristics was necessary.

One of the typical features in this system is that there is a finite time delay between a change in the source of pollution and the detection of that effect by sensors. This will be treated as a problem of convection and diffusion of pollutants with respect to air flow in the tunnel. It is also necessary to gain an understanding of how the velocity of air flow is effected by the change of ventilator operations due to the large mass of air in the tunnel.

If automatic control is to be used in this system, verification must be made that a cross ventilation system concept holds for such a system.

In addition, if a fire breaks out, it is desirable to be able to decelerate and stop the air flow in the tunnel as soon as possible. Information is required as to the best operation mode for such an installation, the effect of vehicles in the tunnel on the movement of air, and natural winds. Numerical simulation is a useful tool for obtaining such information and establishing emergency control procedures.

Steady-state calculations are not sufficient to provide answers to the above questions. Simulation becomes necessary to analyze and understand the timevarying process involved with the velocity of air flow and distribution of pollutant concentrations. In this section, the outline of the simulator developed for this purpose is discussed.

3.2 Structure outline of the simulator.

The ventilation simulator can be divided into four sections by function: the aerodynamic model, pollution model, traffic model, and controller model. These are organically linked, as shown in Fig. 4.

The flowchart of the simulator is shown in Fig. 5. The flow is basically as follows.

First, specifications are made and then the read in of initial data and constants is performed. Then the initial values of pollutant distribution, velocity of air flow, and ventilator settings are read. Before entering the routine calculation a preparatory routine is run for 20 minutes to adapt the status of each value to specific traffic conditions. The time step used for these calculations is 10 seconds. The main iteration loop calls the controller model to obtain ventilation flow rate, the traffic model to read traffic data from tape and the aerodynamic model to obtain the velocity of air flow. Using the velocity of air flow, the pollution model is calculated. It gives the distribution of pollutants at each new time step using the former pollution data and the new traffic and aerodynamic data. This completes the entire calculation for the time step. Results are stored in an orderly fashion into files after performing certain transformations. This is repeated until the simulation time (2 hours) has been completed.

3.3 Explanation of each model.

3.3.1 Aerodynamic model.

The role of the aerodynamic model is to calculate the velocitv of air flow in the tunnel at each time step. For simplicity, we neglect the compressibility of air. In addition to that, it is assumed that the flow rate of blow-in and exhaust are the same at both the Tanigawa and Mantaro vertical duct installations. Therefore, the velocity of air flow V_r is definite in the whole tunnel at each time.

Precisely speaking, there would be some differences between these flow rates. However, they must be small, because the driving force of blowers is much bigger than the fluctuations of other forces. The assumption will be excluded in special cases like an exhaust mode of fire.

The acceleration of air flow is calculated by the Newton's second law as follows:

$$\frac{dV_r}{dt} = \frac{F_t}{M} \tag{1}$$

where

$$F_t = F_p + F_v + F_j + F_w + F_f \tag{2}$$

The V_r and F values are positive when directed towards Yuzawa.

The force F_t must include all forces acting on the air cylinder. These include the driving force of the traffic F_p, the effect of the large ventilators blowing F_v, the momementum effect of the booster fans F_j, outside pressure differences caused by natural winds F_w, and the frictional loss F_f due to flow in the pipe. These forces are expressed as follows.

$$F_p = \frac{\rho}{2} A_e\{n^+(V_t-V_r)^2 - n^-(V_t+V_r)^2\} \tag{3}$$

$$F_v = \rho Q_b\{(Q_b/A_b)\cos\beta - 2V_r+Q_b/A_r\} \tag{4}$$

$$F_j = n\eta\rho|V_j|A_j\,(V_j-V_r) \tag{5}$$

$$F_w = \frac{\rho}{2} A_r(1+\zeta+\lambda\frac{L}{D})V_w|V_w| \tag{6}$$

$$F_f = \frac{\rho}{2} A_r(1+\lambda\frac{L}{D})\,V_r|V_r| \tag{7}$$

To calculate these forces it is necessary that the status of ventilator operation, traffic flow and natural winds, is determined by other models.

In Eq.(3), velocity of vehicles V_t is different for each 100m division of the tunnel. The entrance loss ζ has been assumed to be zero since its significance in view of the Saccard effect is unclear. In Eq.(6), natural wind V_w is defined to be the wind velocity in the case that there are no vehicles and no fan operations. To allow the solution of Eq.(1) by means of a digital computer, time must be divided into finite intervals (10 seconds).

3.3.2 Pollution model.

The pollution model is the simulation block used to calculate the temporal and spatial distributions of smoke and CO in the tunnel. These pollutants are emitted from vehicles whose density are given by the traffic model for each cell of the difference equation. The pollutants are transported at the velocity of air flow which is given by the aerodynamic model, and partially or entirely removed at the dust collectors and vertical ducts. We assume that the concentration of pollutants is constant in the cross section of the tunnel so that the distributions are only in the axial direction.

The distributions of smoke and CO concentrations C are obtained by solving the following equation.

$$\frac{\partial c}{\partial t} = -V_r \frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} + q \qquad (8)$$

Where the right hand side of the Eq.(8) are convection, diffusion and generation terms of pollutants, respectively.
Eq.(8) is transformed into a difference equation with the divisions of 10 seconds and 100m.

3.3.3 Traffic model.

The traffic model is independent of the main program and is used to generate data on vehicular status, and composition with regard to size, etc. This data is stored on magnetic tape to allow recall at the time of the main simulation.

The models for traffic simulations are divided into two major groups: the micro-model which treats the behavior of each vehicle individually and the macro-model which expresses the properties of a group of vehicles. The micro-model considers the dynamics of each vehicle and the relationship between vehicles. In this model, the acceleration of a vehicle is determined by the relative velocity and distance with respect to a preceeding vehicle. In the macro-model, on the other hand, the dynamics of a group of vehicles are considered so that the vehicular density and mean velocity are the quantities considered. Various types of macro-models have been proposed and from them we have chosen to use the model of Payne. (Ref. 2) This is a typical model and will be used in this explanation. As an index to represent the macro-characteristics of a group of vehicles, this model considers vehicular density and spatial mean velocity in a particular division. The temporal change of vehicular density is expressed as an algebraic sum of inflow and outflow of vehicles. The change in mean velocity is given as the sum of inflow terms from the previous cell, and the recurrence terms of the equilibrium velocity and prediction term for density at the next cell. The product of the mean velocity and density is defined as the outflow term at cell and the inflow term to the next cell.

The Payne model has been adopted for our simulation from the standpoint of compatibility to the main routine and economy.

To perform traffic simulation using this model, the total length of the tunnel is divided into an array of 100m length cells and the traffic flow is generated at the point 100m before the tunnel entrance. The method of generation is as follows using random numbers.

a) The traffic conditions are set to yield a parameter for random number generation (mean value). In this simulation, the mean value is varied in time in the range 0.8 to 1.2 of the average. The rate of diesel vehicles is maintained as constant.

b) The traffic flow rate at each time division in accordance with the mean value is generated by a random number generator possessing a Poisson distribution.

c) The number of diesel vehicles is given by a random number possessing a binomial distribution about the mean value of diesel vehicle rate.

3.3.4 Controller model.

The controller model provides the status of ventilator operation to the aerodynamic model, the calculation being based on information concerning pollution and traffic flow.

The controller model is linked to the controlled simulator, the main part of the simulator, by means of interfacing subroutines. The passing of variables between these blocks is accomplished in a manner similar to a real system. That is, the role of the controller model is to generate commands for ventilator operation, based on data from the sensors including smoke density meter, CO meter, and traffic measurement sensors, etc., set at specified locations.

Several modes of control are included in this model, and it is possible to evaluate the methods of ordinary operation. The methods used are constant operation, VI feedback, traffic forecast feedforward, and optimum regulator mode. Details of these of control are discussed in the next section.

4. VENTILATION CONTROL FOR KAN-ETSU TUNNEL

4.1 Longitudinal ventilation system.

The Kan-etsu tunnel uses the longitudinal ventilation system shown in Fig. 1. Two vertical ducts exchange the exhaust gases (CO and smoke) for fresh air. Electrostatic dust collectors remove smoke and soot. The tunnel is divided into nine sections, each fitted with the same array of the above equipment.

The tunnel has four different ventilators. Variable-speed blowers and exhaust fans are installed in the vertical ducts. Variable blade angle dust collector fans are coupled with the electrostatic dust collectors. The booster fans are mounted in-line on the ceiling of the tunnel. Ventilation rate adjustment is by controlling the drive units of the blowers and fans and by selecting their speed settings and blade angle positions.

The direction of the air flow is identical to that of the tunnel. The steady-state distribution of the pollutant concentration is therefore consistent with a linear curve in each section. The highest polluted points are at the end of it. Consequently, the pollutant concentrations should be measured and monitored at these points.

The flow of traffic affects the ventilation pattern not only by the emission of exhaust gases from the vehicle engines but also by the ventilation effect it produces. To evaluate this, it is necessary to monitor the flow of traffic at certain points.

The following factors make it difficult to control the ventilation rate inside the tunnel:

a) Variations in the ventilation effect produced by the flow of traffic;

b) Variations in the exhaust gas emission levels depending on the individual vehicle;

c) Fluctuations in the natural wind flow;

d) Differences in the performance of the various ventilation units used.

To meet the applicable safety, economy and reliability requirements, the ventilation equipment must be designed to respond to the above variations in the ventilating conditions.

4.2 Ventilation control.

4.2.1 Conventional ventilation control system.

The following three types of conventional road tunnel ventilation control system are in widespread use:

a) Program control: The ventilation rate is set to suit the prevailing typical daily traffic flow pattern.

b) Feedback control: The ventilation rate is adjusted in accordance with the monitored deviation of the pollutant concentration from a given target value.

c) Prediction-based control: The ventilation rate is to set to match the predicted rate of traffic flow.

The latter two control methods are generally recognized as being impracticable due to the dramatic fluctuations in the ventilation rate and the pollutant concentrations. As a result, it is the more common practice to control the tunnel ventilation rate manually. In some cases, the pre-programmed control system has been used exclusively.

4.2.2 New ventilation control system.

A linear optimum regulator system has been proposed by two authors for cross-ventilation equipment and successfully applied in the Mt. Ena tunnel. (Ref.3)

We shall now review this type of control system for longitudinal ventilation applications. Fig. 6 is a block diagram of the control system. The normal ventilation rate is determined in terms of a given long-term prediction of the likely traffic flow and subsequently corrected as a function of the real pollutant concentration and the short-term forecast for the traffic flow.

The following is a more detailed description of the various functions involved.

(1) Normal ventilation rate

The optimum setting of the ventilating units and the optimum adjustment of the ventilation rate are achieved in terms of the normal traffic flow, using the non-linear programming method, for example.

The problem can be formulated by means of the following set of equations:

Minimize:

$$J = \sum_{i=1}^{9} E_v(Q_{b,i}) + E_j(N_j) \quad (9)$$

Subject to:

$$F_p(n_i^{+*}, n_i^{-*}) + F_v(Q_{b,i}) + F_j(N_j) + F_w + F_f = 0 \quad (10)$$

$$c_{i,out} = \frac{q(n_i^{+*}, n_i^{-*})}{V_r} x_i + c_{i,in} \leqq c^* \quad (i=1,\ldots,9) \quad (11)$$

The solutions to the above non-linear programming problem $Q_{b,i}^*$ and N_j^* are used as the standard control settings over a long period of time (30-60 min.) to ensure stable and economic ventilation conditions.

(2) Corrections of the standard control setting for the ventilation rate

Corrective adjustments to the standard control setting for the ventilation rate are effected as a function of the actual traffic flow and the prevailing ad hoc pollutant concentration. The linear control theory provides the mathematical basis for correcting the ventilation rate by using the monitored deviations from the standard values as state and control variables:

$$\Delta Q_{b,i} = G_1 \Delta n_i^+ + G_2 \Delta n_i^- + G_3 \Delta c \quad (12)$$

$$\Delta N_j = G_4 \Delta n_i^+ + G_5 \Delta n_i^- + G_6 \Delta V_r \quad (13)$$

$\Delta Q_{b,i}$ and ΔN_j are obtained after each control cycle (5-10 min). The first and second terms of Eqs.(12) and (13) are the feed forward control values for the traffic flow to compensate any errors inherent in the long-term traffic flow prediction model as a result of actual fluctuations in traffic flow patterns. The third terms of Eqs.(12) and (13) represent the feedback control values for the pollutant concentration level and the velocity of air flow.

4.3 Control trial operation evaluation.

Simulation experiments have been carried out modelling the Kan-etsu tunnel ventilating control system. The simulator described earlier was used under the conditions detailed in Table 1.

Fig. 7 9 shows some simulation examples. The simulation experiment reflects the ventilation conditions occurring in the section 3 as shown in Fig. 1. The representative value for the ventilating conditions is the ventilation rate prevailing at the exhaust fans in the first vertical duct. The pollutant level (CO and smoke) at the outlet point of this section served as a basis for the simulation experiment.

Fig. 7 gives the traffic conditions in this section. Fig. 8 gives the simulation results for a conventional pollutant concentration-actuated feedback control system. Fig. 9 shows the simulation results obtained with the proposed optimum regulator system. A comparison of the results indicates that with the optimum regulator system, the fluctuations in the velocitv of air flow and the ventilation rate values are smaller than those encountered in the feedback control system. According to the pollutant concentration, the optimum regulator system shows some improvements over the conventional feedback control system.

The following two criteria are imposed to enable the results of the control trial operation to be evaluated in a more stringent manner.

a) Total electric energy

$$E = \sum_{i=1}^{9} E_v(Q_{b,i}) + E_j(N_j) \qquad (14)$$

b) Ventilation quality

$$\sigma_c{}^* = \sqrt{\frac{\int_0^T \{f(c_i - c^*)\}^2 dt}{T}} \qquad (15)$$

where

$$f(c_i - c^*) = \begin{cases} 0 & : (c_i < c^*) \\ c_i - c^* & : (c_i \geq c^*) \end{cases} \qquad (16)$$

From these simulation experiments it becomes apparent that the optimum regulator system is promising in terms of its high efficiency and quality.

5. CONCLUSION

We have discussed the ventilation system to be used in the Kan-etsu tunnel and its performance. It is noteworthy that longitudinal ventilation with vertical ducts has been adopted in spite of the fact that this tunnel is one of the longest in the world. In such a complex ventilation system with many elements combined for operation, it is difficult to estimate dynamic performance. Here we have succeeded in predicting the characteristics of ventilation and strengths and weaknesses of various control methods by means of numerical simulation. The mathematical model for the longitudinal ventilation system is basically a model of diffusion and convection. We have solved these problems by modelling in one dimension, using dynamic difference equation.

The controller model used in the simulation is almost independent of the models of tunnel dynamics and has essentially the same function as those models.

It was found that, using a designed traffic and pollution value varying between +-20%, it is possible to keep concentrations of pollutants within permissible limits. With regard to the selection of the control method, it was noted that the proposed optimum regulator control method provides the promising performance, using a combination of traffic forecasting and concentration feedback.

ACKNOWLEDGEMENT

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REFERENCES

1. Hirakawa, E. and Kohno, K. "Outline of Kan-etsu Tunnel Construction". Civil Engineering in Japan, vol.19, 1980, pp.101-114.

2. Payne, H.J., Thompson, W.A. and Isaksen, L. : "Design of a traffic-responsive control system for a Los Angeles freeway". IEEE Trans., SMC-3-3, 1973, pp.213-224.

3. Ueki, M., Maeda, K. and Nakahori, I. : A New Ventilation Control Method for the Mt. Ena Tunnel of chuo Expressway". Proceeding of IFAC Simposium, Environmental Systems Planning Design and Control, Kyoto, Japan, 1977, pp.579-585.

Table 1. Simulation experiment conditions

Number of lanes	2
Traffic directions	2-way
Tunnel length	10.9 km
Cross-sectional area	61.5 sq.m.
Highway gradient	1.0%-0.5%
Altitude	650 m
Traffic flow Max.	1820 /h
Average	1515 /h
Min.	1210 /h
Tokyo/Niigata bound traffic flow	60% / 40%
Rate of diesel engined vehicles	34.2 %
Average speed	60 km/h
Exhaust gas emission per vehicle:	
CO from gas engines	250 ppm/s
CO from diesel engines	250 ppm/s
Smoke from gas engines	2000 ppm/s
Smoke from diesel engines	58000 ppm/s
Allowable CO concentration	100 ppm
Allowable light transmissivity (for 100m)	40 %
Traffic ventilation effect due to:	
diesel engines	5.4 sq.m
gas engines	1.1 sq.m
Direction of ventilation air flow	Toward Niigata
Natural winds	2.5m/s towards Tokyo

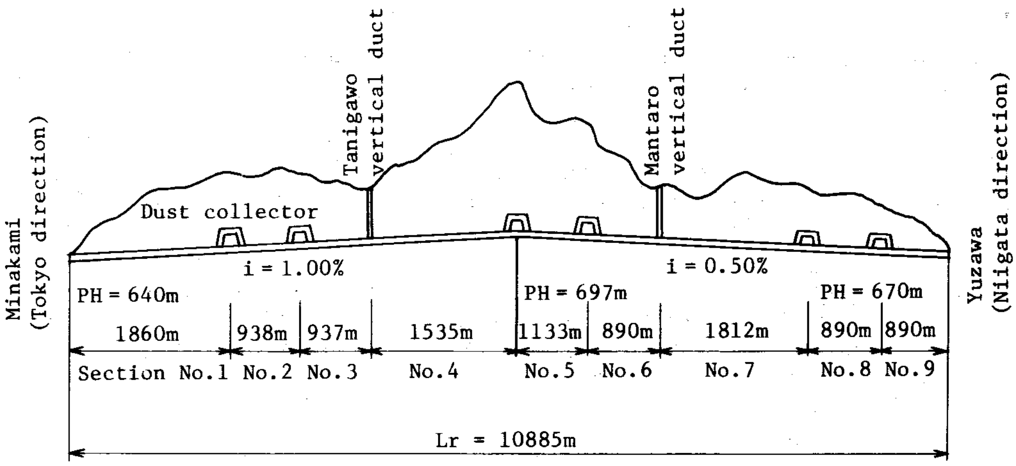

Fig. 1 Ventilation structure of Kan-etsu tunnel.

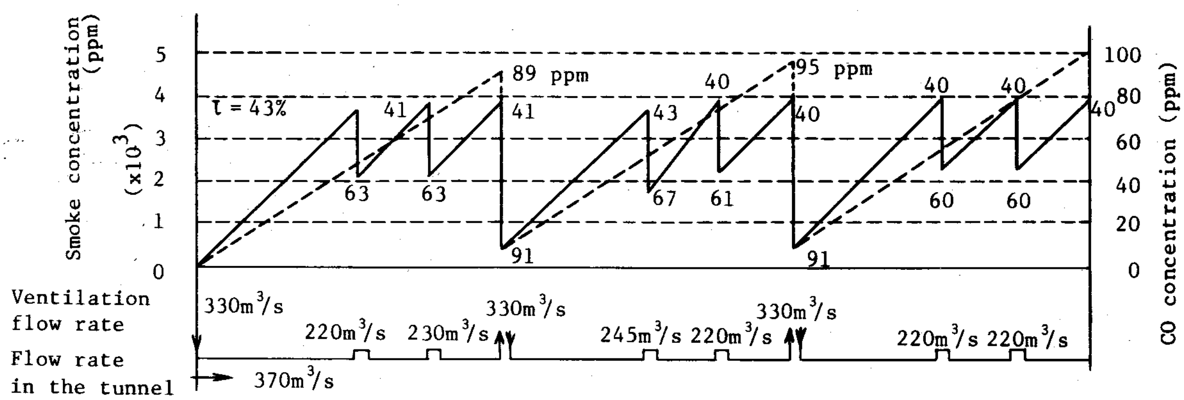

Fig. 2 Distribution of smoke and CO.
(for designed opposing traffic)

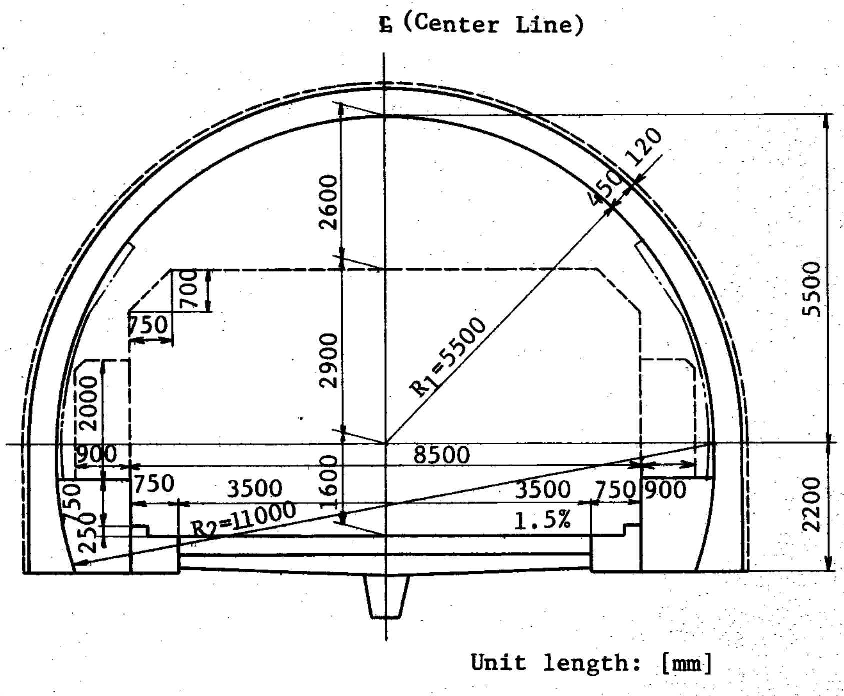

Fig. 3 Tunnel cross section.

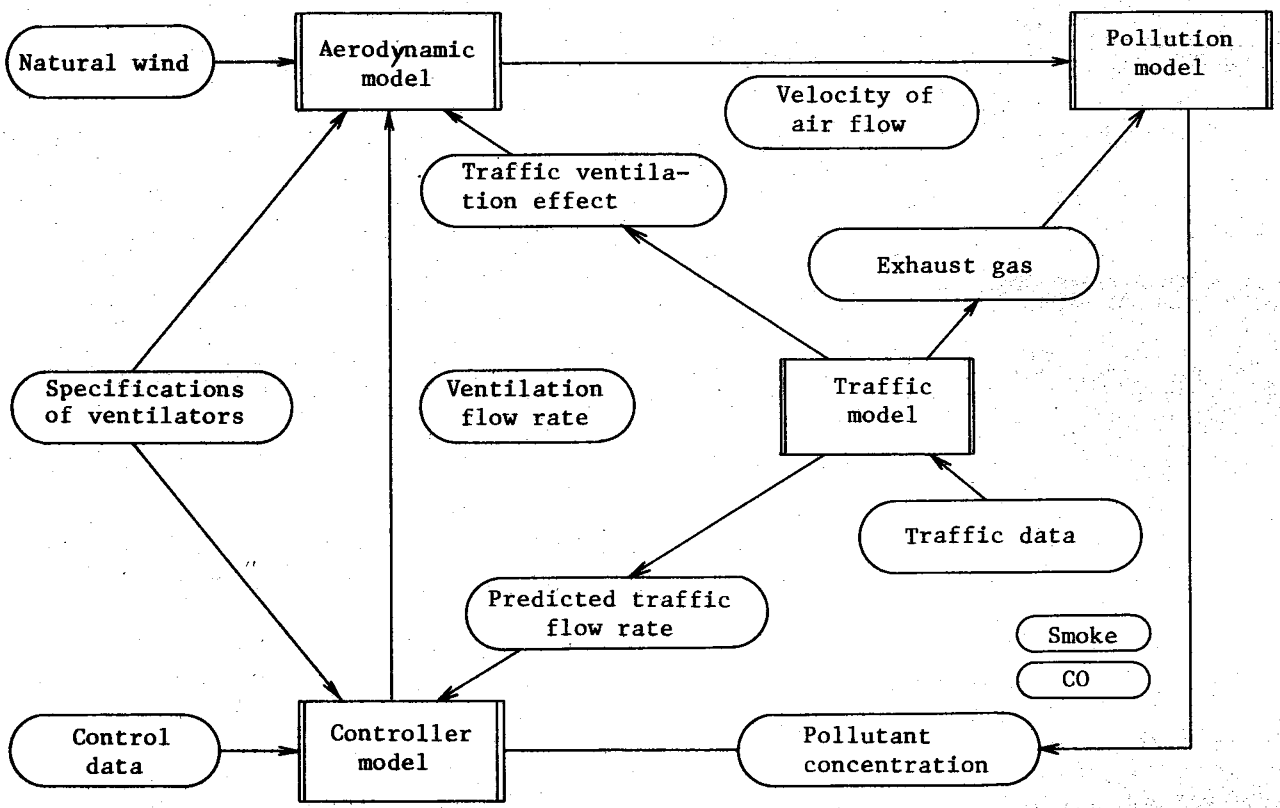

Fig. 4 Structure outline of the simulator.

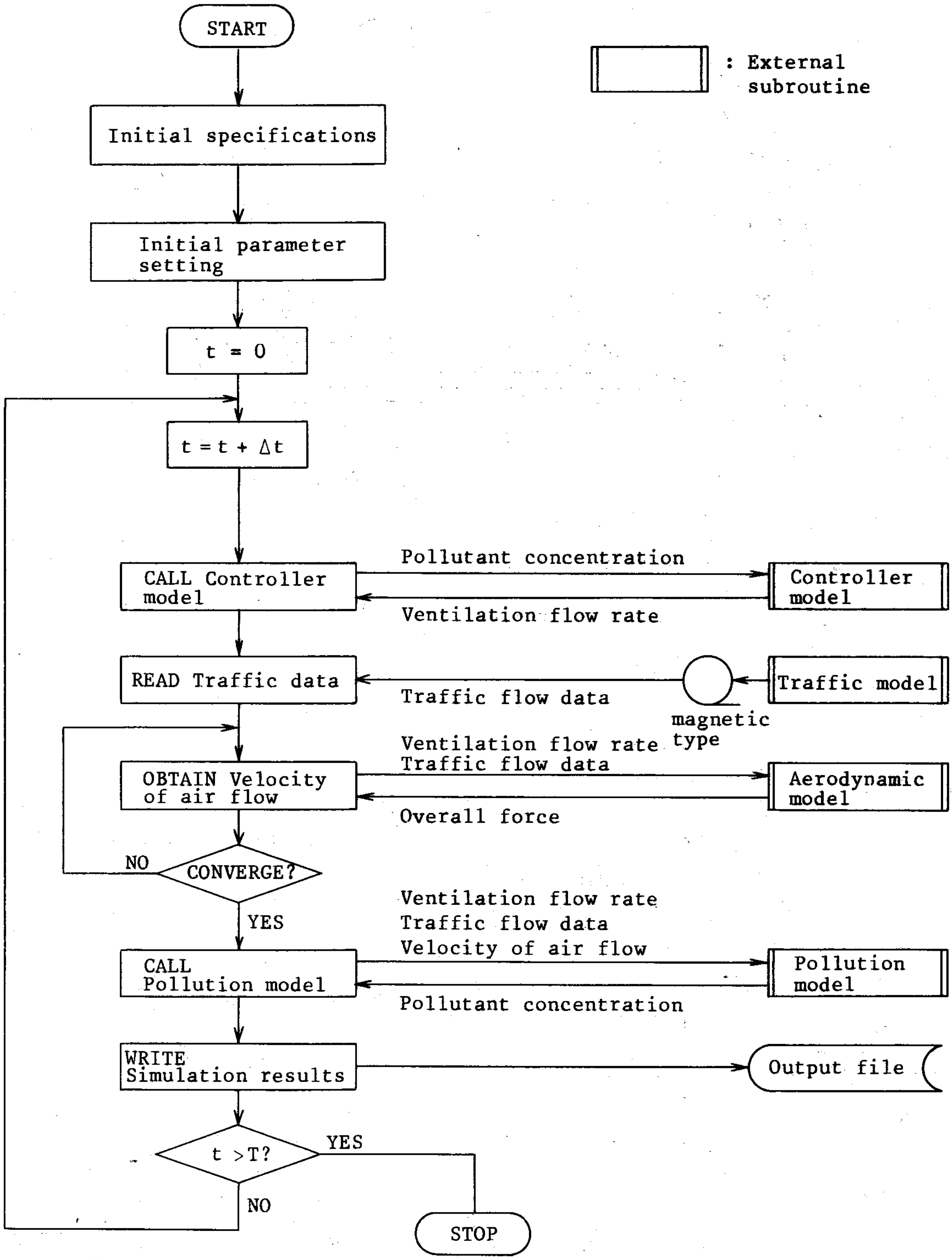

Fig. 5 Ventilation simulator flowchart.

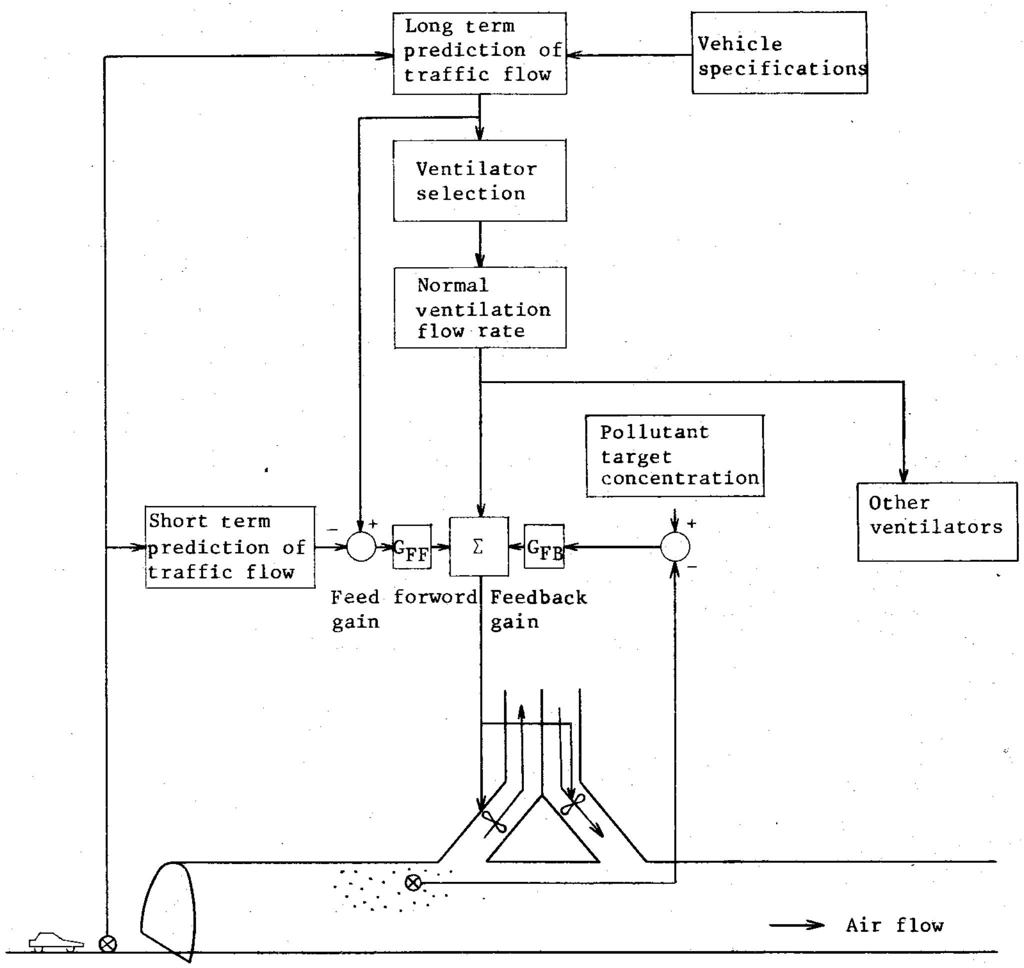

Fig. 6 Block diagram of the ventilator control system.

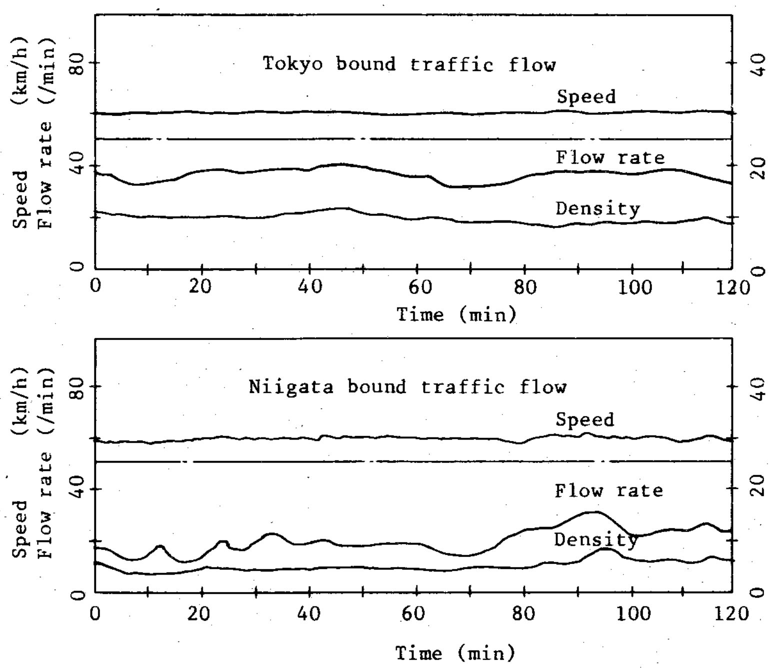

Fig. 7 Traffic conditions of the simulation

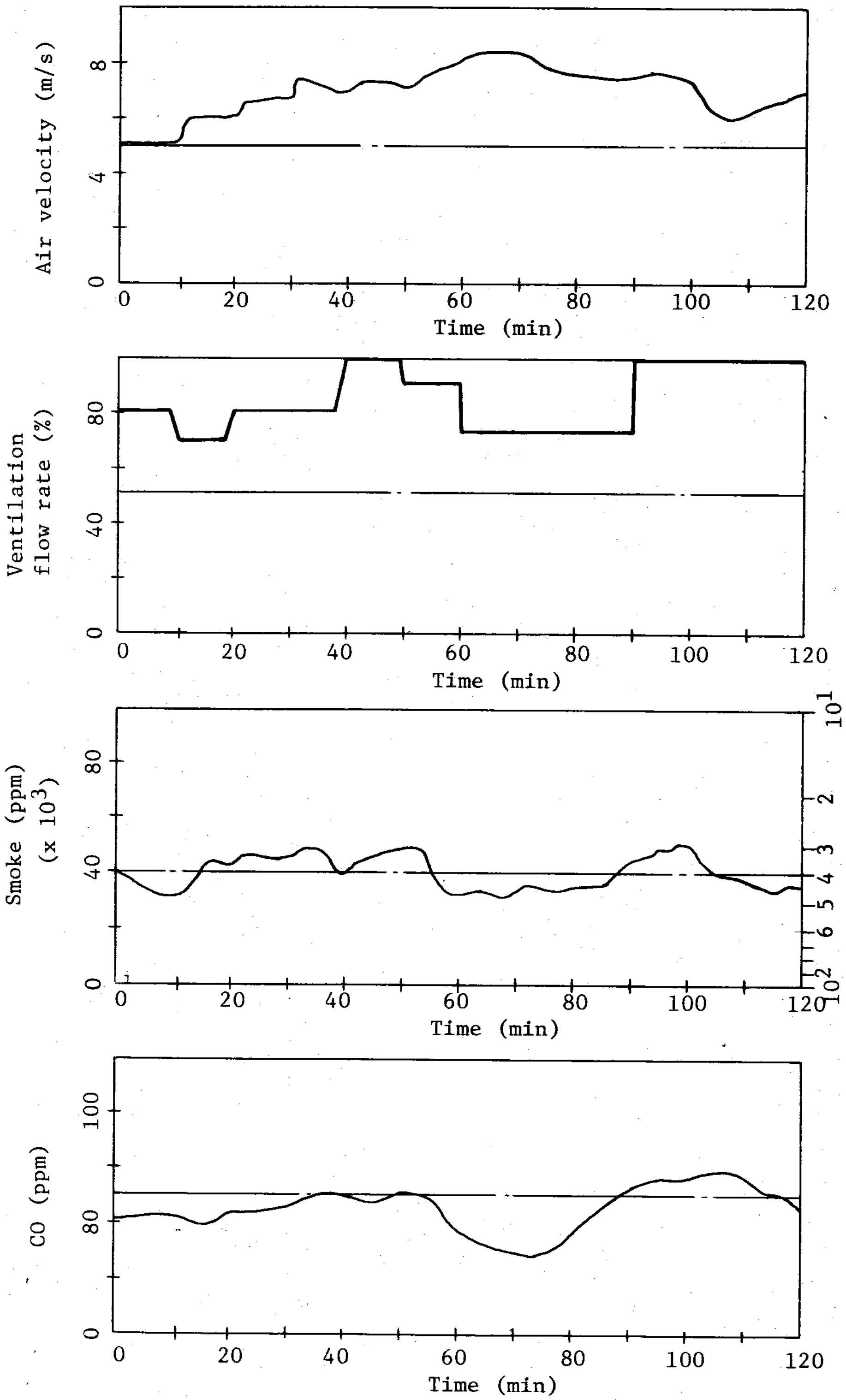

Fig. 8 Simulation results of a conventional feedback control system.

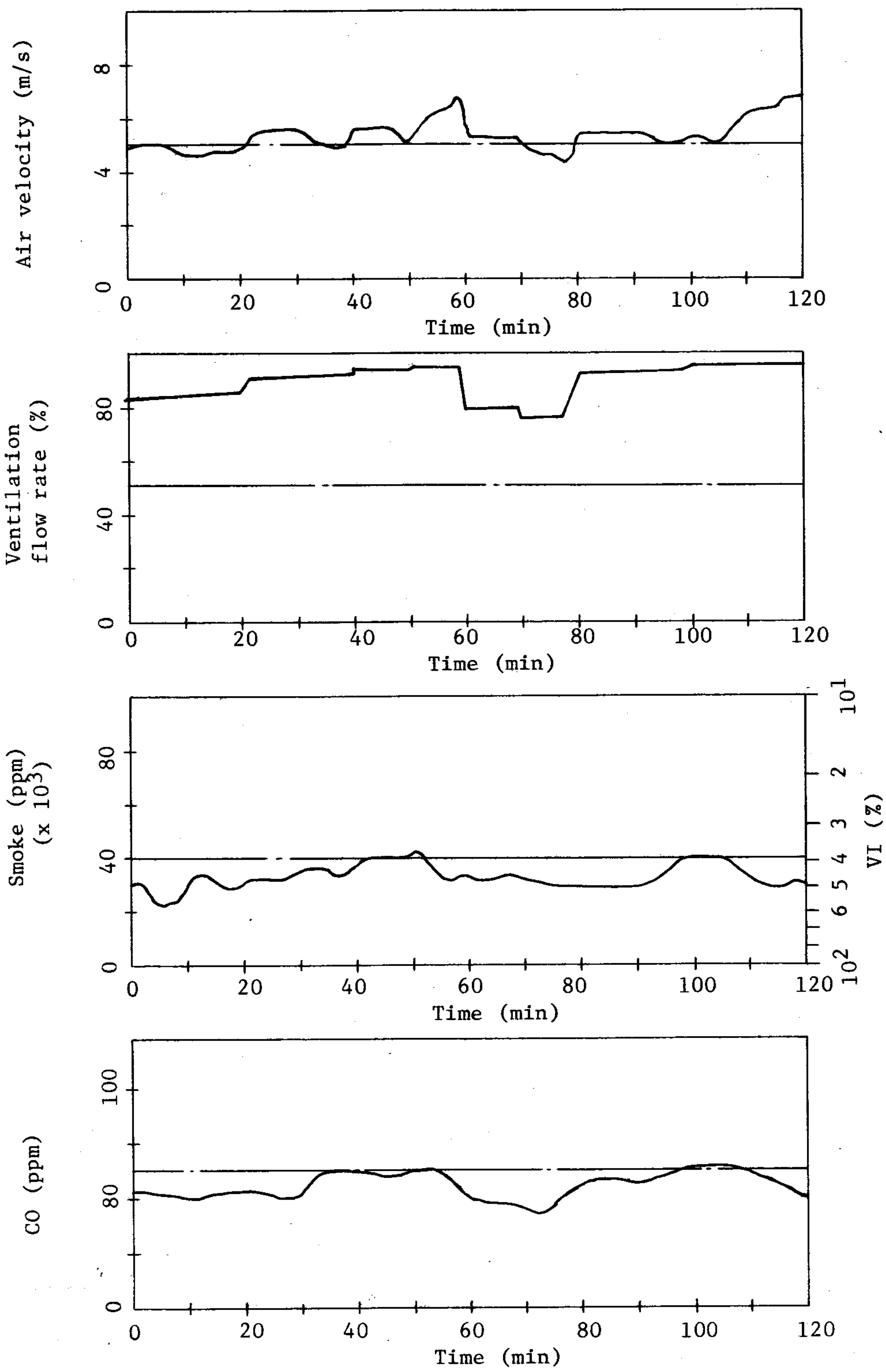

Fig. 9 Simulation results of the proposed optimum regulator system.