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Evaluation of the Performance of Control of the Road Tunnel Ventilation

Akisato MIZUNO: Kogakuin University
Yoshihiro HIRUKAWA: Kogakuin University
Shinji EMOTO: Kogakuin University
Hideo OHASHI: Kogakuin University

Abstract

In tunnel ventilation, the clearness of the air, which corresponds to the degree of safety and amenity to the drivers, and economy are contradictory. Hence it can be stated that the purpose of ventilation control is to keep the required pollution level with minimum consumption of energy. But as the object of control, tunnel ventilation has large disturbances caused by discharge of pollutants, traffic forces etc., which affect especially strongly to longitudinal ventilation. It means that if one tries to reduce cost, and keeps the concentration level close to the critical one, it will often violate the prescribed limit. Under these situations, the authors have felt the necessity of establishing the quantitative and objective means to evaluate the performance of ventilation control. It is supposed that an evaluation function can be defined which expresses the balance of pollution and economy. And the function will be the summation of penalties both in violation of the pollution level and in excessive power consumption for ventilation. The authors propose a concrete formulation of evaluation function and apply it to the numerically simulated data in order to observe if it behaves reasonably.

1. Introduction

Road tunnels are ventilated in order to dilute pollutants emitted from vehicles. In Japan, soot is often the object of control due to being high concentration of Diesel vehicles. The allowable level of pollutant concentration in the tunnel will be determined from the viewpoint of driving circumstances, namely through consideration of safety and amenity. It is not desirable, however, to ventilate too much because of too much power consumption. The purpose of control of tunnel ventilation is therefore to maintain the quality of circumstances in the tunnel, while trying to reduce power consumption. As the clearness of air and the energy consumed are contradictory, it is necessary to have a measure in order to evaluate objectively and quantitatively how properly the ventilation is controlled. For this purpose an evaluation function has to be defined.

According to the authors' opinion, it is essential to establish a numerical simulator for the test of evaluation function for two reasons; firstly because the definition of an evaluation function is not an easy work to do including cut-and-try procedure, and also because the reproductivity in testing the function is important. The authors have developed a numerical simulator to describe ordinary ventilation situation. Special attention is paid in the traffic model so that the simulator is realistic enough in expressing the behavior of smoke distribution in the tunnel. The traffic model used in former research[1] is based on so called "macro model", and could not express detailed traffic situation affecting the fluctuation of pollutant distribution in the tunnel. In using the improved model, the traffic data is prepared from the video recording taken at an overbridge over an actual highway.

The authors propose an evaluation function in the simplest form, which combines two different parameters with different dimensions; the degree of pollution and the power consumption. Each item is expressed with corresponding penalty function, and added into a single function with specified weighting coefficients multiplied. By setting different values of control target, the basic characteristics of the function is illustrated. The meaning of the evaluation function can be discussed more easily through simulations under same traffic condition and same control algorithm.

2. TTB Tunnel as a Simulation Model

The Trans-Tokyo-Bay Tunnel (TTB Tunnel) is the undersea tunnel connecting two cities of Kawasaki and Kisarazu. It is now under construction and will be completed in 1997. In the current study, TTB Tunnel is selected as the object of analysis, because it is a longitudinally ventilated tunnel with various elements such as jet fans, ventilators at the vertical shaft and electrostatic precipitator (EP) stations (see fig. 1). The tunnel has two tubes and each of them is served for one way traffic. Total length of the tunnel is 9,547 m, and the cross sectional area of the traffic room is 78.4 m^2. At the center of the tunnel (at the manmade island), there is a vertical shaft station, dividing the two sections, where the polluted air is replaced with the fresh one by 100 %. In addition, 31 jet fans and 7 EP stations are equipped. Visibility meters and anemometers are installed at each division.

3. Structure of the Numerical Simulator

The structure of the numerical simulator developed in the current research is schematically shown in fig. 2. It consists of a plant part and a controller part. The former is made of aerodynamic model, pollution model, traffic model and ventilator model. The two parts are combined through sensors of visibility, air velocity etc.

The aerodynamic model describes the acceleration of the air flow in the tunnel, under assumption of incompressibility. The ordinary differential equations are solved numerically to solve the air flow velocities at each division with a time step of one second. For detailed formulation, see authors' former work[2]. Two equations for each division are connected according to principle of mass conservation and continuity of pressure at the vertical shaft.

The pollution model solves the time dependent soot distribution in space in terms of analyzing one dimensional convection diffusion equation. The partial differential equation is converted to difference equation with a time step of one second and a spatial segment of 10 m. In the current study the diffusion effect is suppressed in order to avoid the result to be ambiguous. The objects of analysis are soot and carbon monoxide, but the discussion is focused mainly on soot for simplicity.

The traffic model is the one which is newly developed by the authors for the current study so that it can describe much more realistic phenomena than ever. Until now, the expression of traffic has been in the form of difference equation, in which the traffic is averaged in the sub-grid, which makes it difficult to express realistic traffic. In the current work, the vehicle is modeled one by one, being identified by its exact time of entrance to the tunnel. The traffic data is made from video recording on an actual highway with similar traffic density desired in the analysis. The vehicles are categorized to large diesel ones and small gasoline ones. The vehicles are supposed to go in a constant speed in the tunnel, emitting pollutants with a value modified by the coefficient of inclination.

4. Results of Model Simulations

Fig. 3 shows a simulation result, using the traffic data composed from actual traffic by video recording. The ventilators are operated constantly. The soot density is expressed in extinction coefficient. The peaks observed around t=60 min. are caused by dense traffic of large diesel vehicles passing at the location of the visibility meters. The distance between the peaks corresponds to the one calculated from the speed of vehicles. Fig. 4 is the three dimensional illustration of the soot concentration in space and time, with which the speed of convection is confirmed to be in the speed of vehicles. This can be understood more clearly through comparison between fig. 5 and fig. 6, which are spatial distribution with the time difference of 5 min.. Obvious drop at the center of the tunnel is caused by the exchange of polluted and fresh air at the vertical shaft station.

In the next two simulation cases, the effect of feedback control is observed. In these cases, the traffic data is different from the one used in case 1. Under full load operation of ventilation, the result shows as in fig. 7 (case 2). A simple feedback control is applied in the same traffic condition, which is shown in fig. 8 (case 3). The target value of control is set to $\tau_c = 55$ %, and very little violation above the allowable level of $\tau_0 = 50$ % is observed, except in the first 20 min., where the initial conditions of the simulation still have influence. It is observed from the figure that the fluctuation of the soot density is limited in a smaller range in comparison to the constant operation case (fig. 7). In this control scheme, the operation of vertical shaft fans, jet fans and EPs are set to be proportional, and the control period is 5 min.. In the actual control, a more sophisticated combination of ventilators will be introduced in view of economy.

The comparison between fig. 7 and fig. 8 shows that a reasonable control is performed in fig. 8, in that less power consumption is attained at sacrifice of very little violation in soot density.

Through these simulations, it is confirmed that the simulator is realistic to describe the fluctuation of pollutant distribution in the tunnel, compared to conventional simulators developed earlier[1].

5. Evaluation of Ventilation Control

It is idealistic if the tunnel ventilation is controlled in the way that clear circumstances are achieved with little power consumption. But the level of clearness and the economy are contradictory, and we have to find out a point where they are reasonably compromised. Therefore, if one wants to evaluate the performance of ventilation control quantitatively and objectively, it is necessary to establish a measure to unify these two contradictory factors to form an evaluation function. It will also help the development of new control algorithms. The penalties based on two viewpoints are introduced as in the followings.

Visual Circumstances The ventilation control is executed in order to keep the pollution level to be at or around a certain target value, which is lower than the allowable limit, because the pollution level has pretty much fluctuation. As the index to evaluate the degree of pollution, penalty is imposed proportional to the variation of actual visibility to the allowable limit, only when the visibility is worse than the limit. When the visibility is better than the limit, no penalty is imposed. The time averaged penalty using visibility τ

$$\pi_{poll} = \frac{1}{T}\int_0^T F(t)\,dt, \text{ where } F(t) = \begin{cases} \tau_0 - \tau(t) & \text{for } \tau(t) < \tau_0 \\ 0 & \text{for } \tau(t) \geq \tau_0 \end{cases} \qquad (1)$$

is used in the later unification.

Power Consumption The total power of operated ventilators at each time is normalized by the power of the total ventilation facilities. The ratio is also averaged by time to become the penalty of the power consumption.

$$\pi_{power} = \frac{1}{T}\int_0^T \frac{P(t)}{P_0}\,dt \qquad (2)$$

More sophisticated functions can be proposed in view of necessary power corresponding to traffic density. It means that low energy consumption is not properly evaluated in the current formulation when the traffic density is in low level. The current discussion is limited to the simplest formulation shown in eq. (2).

Unification of the Penalties For getting a measure of evaluation, the above two penalties are combined as

$$\pi_{total} = a\pi_{poll} + (1-a)b\pi_{power}, \qquad (3)$$

in which a is the weighting parameter and b denotes the conversion coefficient between the two different quantity in different physical dimensions. (In the present case both happen to be non-dimensional.)

Sample calculations are performed with different target values of control (50 %, 55 % and 60 %), with a common feedback control algorithm. Visibility and the power are shown from in fig. 9 through fig. 11, for which the latter hour is subjected to the evaluation in order to avoid the influence of initial conditions. The visibilities are converted from the soot density (extinction factor) by means of exponent function. The variation of penalties is shown in fig. 12 using the same scale ($a = 0.5, b = 1$). The summation (solid line) shows a bottom at the target value of around 56 percent. It means that it is recommendable to set the target value of ventilation control to be at the value under assumed weighting parameters.

6. Conclusion

The evaluation of ventilation control is discussed by means of numerical simulation, which has been improved to be able to express realistic traffic and emission of pollutants. The process of decision making of the target value of control is suggested in terms of systematic consideration proposed in the study. The measure of evaluation can have a wide variety of alternatives in taking various elements into account, but in the present study, a simplest evaluation function is presented for better understanding. In unifying the two functions with different dimensions, a weighting parameter and a conversion factor are introduced, which is to be decided according to overall consideration. The parameter is also affected by economic situation such as oil price. When the oil price hikes, a less clear circumstance in the tunnel may be imposed to the drivers, and a smaller parameter of a should be adopted.

The authors wish to induce open discussion on the necessity of establishing the measure of evaluation of ventilation control. The evaluation function is not easy to define for multiple purposes applicable for various tunnels. It is hoped that the study on this problem is encouraged in the future triggered by the paper.

References

[1] Ohashi, H. et al, "A new ventilation method for the Kan-etsu road tunnel", *Proc. 4th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels* (York, U.K., Mar. 23–25, 1982), Cranfield, U.K., BHRA Fluid Engineering Centre, 1982, pp.31–47.

[2] Mizuno, A. et al, "The emergency control of ventilation for the Trans-Tokyo-Bay Tunnel", *Proc. 7th International Symposium on the Aerodynamics and Ventilation of Vehicle tunnels* (Brighton, U.K., Nov. 27–29, 1991), Cranfield, U.K., BHR Group Ltd., 1991, pp.365-384.

Nomenclature

a	[–]	Weighting parameter.
b	[–]	Conversion parameter.
P	[–]	Power for ventilation (function of time).
P_0	[–]	Total power of the ventilation facilities.
t	[s]	Time.
T	[s]	Reference time period in which values are averaged.
π_{poll}	[–]	Averaged penalty on pollution.
π_{power}	[–]	Averaged penalty on power consumption.
π_{total}	[–]	Summation of two penalties with weighting parameters.
τ	[–]	Visibility of 100 m distance.
τ_0	[–]	Allowable limit of visibility.
τ_c	[–]	Target value of visibility in control.

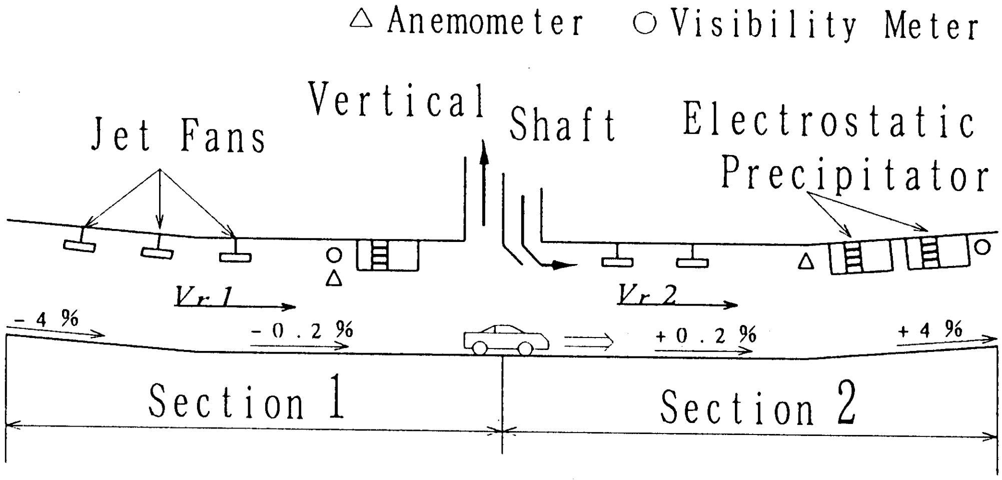

Fig. 1: Ventilation system of the Trans-Tokyo-Bay Tunnel

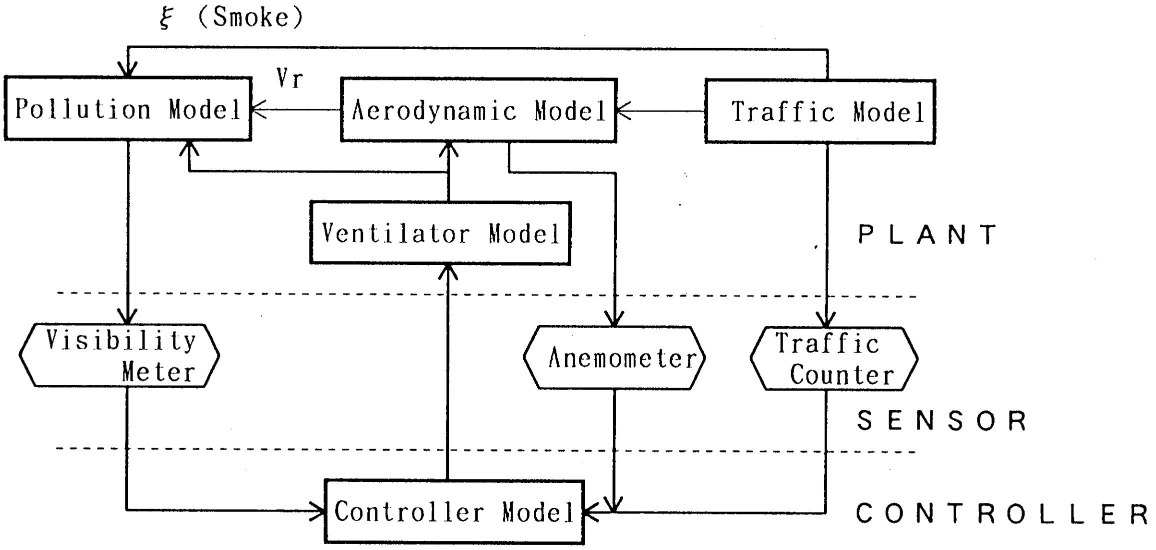

Fig. 2: Structure of the numerical simulator

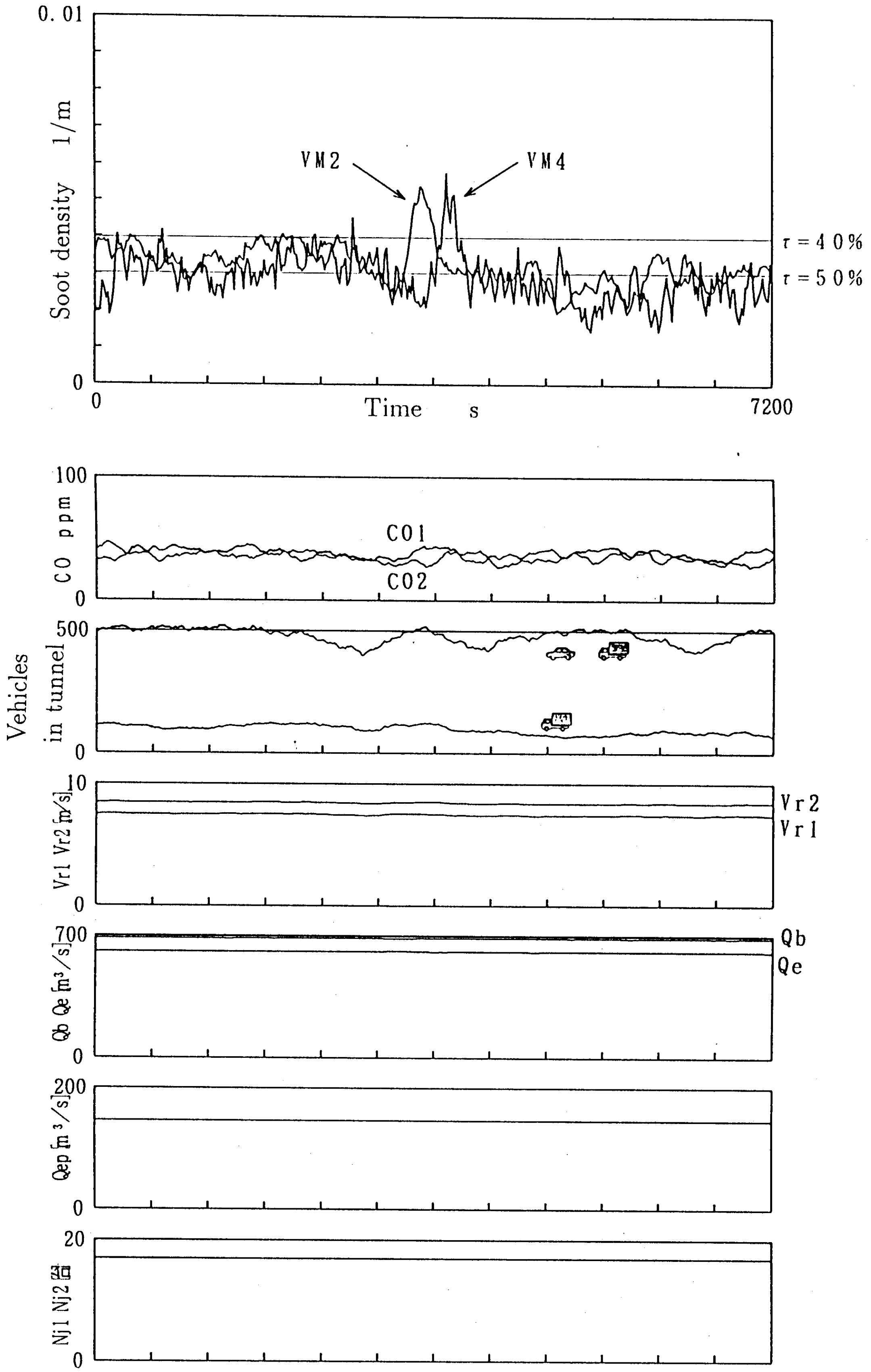

Fig. 3: Temporal variation of soot density under constant operation of ventilation (case 1)

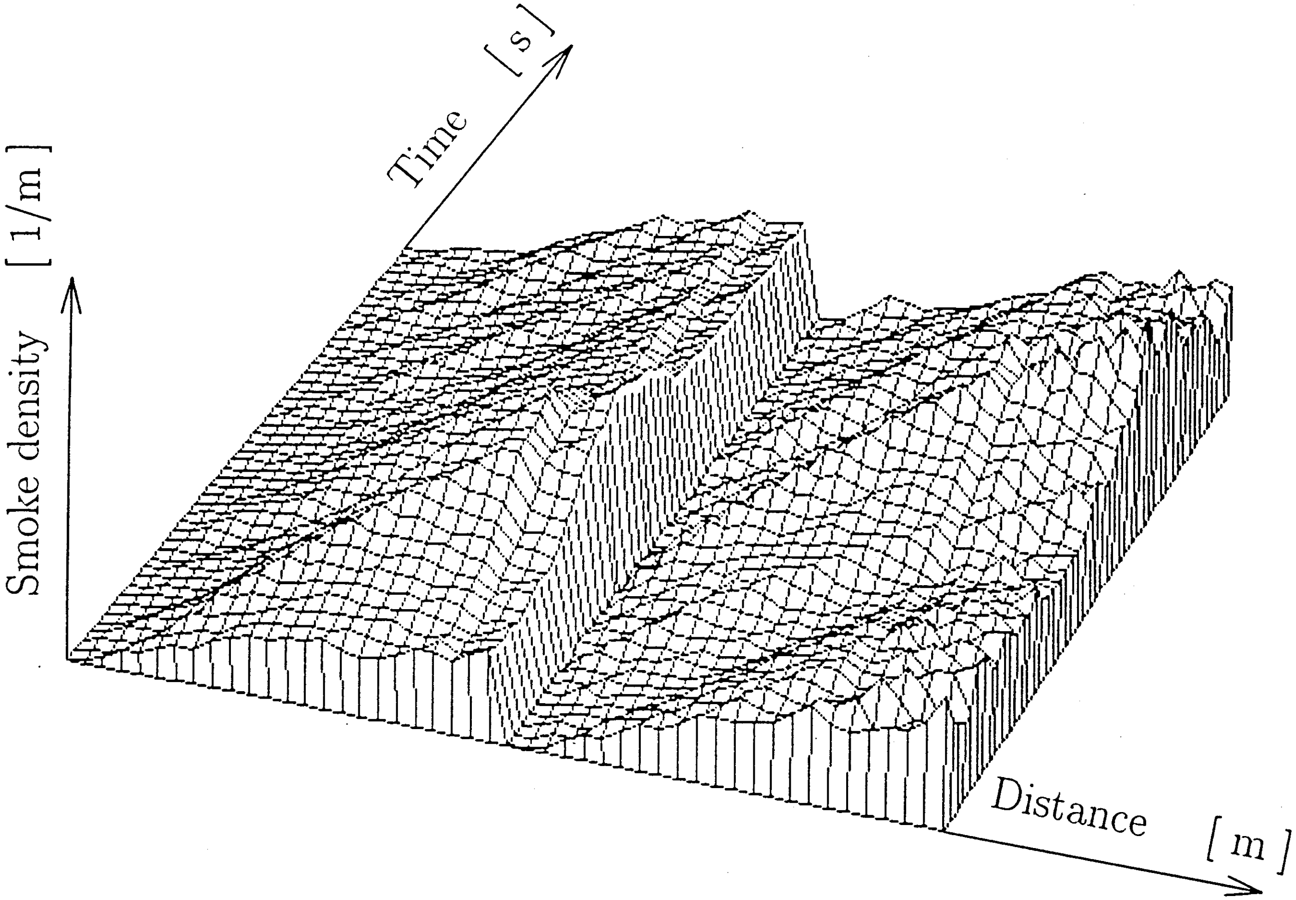

Fig. 4: Three dimensional illustration of density distribution in time and space ($t \geq 3000$ s, case 1)

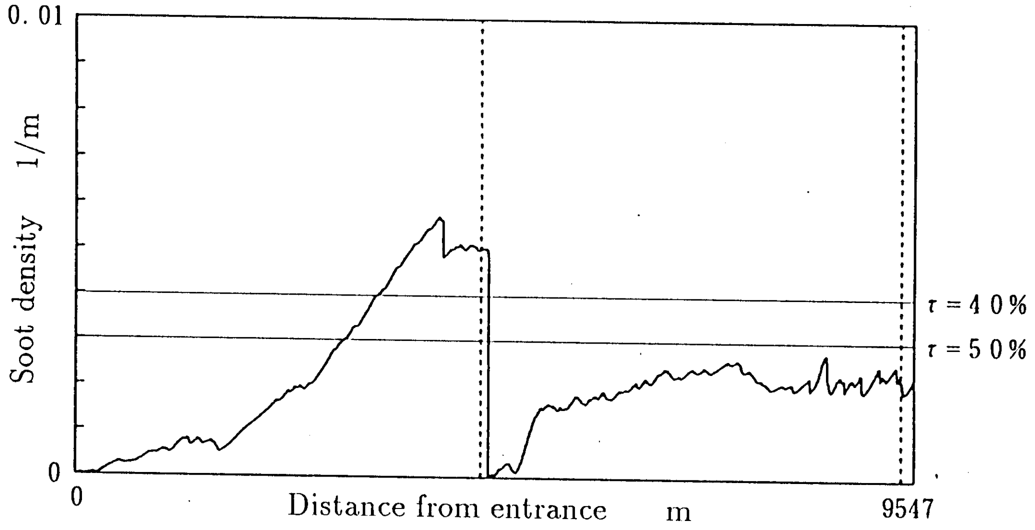

Fig. 5: Spatial distribution of soot density
($t = 3440$ s, case 1)

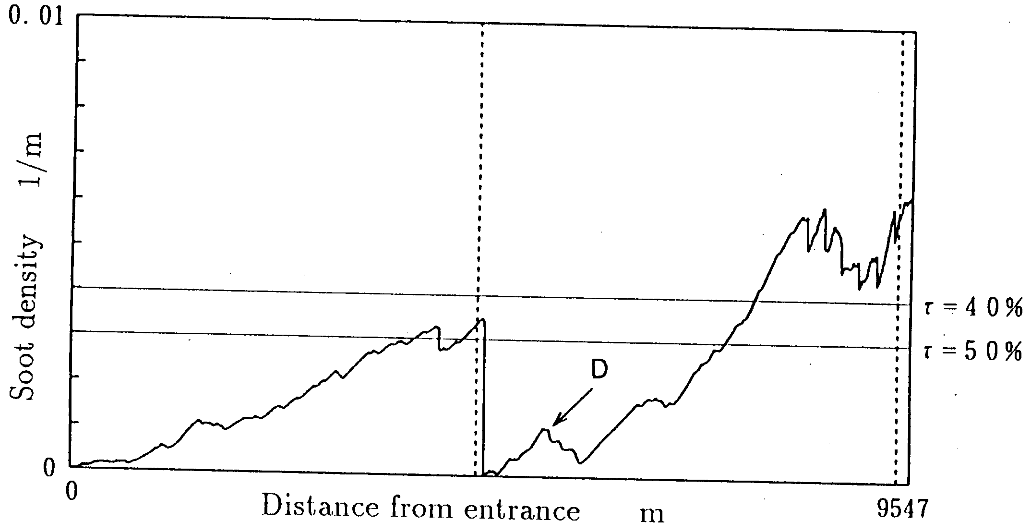

Fig. 6: Spatial distribution of soot density
($t = 3740$ s, case 1)

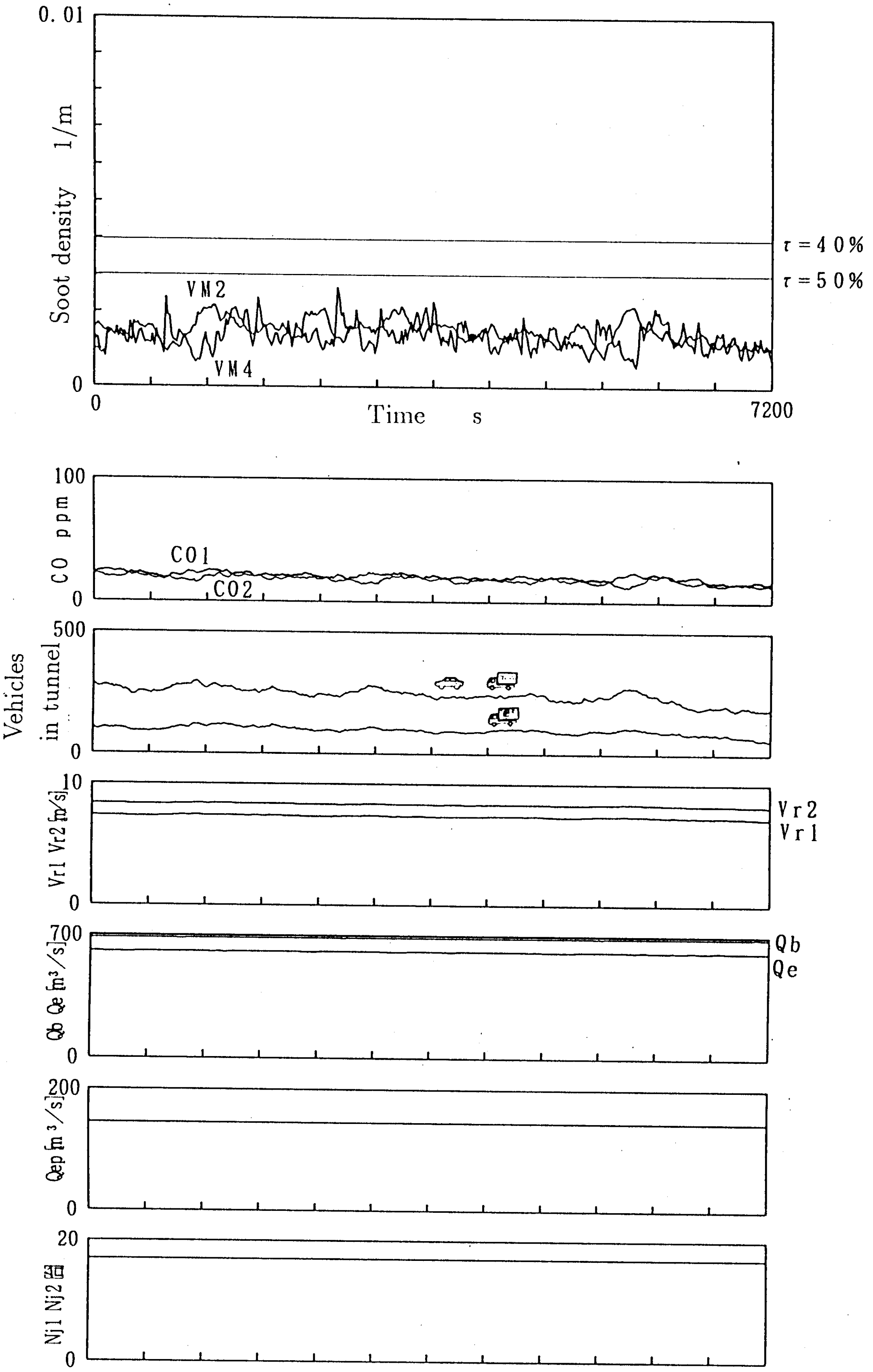

Fig. 7: Temporal variation of soot density under constant operation of ventilation (case 2)

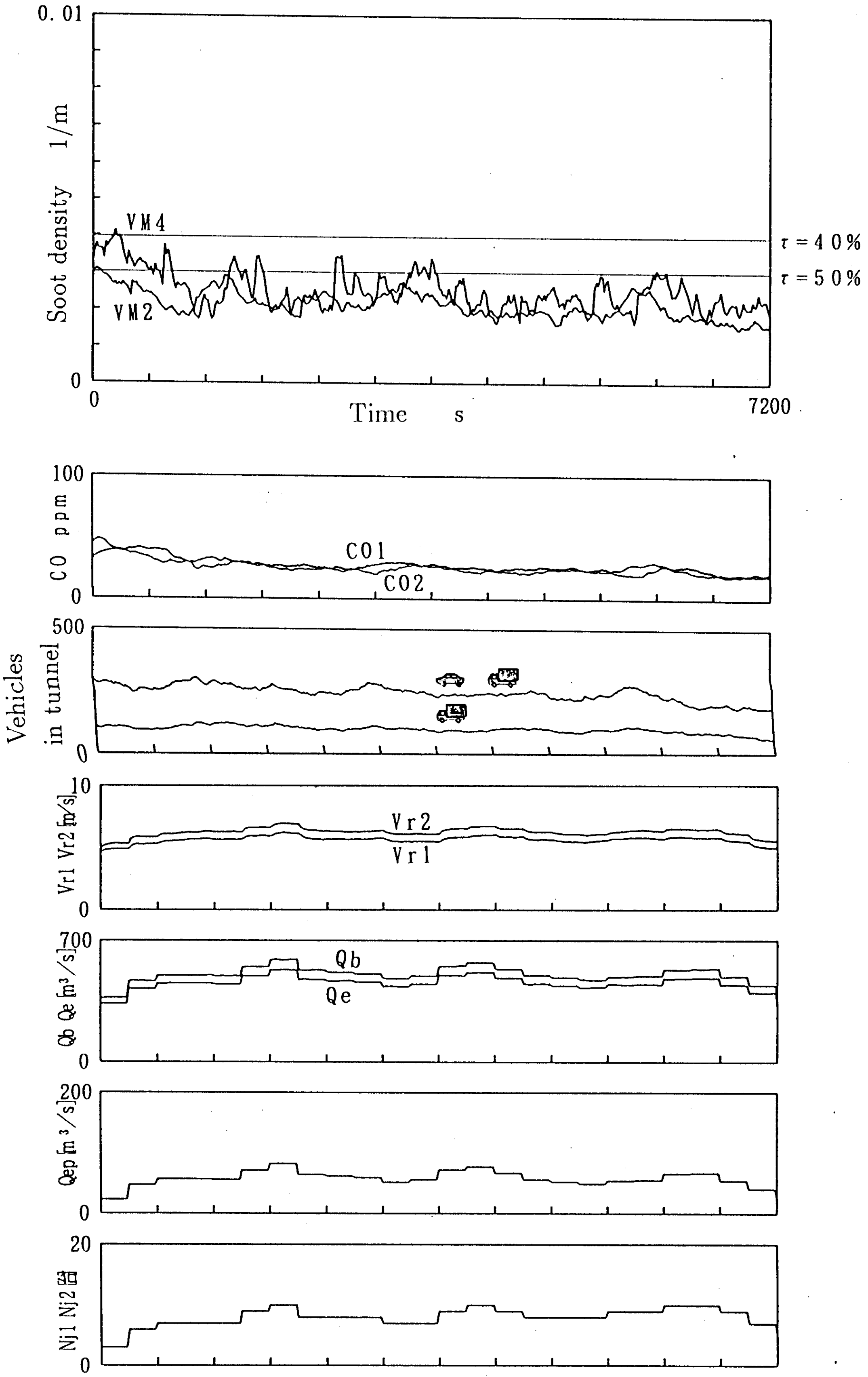

Fig. 8: Temporal variation of soot density under feedback control of ventilation (case 3)

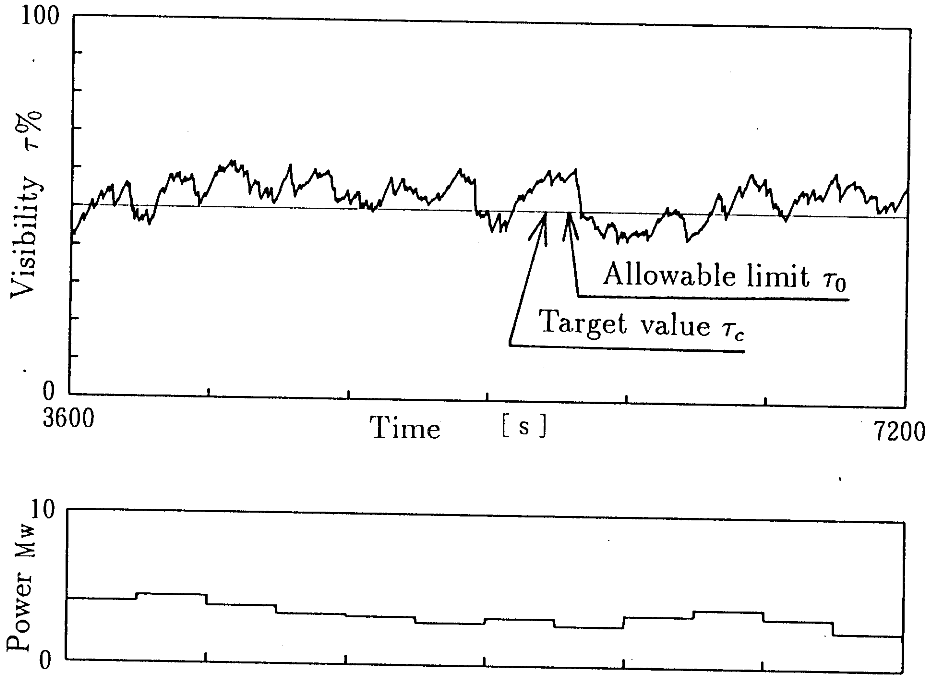

Fig. 9: Visibility and power consumption under feedback control with a target value of $\tau_c = 50\%$ (case 4)

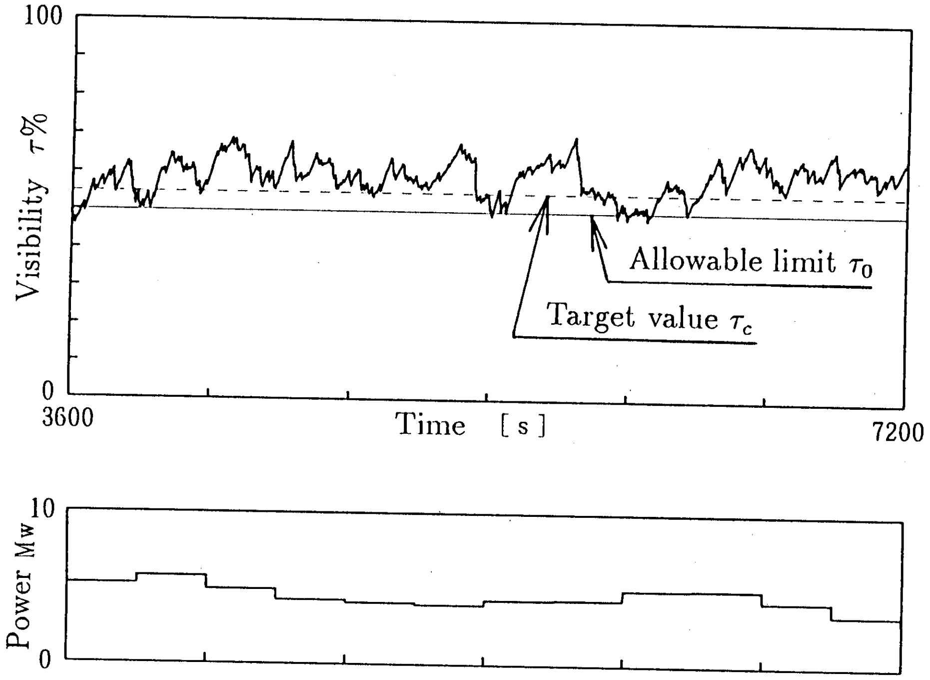

Fig. 10: Visibility and power consumption under feedback control with a target value of $\tau_c = 55\%$ (case 3)

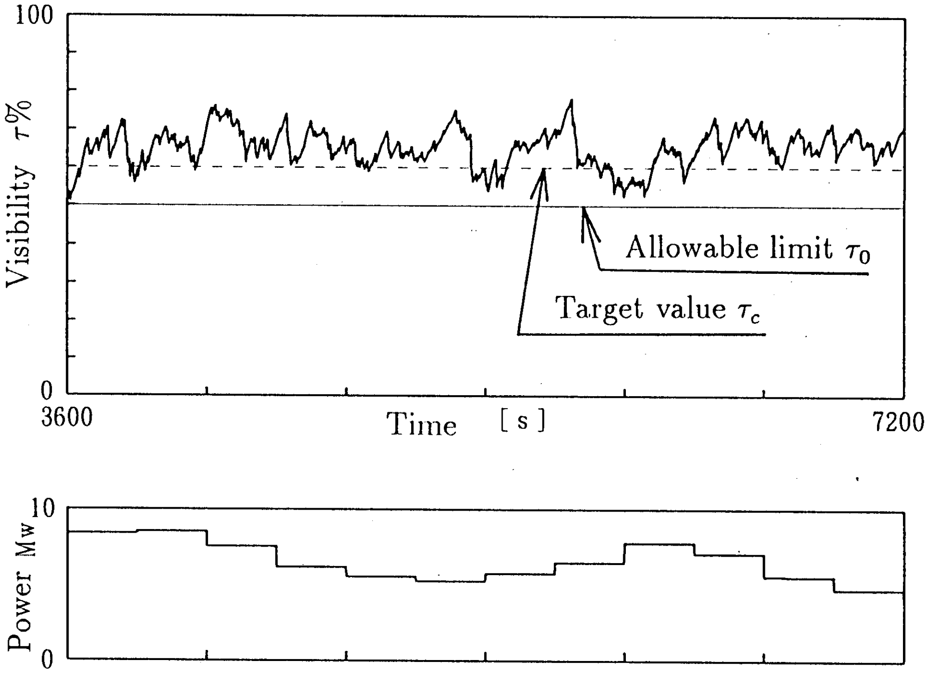

Fig. 11: Visibility and power consumption under feedback control with a target value of $\tau_c = 60\%$ (case 5)

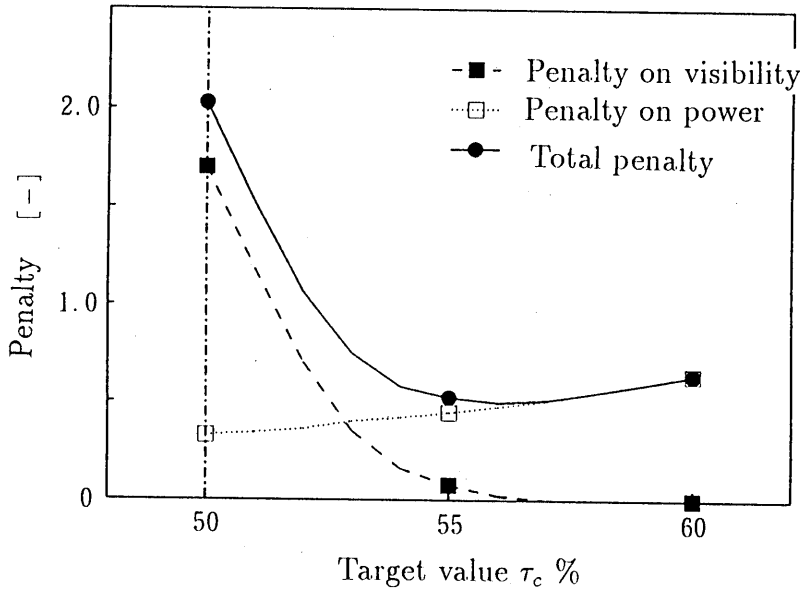

Fig. 12: Penalties in visibility and power consumption