Is the ventilation control for longitudinal system difficult?

Akisato MIZUNO and Tomoaki OKUBO,
Kogakuin University, Tokyo, Japan

ABSTRACT

By adopting longitudinal ventilation system, construction costs as well as running costs are considered to be reduced. However, it is important to notice that the response time is much larger in the longitudinal system, while a transverse system has less delay. The present work is to clarify the basic characteristics of the longitudinal ventilation system as an object of control. In a numerical simulation, the authors have applied four operation strategies; no operation of jet fans, full operation, feedback control and feed forward control. Detailed consideration is given to the simulation results, how the control performance is affected by control method. The control allowing negative ventilation flow is also simulated, and it is presented that the possibility of a practical application exists. By applying the evaluation function to the simulation results, it is shown that the function can give objective indices for the performance of control. The feed forward control is found to be most suitable for the longitudinal ventilation system.

1 INTRODUCTION

Road tunnels are ventilated artificially in order to avoid accumulation of pollutants. In Japan, longitudinal ventilation systems have often been adopted in recent years even for long tunnels from the standpoint of economy, both in construction and operation. However, the control of longitudinal ventilation is considered to be more difficult for several reasons. Although various methods or algorithms are introduced for the ventilation control of longitudinal systems in order to cope with the problem, it is not yet established well, nor is the methodology of evaluation of the control defined clearly.

The present work deals with several control strategies applied to a longitudinal ventilation system, and a series of numerical simulations are carried out. The behavior of pollutant distribution under different control is observed and discussed. The evaluation function, which was defined in previous works[1],[2], is a unified parameter of pollution and ventilation cost. The function is applied to the results of simulation, with which compatibility of the control method to the ventilation system can be judged.

2 SIMULATOR FOR LONGITUDINAL VENTILATION

2.1 STRUCTURE OF THE NUMERICAL SIMULATOR

The simulator for longitudinal ventilation is basically composed of so called “Plant” and “Controller” parts, which are connected through sensor information and instruction of ventilator operation, as is shown in figure 1. The plant part describes the physical phenomena in the tunnel and includes the aerodynamic model, the pollution model, the traffic model and the ventilator model. The data are exchanged between these models according to arrow lines in the figure. The controller model acquires traffic data, visibility at both portals and air flow velocity from sensors and outputs the number of jet fans to be operated in the next control period.

2.2 AERODYNAMIC MODEL

The air in the tunnel is considered to be incompressible, and it is accelerated or decelerated according to the total force which is the summation of the natural wind force F_w, the force exerted by the jet fans F_j, the piston force due to vehicles F_t and the force by friction loss F_r. Thus the governing equation for the air flow velocity in the tunnel is derived from Newton's second law of motion as

$$m\frac{dV_r}{dt} = F_w + F_j + F_t + F_r \,. \qquad (1)$$

Detailed explanation and expressions for each term in the equation is given in reference [3].

2.3 POLLUTION MODEL

One dimensional convection diffusion equation with source term is used in order to deal with the time dependent distribution of the pollutants in the tunnel.

$$\frac{\partial c}{\partial t} + V_r \frac{\partial c}{\partial x} = D\frac{\partial^2 c}{\partial x^2} + \xi \,, \qquad (2)$$

where t is time, x distance from the portal, V_r the air flow velocity D the diffusion coefficient and ξ the production term. "c" can be the concentration of any pollutant. In the following calculations, the diffusion coefficient is set to be zero, in order to observe the contribution of the convection term more clearly.

In the present work, soot is considered as the main pollutant, which comes form the fact that diesel vehicle ratio is rather high in Japan. Other pollutants such as CO or NO_x can be also treated in the same manner. Visibility τ is related to soot concentration c with the expression

$$\tau = e^{-lc} \,, \qquad (3)$$

where l is the measurement length, which is usually 100m. From this expression it is noted that the soot density has the dimension of [1/m].

2.4 TRAFFIC MODEL

In the longitudinal ventilation system, traffic has a large influence on the air flow velocity in the tunnel, as well as to pollution in the tunnel. Therefore, the authors considered that the traffic model is crucial in carrying out realistic simulation, and the model is adopted, in which each vehicle is treated individually, using the measured actual traffic. This model is especially meaningful for the simulation of a rather short tunnel as in the current study, in which pollution distribution and wind velocity change rather quickly.

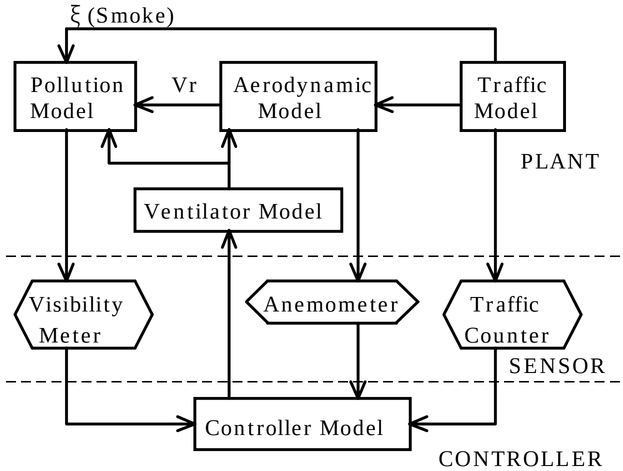


Fig. 1 Structure of the numerical simulator[3]

2.5 CONTROL MODEL

The purpose of ventilation control is to minimize the power consumption, while maintaining the allowable level of pollution in the tunnel. In order to attain it, various control algorithms are applied to the actual tunnels, which are feedback control or feed forward control, and more recently, AI(artificial intelligence) or fuzzy logic. In the present paper, feedback control and feed forward control are introduced to the simulator as fundamental means of control, with which the consideration of the problem in control for the longitudinal system can be derived.

2.5.1 FEEDBACK CONTROL

In the present feedback control, the authors defined that the necessary number of jet fans to be operated is decided from two aspects of tunnel situation, which are the degree of pollution and the air flow velocity. At every control interval t_c, the number of operating jet fans for the next period is calculated based on the measured visibility τ (the worse value from the ones at both portals is taken), so that it becomes closer to the target value τ_c.

$$J^i{}_1 = J^{i-1} - K_1 \times (\tau - \tau_c) \times J_{\max} \quad , \qquad (4)$$

where i is the sequential number of the control period, and K_1 is the control gain. $J_{\max}$ is the number of jet fans installed. Here, τ_c should be decided with an enough margin, say 10% to 20%, from the allowable limit, τ_0. On the other hand, in order to avoid reverse flow, the operating jet fans

$$J^i{}_2 = J^{i-1} - K_2 \times (V_r - V_{r0}) \qquad (5)$$

are necessary. Above two numbers are compared and the larger one ($J^i = \max\left(J^i{}_1, J^i{}_2\right)$) is adopted for the next t_c period.

2.5.2 FEEDFORWARD CONTROL

In the feedback control, it was pursued to attain the necessary visibility based on the measured pollution level and the air flow velocity. However, due to large delay which is inherent in the longitudinal system, it seems to be difficult to properly respond to the change of visibility. By using the incoming traffic data, the situation can be estimated, and a better operation can be done without delay. From the estimated number of vehicles existing in the tunnel, necessary ventilation flow Q is given in the following manner.

$$Q_0 = q_0 \times N \times L \times \frac{1}{1000}, \tag{6}$$

$$Q = \{(Q_0 \times r_t \times k_{i1}) + (Q_0 \times (1 - r_t) \times k_{i2})\} \times k_h, \tag{7}$$

where q_0 is the standard ventilation flow per unit length[m^3/s/km/h], Q_0 the standard ventilation flow [m^3/s], N the estimated traffic density [veh./h], L the tunnel length[m], r_t counter traffic ratio, k_{i1} , k_{i2} the correction coefficients for inclination, k_h correction coefficient for altitude. Necessary air flow velocity $V_r = Q / A_r$ specifies the necessary number of jet fans

$$J = \frac{p_w - p_r - p_t}{p_j} \times k, \tag{8}$$

in which p_r is equivalent pressure by friction loss, p_w by natural wind, p_t by traffic force, p_j by jet fans. Here, p_r, p_t and p_j are functions of V_r. p's in the formula are the value of F's divided by the tunnel cross sectional area A_r. An extra coefficient k is multiplied in order to reduce substantial ventilation cost.

3 EVALUATION OF VENTILATION CONTROL

Maintaining the pollution in the tunnel to be under a certain level and reducing ventilation costs are contradictory. And it is difficult to define an absolute criterion of the balance of these two, while the necessity of objective evaluation seems to be rising[1],[2]. According to the authors' proposal, the evaluation function is the weighted summation of two penalties of the violation of visibility below the allowable limit, and the excessive consumption of ventilation power.

3.1 PENALTY OF POLLUTION

While the visibility is below its allowable limit $(\tau < \tau_0)$, the pollution penalty is imposed according to the degree of violation. On the other hand no penalty is imposed so long as it is in the permissible range. Thus the time averaged pollution penalty is

$$\pi_{poll} = \frac{1}{T} \int_0^T F(t)\, dt, \tag{9}$$

where

$$F(t) = 1 - \frac{\tau}{\tau_0} \qquad (\tau < \tau_0),$$
$$= 0 \qquad (\tau \geq \tau_0).$$

In this formula, visibility τ is the worse of the measured visibilities at both portals. T is the time period to be averaged over, and is decided according to the purpose of the evaluation. In the current study, T is set to 24 hours.

3.2 PENALTY OF POWER CONSUMPTION

It is not appropriate to count the power consumption directly as penalty of power, because the penalty should not be imposed to the power which is necessary for the passing traffic. The aim of the penalty is to evaluate the excessive quantity of power consumption. It is, however, not easy to divide the power to necessary and unnecessary part. Our proposal here is to put the traffic density ratio powered by an index to be the necessary minimum of the ventilation power, and the time averaged penalty of power is

$$\pi_{power} = \frac{1}{T}\int_0^T \left\{ \frac{P}{P_0} - \left(\frac{N_d}{N_{d0}} \right)^j \right\} dt , \tag{10}$$

in which P is the power for ventilation, P_0 the total power of the installed ventilators, N_d the traffic density of diesel vehicles, N_{d0} the design value of N_d.

3.3 UNIFICATION OF THE PENALTIES

Let us consider how the above two penalties can be summarized. Although in the current definitions in equations (9) and (10), it does not seem to be necessary to convert the dimensions because the both are non-dimensional, it becomes necessary to adjust the dimensions of both terms, in a more general case. The conversion parameter b is necessary for this purpose. The other parameter a $(0 \le a \le 1)$ is introduced in order to define the balance of importance of the two penalties. a should be a larger value when the pollution level is considered to be more important, while it would take a smaller value when the cost of power becomes higher concern due to the reasons such as boosting of the oil price.

$$\pi_{total} = a\pi_{poll} + b(1-a)\pi_{power} . \tag{11}$$

The summarized penalty π_{total} is the proposed value for evaluation.

4 SIMULATION CONDITIONS

4.1 THE OBJECT TUNNEL

As the object of numerical simulation, a longitudinally ventilated tunnel is selected, which is the Oyama tunnel. The tunnel has two lanes for two-way traffic with the length of 1,722m, driven with 18 jet fans. This ventilation system is designed under the condition of traffic density 1,850 [veh./h] with the speed of 60 km/h. The ratio of heavy duty vehicles with diesel motors is supposed to be 35.3%. This tunnel is selected as the object of simulation, because it has a jet fan driven simple ventilation system with proper length. Figure 2 shows the configuration of the tunnel. It is equipped with an anemometer and visibility meters close to both (east and west) portals.

4.2 TRAFFIC DATA

The simulator of ventilation control which is prepared for the present study uses the traffic data in the form that the entrance time of each vehicle is described, with which higher reality and reproductivity is aimed. The entrance timings of the cars are from the data obtained from traffic counters located in a similar condition to the one considered in the simulation. 24 hours are simulated upon the traffic data taken on July 29, 1996. Figures 3(a) and 3(b) show the traffic density in both directions used, whereby the ordinate is the number of vehicles existing in the tunnel. The strength of emission from each heavy duty vehicle is decided by random numbers, keeping the average and deviation to be the values of our design standard.

The effect of natural wind is neglected in the following simulation cases.

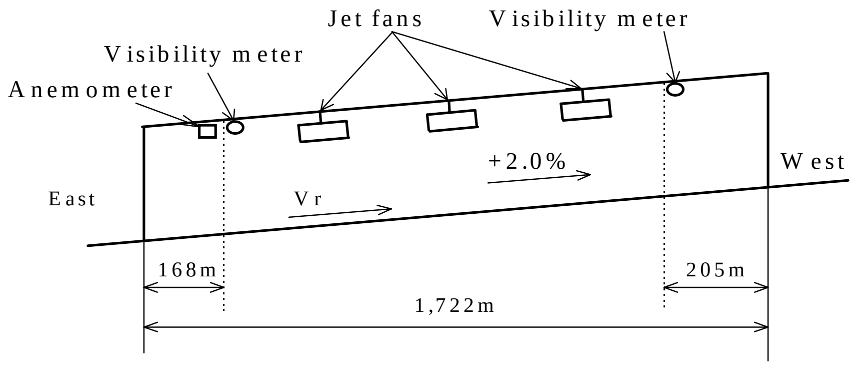
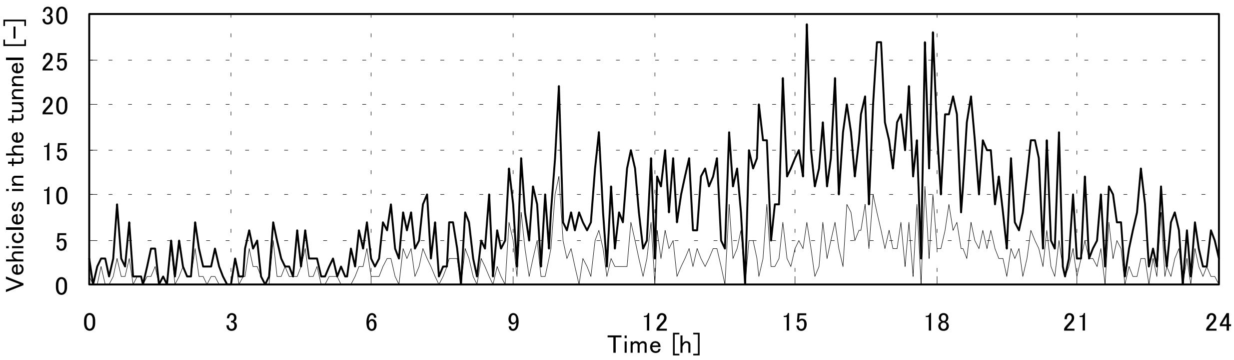
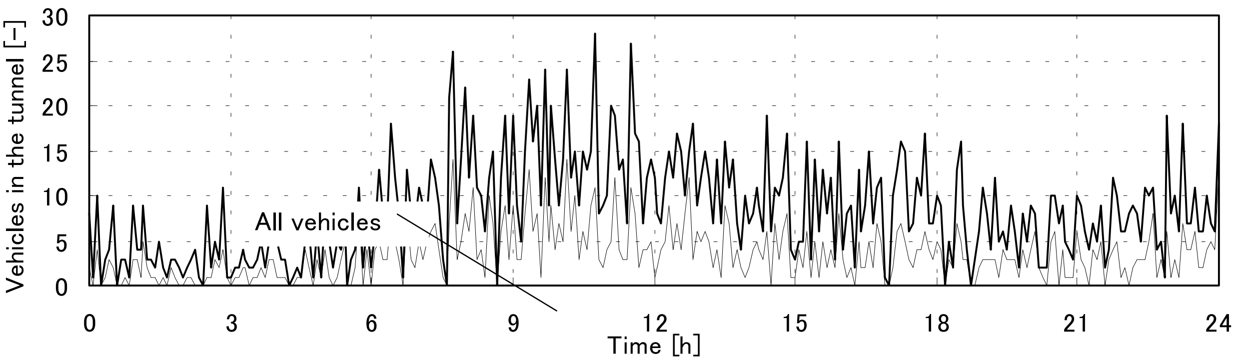


Fig. 2 Oyama Tunnel



(a) West bound traffic



(b) East bound traffic

Fig. 3 Traffic density

5 BEHAVIOR OF VISIBILITY UNDER VARIOUS OPERATIONS

Heavy duty vehicles

The following four operation strategies are introduced in the simulation.

Case 1: No operation of jet fans.

Case 2: Full operation of jet fans.

Case 3: Fe All vehicles l.

Case 4: Feed forward control.

The explanation for each case follows:

5.1 CASE 1

The jet fans are not operated during the simulated 24 hours. Figure 4 shows the result of the simulation for this case. The figure 4(a) shows the visibility, and 4(b) the wind velocity in the tunnel. The air flow in the tunnel is solely dependent on the piston effect of the traffic. Until around noon the flow direction is negative, while it turns to positive due to the west bound/east bou Heavy duty vehicles ally of heavy duty vehicles. As the traffic is not sufficiently heavy, the visibility does not exceed the allowable limit at all from midnight to 1100h. On the other hand the traffic grows heavier and the violation occurs around noon and 1800h, and the worst visibility reaches to about 20%.

5.2 CASE 2

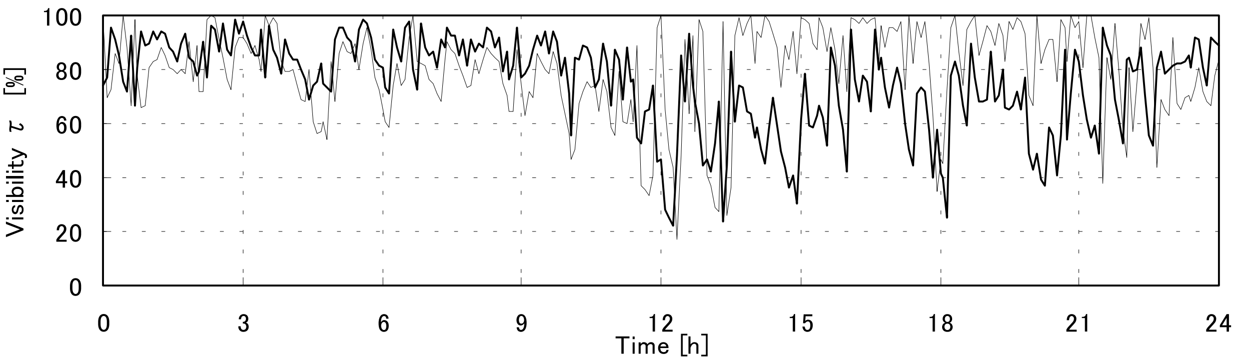
When all of the 18 jet fans are fully operated during the 24 hours, the visibility is maintained mostly above 80 %, and the air velocity is also kept in a high value between 4 to 12 m/s, as shown in figure 5. It is obvious that this is an ideal operation in view of visibility in the tunnel if economy is not taken into account.

5.3 CASE 3

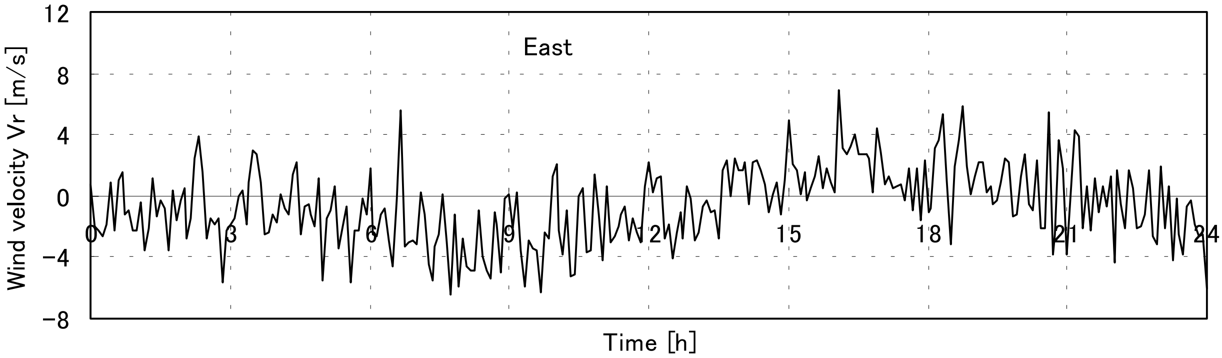
Under the feedback control enforced every 5 minutes (t_c) by formula (4) and (5), simulation was carried out, obtaining the results as in figure 6. The target value τ_c was decided to 60% after trial calculations, including evaluation of the results. From midnight to 0600h, jet fans are operated to compensate the negative air flow due to heavier east bound traffic (eq.(5)). After 0900h, the visibility comes down below 60%, and the jet fans are employed due to eq. (4), as the feedback of visibility. From 1800h to 2100h, west bound traffic is dominant, and the jet fans are in operation only when the visibility exceeds the limit.

5.4 CASE 4

Now the result by the feed forward control is discussed. As is shown in figure 7, very few jet fans are operated between midnight and 0600h because the traffic is not heavy. Around 0700h, the visibility exceeds the limit, while about half of the jet fans are employed. Between 1500h and 1800h, more jet fans are operated than in the former case. These two phenomena comes from that the ventilation operation is decided from the estimated (heavy/normal) vehicles in the tunnel, and the mean emission is used in the calculation of jet fan operation. In spite of these observations, total consumption of power is less than the one in the former case (case 3), as will be discussed later in further detail. In eq.(8), k is set to 0.8, because over operation is observed when it is 1.0.

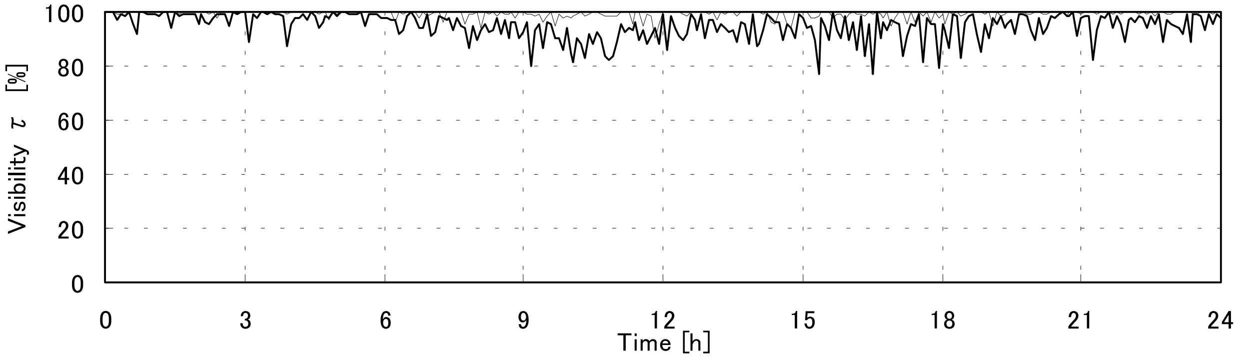


(a) Visibility

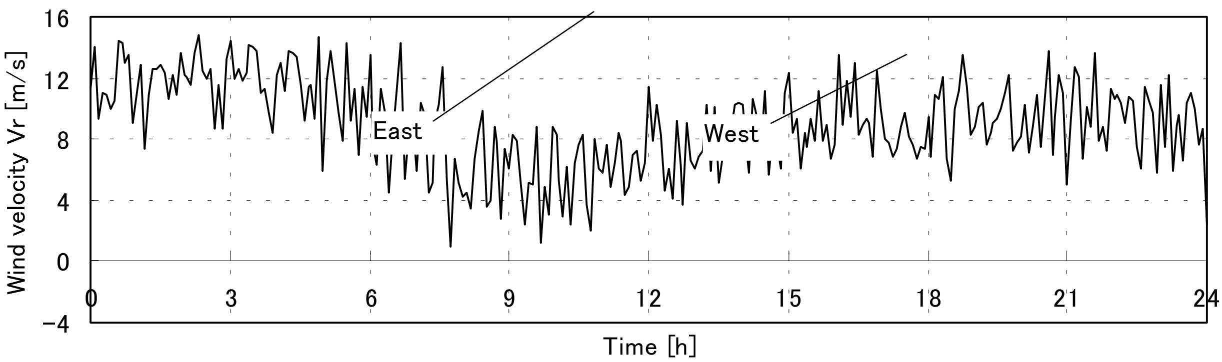


(b) Wind velocity

Fig. 4 Temporal variation of visibility, wind velocity under no jet fan operation. (case 1)

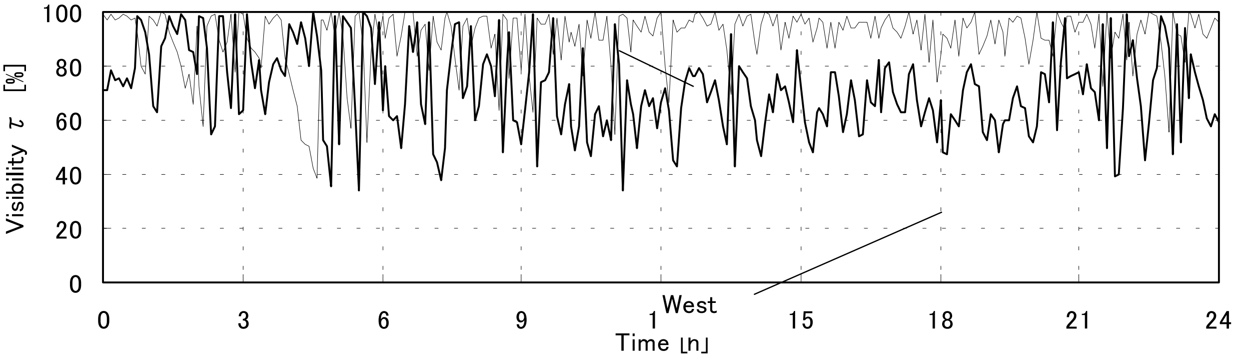


(a) visibility

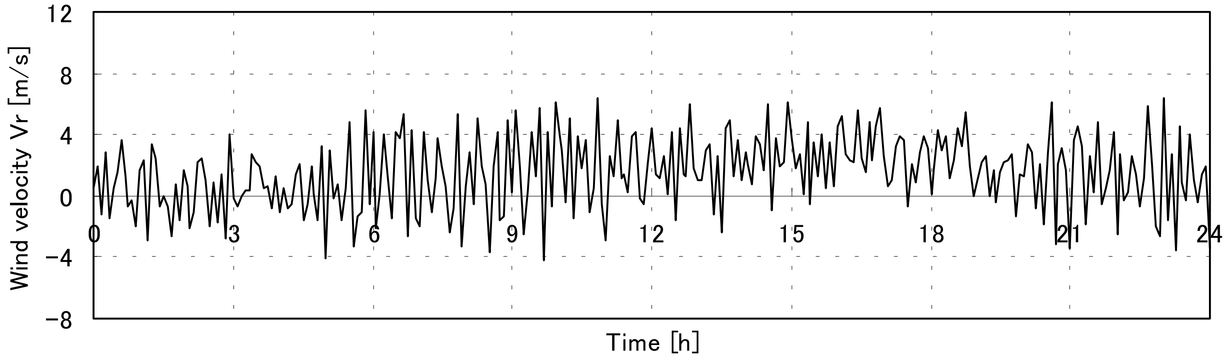


(b) Wind velocity

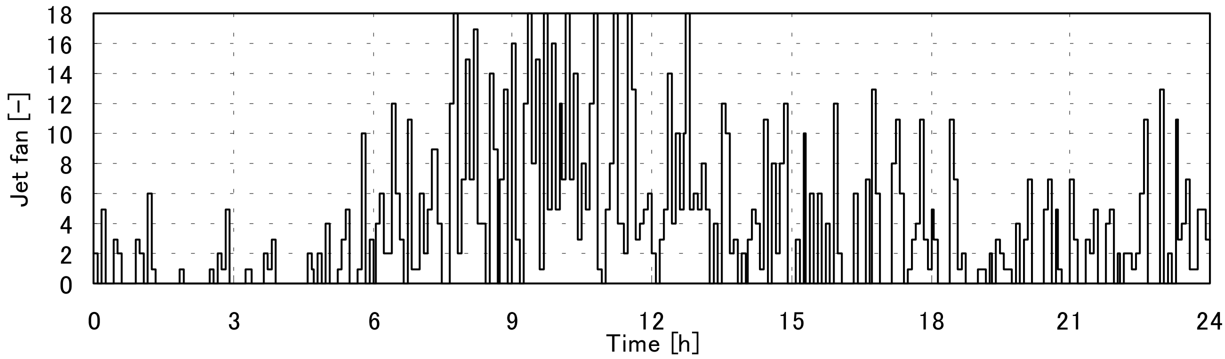
Fig. 5 Temporal variation of visibility, wind velocity under full jet fans operation. (case 2)



(a) Visibility

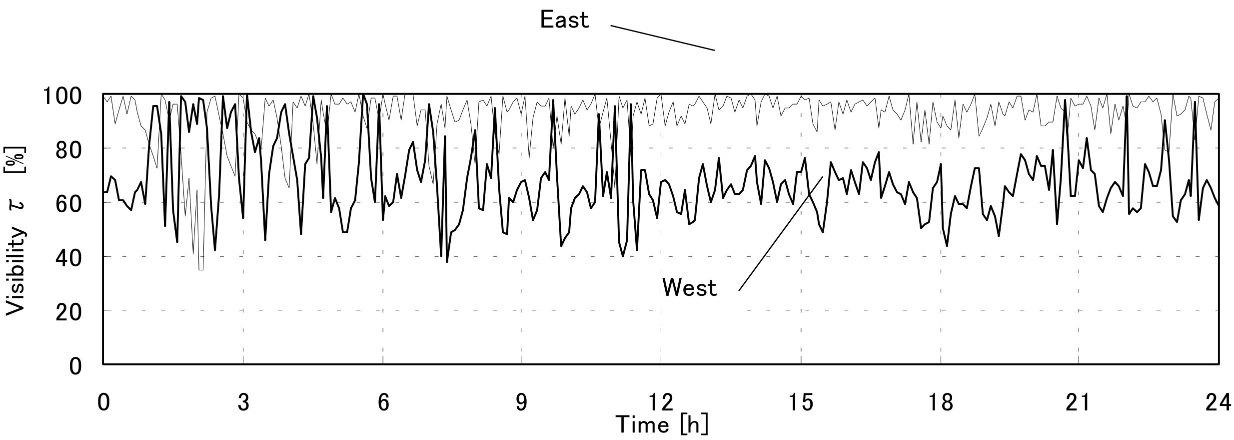


(b) Wind velocity

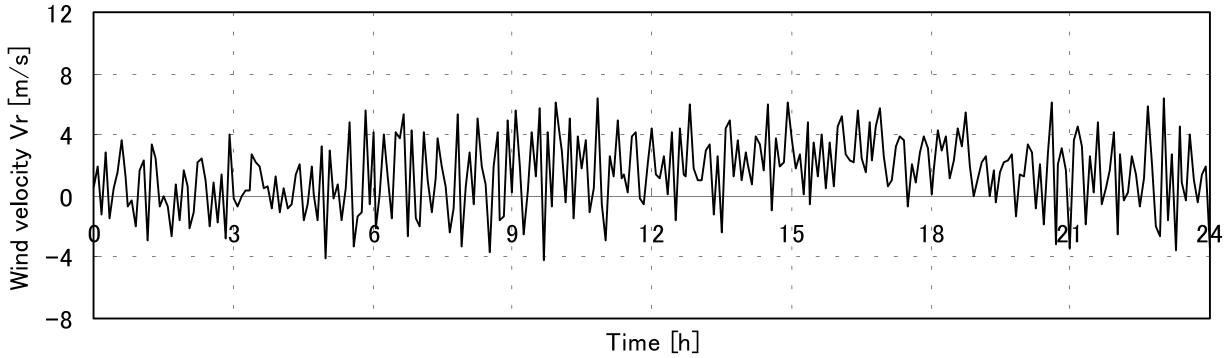


(c) Jet fan

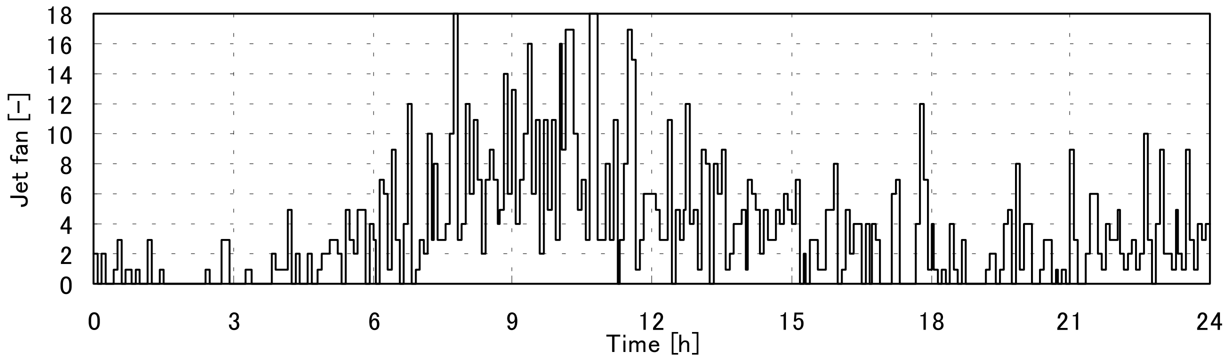
Fig. 6 Temporal variation of visibility, wind velocity and jet fan operation under feedback control. (case 3)



(a) Visibility



(b) Wind velocity



(c) Jet fan

Fig. 7 Temporal variation of visibility, wind velocity and jet fan operation under feed forward control. (case 4)

6 PARAMETERS FOR EVALUATION

In order to apply the evaluation function to the above results, it is necessary to set the parameters a and b in the formula (11). The conversion factor is 1, because both penalties are non-dimensionalized, and not necessary to convert in the present case. After some trial in case 4 presented above, the weighting parameter is fixed to be 0.9. As is stated earlier, the weighting parameter is set from the consideration of the balance between the pollution level and economy. The value 0.9 is the one which requires higher quality of air rather than power consumption. $a = 0.9$ and $b = 1.0$ is used for evaluation of all the cases in the next section.

7 CONSIDERATION

7.1 PROBLEMS AND COUNTERMEASURE

In Japan, longitudinal ventilation system has been adopted even for long tunnels on the inter-city highways for more than ten years, even for temporarily two-way tunnels. This period was synchronized with the wide spread application of digital control. The authors have pointed out that the control of longitudinal system is more difficult and a part of the saved cost of construction should be used for study and development of proper control method. Actually, when the pollution is detected at the exit portal, the block of polluted air is going out of the tunnel, which means the feedback control is not appropriate in principle. In the longitudinal system, traffic causes pollutant emission, while having a large affect on the air flow in the tunnel. A favorable control scheme should be constructed with these various characteristics taken into account. So far, the longitudinal system can be said to be more difficult to control, in comparison to transverse system.

In the feedback control, larger deviation of pollutant density is inevitable caused by the intrinsic character of the longitudinal ventilation system. It means that the target value of control has to be set with a larger margin from the allowable limit.

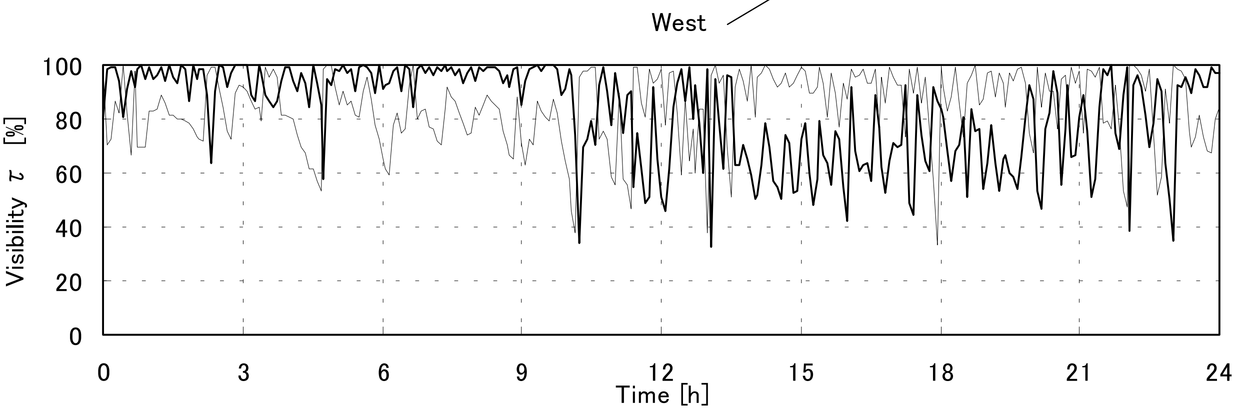
The feed forward control is more suitable for the longitudinal system from the consideration of the dynamic characteristic of the system. By using this control, necessary power should in principle coincide with the second term of the evaluation function of the penalty of power. The evaluation is not dramatically better in comparison to other control schemes for some reasons, such as deviation of pollution emission or unsteadiness of the phenomena. In spite of that, according to the authors' opinion, the basic concept of the feed forward control seems to be promising, and the improvement is expected by combining with more sophisticated schemes.

7.2 CONTROL ALLOWING NEGATIVE VENTILATION FLOW

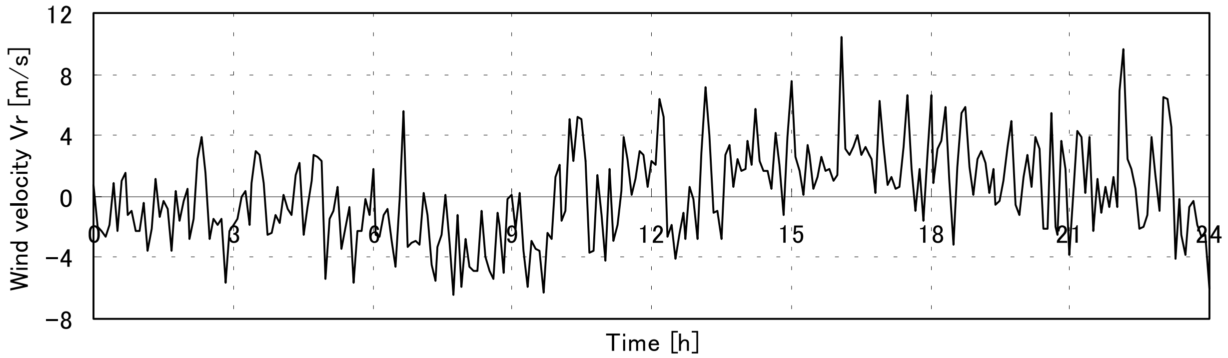
The feedback control based only on the visibilities at both portals is applied to the system, in which the air flow velocity is not referred (case 5; shown in figure 8), namely the formula (4) is used without adding (5). The target value τ_c is also 60%. Usually it is considered that the ventilation direction is fixed in a longitudinal system, because a heavily polluted condition can occur at the switch-over of the wind direction. The most remarkable difference occurs from midnight to 1000h, where almost no operation is required. It is observed that the reverse air flow caused by the traffic can ventilate the emission. Although the air flow direction changes several times during the whole simulation period, no serious problem seems to have occurred, except that short term swings of low visibility have happened. Although a lot of study should be required until "free directional longitudinal ventilation system" is established and become practically applicable, the authors could show the possibility under the simulation conditions.

7.3 APPLICATION OF THE EVALUATION FUNCTION

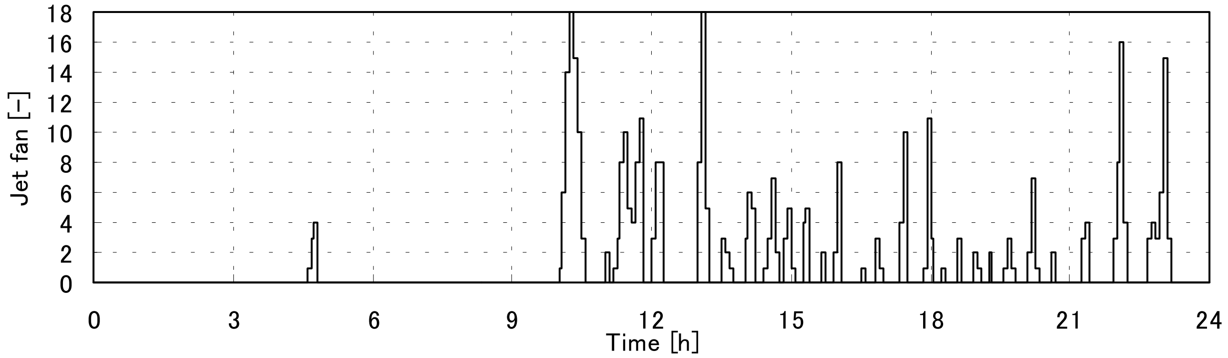
The evaluation function described in section 3 is applied to the simulation results obtained from section 5 over the 24 hours concerned. The penalty of visibility violation and excessive consumption of power are summed up with the parameters of $a = 0.9$ and $b = 1.0$, giving table 1. Allowable level τ_0 is set to 40 %, and the power to be $j = 2$. Case 1 (no operation) shows the largest penalty in visibility while no penalty on power. On the contrary, the full operation leads to zero penalty of pollution and the largest penalty of power, which is quite understandable. In the present situation, case 1 attains much better evaluation, as the traffic is not too heavy. In case 3 and 4, the target value or the coefficient are adjusted so that the best performance is attained. The overall penalty in case 4 (feed forward) is significantly lower in comparison to the one in case 3.



(a) Visibility



(b) Wind velocity



(c) Jet fan

Fig. 8 Temporal variation of visibility, wind velocity and jet fan operation.
(case 5)

Table 1 Penalty

	Penalty on visibility	Penalty on power	Total penalty
case1	0.01867	0.0	0.0168
case2	0.0	0.841	0.0841
case3	0.0017	0.136	0.0152
case4	0.0015	0.094	0.0108
case5	0.0020	0.035	0.0053

8 CONCLUSION

A longitudinal ventilation and its control for a road tunnel driven by jet fans are numerically simulated. Four operation strategies are applied to the system; no operation of jet fans, full operation, feedback control and feed forward control. The followings can be stated from the simulation results under the traffic data of a 24 hour period. Although the simulation would give slightly different results if the hypothetical conditions such as tunnel length, traffic data, etc. are replaced with others, the authors consider the general property will not change largely.

Even with feedback or feed forward control, the deviation range is rather large, and a margin of some 20% is found to be necessary in order to keep the visibility to be above the allowable level. It is considered that a smaller margin could be possible for a transverse system from consideration of the difference in ventilation principle.

By applying the evaluation function to the simulation results, the penalties of pollution and excessive power are obtained as well as the total penalties. As the traffic is not heavy under the situation supposed in the simulation, the no operation case marked a much better point than the full operation case. Feed forward control showed a better result than feedback control, but the difference is not as remarkable as the authors have expected. From the viewpoint of ventilation principle, the feed forward control is recommended as the basis of further improvement.

Test simulation was carried out for the case in which reverse air flow is allowed, which is not the case at present for the longitudinal ventilation. It showed a remarkable performance in terms of the present evaluation method. Although more study is needed, the authors could show the possibility of applying this concept to the tunnels with certain conditions.

REFERENCES

[1] A. Mizuno et al., “Evaluation of the Performance of Control of the Road Tunnel Ventilation,” Proc of the 8th ISAVVT, Liverpool 1994, pp. 903-917.

[2] A. Mizuno, “Necessity of Evaluation of Ventilation Control and its Future Prospect,” Proc. Of the First ICTCC, Basel 1994, pp. 195-201.
[3] H. Ohashi at al., “A New Ventilation Method for the Kan-etsu Road Tunnel,” Proc. of 4th ISAVVT, York 1982, pp. 31-47.