1992 Basel
Safety

Controllability of Longitudinal Air Flow in Transversely Ventilated Tunnels with Multiple Ventilation Divisions

Akisato MIZUNO* Atsushi ICHIKAWA†

Abstract

In a transversely ventilated automobile tunnel, the flow rates of fresh air supply and exhaustion are kept equal in ordinary operation. But it is not possible in principle to control the longitudinal air flow velocity through this ordinary operation. It is, however, strongly desired to suppress longitudinal air flow in case of fire in the tunnel with two-way traffic so that the passengers can safely evacuate, because the exhaustion flow rate to suck the smoke is considered in most cases to be insufficient if the fire exceeds a certain level of intensity.

The authors extend the aerodynamic theory for two ventilation divisions and enable to estimate the air flow velocity under transient traffic condition and imbalance operation of ventilators for the tunnel with multiple ventilation divisions. In the analysis, it is assumed that the flow rates of blowing fresh air and the exhaustion can be independently controllable at each division. An ordinary differential equation is formulated and it is solved numerically in the simulator. The model tunnel is assumed to be with two and four ventilation divisions (1,000 m each).

According to a series of numerical simulations, it is made clear that the air flow velocity can be brought to zero in a minute through the imbalance operation in the tunnel with four ventilation divisions, while the velocity even increases by ordinary operation. In the four-divisions tunnel, it is also shown to be possible to keep the air flow velocity to be zero by feedback control. In the tunnel with two ventilation divisions, on the other hand, it is not always possible to keep the velocity to be zero according to traffic and natural wind condition.

NOMENCLATURE

Attatched values are the ones used in the model simulations.

$A_r = 42.0$ [m^2]	: Cross sectional area of the traffic room in the tunnel.
$A_t = 2.8$ [m^2]	: Mean frontal projection area of a vehicle with drag coefficient included.
$D_r = 6.0$ [m]	: Reference diameter of the tunnel cross section.
F_r [N]	: Force by friction.

*Department of Mechanical Engineering, Kogakuin University, Nakano-machi 2665, Hachioji-shi, Tokyo 192

†Nihon Doro Kodan(Japan Highway Public Corporation), Highway Facilities Division, 3-2, Kasumigaseki 1, Chiyoda-ku, Tokyo 100

F_t [N]	: Force by traffic.
I_j [Pa]	: Integration of traffic and frictional force in division j.
K_p [m^2]	: Proportional gain.
l [m]	: Total length of the tunnel.
l_j [m]	: Length of division j.
L_j [Pa]	: Entrance loss at the portals.
dm [kg]	: Mass of air in the infinitesimal control volume.
n [-]	: Number of ventilation divisions.
$n_t = 1000$ [veh./h]	: Traffic density in each direction.
p [Pa]	: Pressure of air.
p_j [Pa]	: Pressure of air at the left end of division j.
Q_{bj}, Q_{ej} [m^3/s]	: Flow rate of fresh air/exhaustion in division j.
$Q_{bjd} = 150$ [m^3/s]	: Designed flow rate of fresh air supply in division j.
$Q_{ejd} = 150$ [m^3/s]	: Designed flow rate of exhaustion in division j.
ΔQ_j [m^3/s]	: $Q_{bj} - Q_{ej}$.
t [s]	: Time.
t_a [s]	: Time of accident.
t_c [s]	: Time of inception of the emergency control.
$T = 10$ [s]	: Control Period.
$T_Q = 30$ [s]	: Period of changing the load of ventilators in full span.
V_n [m/s]	: Natural wind velocity.
V_r [m/s]	: Longitudinal air flow velocity at an arbitrary point.
V_{ra} [m/s]	: Air flow velocity at the point of accident.
V_{rj} [m/s]	: Longitudianl air flow velocity at the left end of division j.
$V_{r0} = 0$ [m/s]	: Target value of V_{ra}.
$V_t = \pm 50$ [km/h]	: Velocity of vehicles.
x [m]	: Coordinate along the tunnel axis.
dx [m]	: Length of infinitesimal control volume.
x_a [m]	: Location of accident.
$\lambda_r = 0.025$	: Coefficient of pipe friction loss.
$\rho = 1.205$ [kg/m^3]	: Density of air.
$\rho_t = 0.02$ [veh./m]	: Traffic density. $(= n_t/V_t)$
$\zeta_e = 0.6$	: Coefficient of entrance loss.

Subscripts

j	: Ventilation division.
$+, -$	: denote the value to be in positive/negative direction.

Superscripts

$*$	: Flow rate requested by the controller.

1. INTRODUCTION

In a transversely ventilated tunnel, main strategy against fire is to suck the smoke through exhaust fans. The capability of removing smoke, however, is usualy very limited because the exhaustion is distributed along the tunnel axis and the flow rate ranges 0.1 to 0.3 cubic meters per second per meter. It means that in most cases the scale of fire is more than the level for which above strategy is efficient. From this point of view, especially for tunnels for two way traffic, it seems essential to find out a strategy to suppress the air flow velocity in case of fire, in addition to sucking operation in the concerned ventilation division.

The authors have presented the study on the possibility of controlling the longitudinal air flow velocity in the transversely ventilated model tunnel with two ventilation divisions(Mizuno & Ichikawa, 1991). According to the study, it was made clear that the imbalance operation of fresh air supply and exhaustion in the division in which the accident did not happen was effective in suppressing the air flow velocity at the site of accident. And it was also tried to control by feedback to bring the air flow velocity at the accident point to zero, which was also successful under hypothesised conditions.

However, the theory in the above mentioned study was limited to the tunnel with two ventilation divisions, and it was desired to develop more general theory and corresponding simulator. In the present paper, the aerodynamic model for the transversely ventilated tunnel with an arbitrary number of ventilation divisions has been developed as extension of the former study. The model is also generalized in that each division can have arbitrary length and its own flow rates of fresh air and exhaustion respectively. The simulation is performed for the tunnels with two and four ventilation divisions (1,000 m each) to find out the aerodynamic characteristics in such a complex ventilation system. Then the controllability of the longitudinal air flow velocity is discussed, mainly for the tunnel with four ventilation divisions. Feedback control is applied to the system with four ventilation divisions and it is found effective for the countermeasure against fire.

2. AERODYNAMICS IN A TRANSVERSELY VENTILATED TUNNEL

2.1 Aerodynamics for a Single Ventilation Division

The aerodynamic relation of the longitudinal air flow velocity to the forces applied on the air column in the transversely ventilated tunnel is presented in the section. In the first stage, the governing equations for a single ventilation division are formulated.

In ventilation division j, as is shown in figure 1, it is assumed that the flow rate of fresh air supply Q_{bj} and exhaustion Q_{ej} are uniformly distributed along the division, and they can be controlled independently between zero and the design value. From the continuity principle, the longitudinal air flow velocity at an arbitrary point is expressed as

$$A_r V_r(x) = A_r V_{r\,j} + (Q_{bj} - Q_{ej})\, x / l_j, \tag{1}$$

in which x is the local coordinate ($0 \leq x \leq l_j$). Hence, the difference of the velocities at both ends of the division is

$$V_{r\,j+1} - V_{r\,j} = (Q_{bj} - Q_{ej}) / A_r. \tag{2}$$

The forces applied on the infinitesimal control volume (axial length: dx) can be described as followings. The traffic force in both directions can be expressed as

$$dF_t = \frac{\rho}{2} A_t \{\rho_{t+} (V_{t+} - V_r) |V_{t+} - V_r| + \rho_{t-} (V_{t-} - V_r) |V_{t-} - V_r|\}\, dx, \tag{3}$$

where ρ_{t+} and ρ_{t-} are the traffic density (function of t and x) toward each direction, and V_{t+} and V_{t-} are the velocities of vehicles with different signs. The resistance force due to

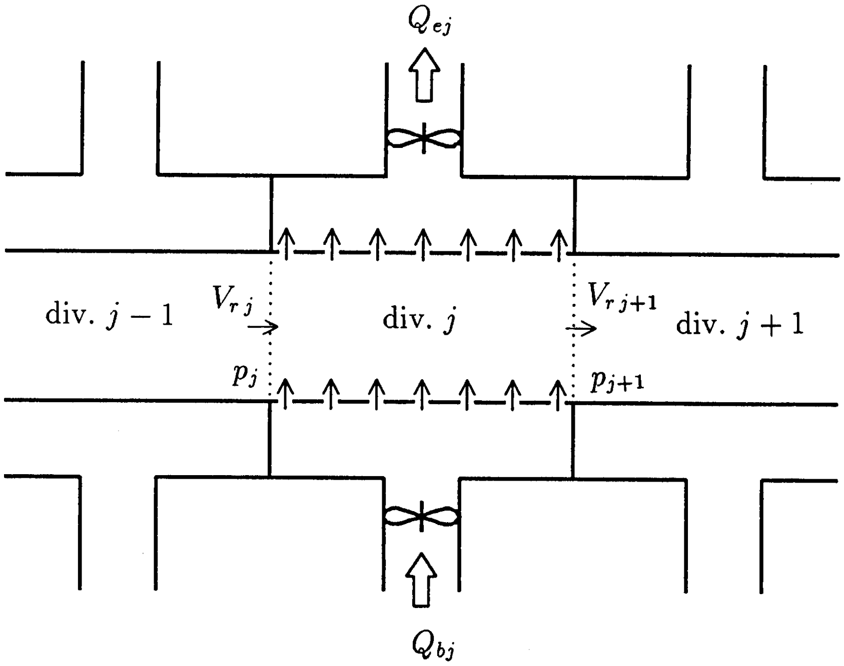

Figure 1: Transverse ventilation model for a single division

pipe friction is

$$dF_r = -\lambda_r A_r \left(\frac{dx}{D_r}\right) \frac{\rho}{2} V_r \left|V_r\right|. \tag{4}$$

The momentum equation for the control volume is

$$dm\left(\frac{\partial V_r}{\partial t} + V_r \frac{\partial V_r}{\partial x}\right) = -A_r \frac{\partial p}{\partial x} dx + dF_t + dF_r, \tag{5}$$

where dm is the mass of air in the control volume; $dm = \rho A_r dx$. The left hand side terms are local and convective acceleration. In eqn. (5) the force due to exchange of momentum by supply and exhaustion air flow is neglected in the current study, because it is considered to be small. Substituting eqn. (1) into eqn. (5), and integrating each term over the whole division the relation

$$p_j - p_{j+1} = \rho l_j \left[\frac{dV_{rj}}{dt} + \frac{1}{2A_r}\frac{d}{dt}(Q_{bj} - Q_{ej})\right] + \frac{\rho}{2}\left(V_{rj+1}^2 - V_{rj}^2\right) - (I_j + L_j) \tag{6}$$

is obtained, where

$$I_j \equiv \frac{1}{A_r}\left(\int_0^{l_j} dF_t + \int_0^{l_j} dF_r\right). \tag{7}$$

The integration in eqn. (7) is to be performed numerically under local coordinate of x. The entrance losses are

$$L_1 = \begin{cases} -(1+\zeta_e)\frac{\rho}{2}V_{r1}^2 & \text{for } V_{r1} > 0 \\ 0 & \text{for } V_{r1} \le 0 \end{cases} \tag{8a}$$

$$L_n = \begin{cases} (1+\zeta_e)\frac{\rho}{2}V_{rn+1}^2 & \text{for } V_{rn+1} < 0 \\ 0 & \text{for } V_{rn+1} \ge 0 \end{cases} \tag{8b}$$

$$L_j = 0 \qquad \text{for } 2 \le j \le n-1. \tag{8c}$$

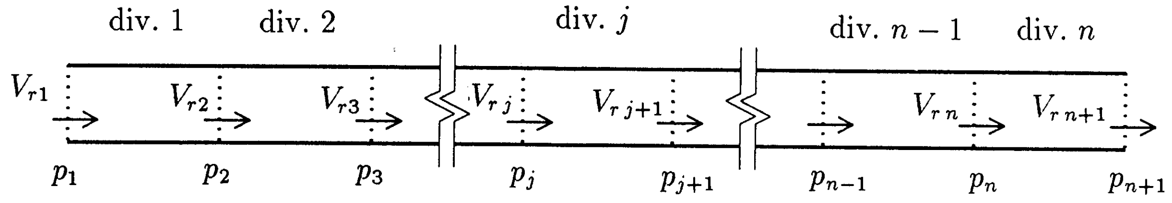

Figure 2: Transverse ventilation system with multiple divisions

The natural wind velocity V_n is related to the pressure difference at both portals as

$$p_1 - p_{n+1} = \left(1 + \zeta_e + \lambda_r \frac{l}{D_r}\right) \frac{\rho}{2} V_n \left|V_n\right|, \tag{9}$$

where V_n is the air flow velocity which would occur if there were no disturbance by vehicles and ventilators.

2.2 Aerodynamic Model as the Superposition of Local Equations
The local equations (6) are summarized over $1 \leq j \leq n$ as

$$\begin{aligned}\sum_{j=1}^{n}(p_j - p_{j+1}) &= \sum_{j=1}^{n}\rho l_j \frac{dV_{rj}}{dt} + \sum_{j=1}^{n}\frac{\rho}{2}\frac{l_j}{A_r}\frac{d}{dt}(Q_{bj} - Q_{ej}) \\ &+ \sum_{j=1}^{n}\frac{\rho}{2}\left(V_{r\,j+1}^2 - V_{r\,j}^2\right) - \sum_{j=1}^{n} I_j - \sum_{j=1}^{n} L_j,\end{aligned} \tag{10}$$

based on the condition that the pressures and velocities at the node points are common between divisions, as is shown in figure 2.

V_{rj}'s can be reduced to V_{r1} by utilizing the relation of continuity, eqn. (2), repeatedly to yield the final ordinary differential equation for V_{r1} as

$$\begin{aligned}\frac{dV_{r1}}{dt} &= \frac{1}{\rho l}(p_1 - p_{n+1}) - \frac{1}{A_r l}\sum_{j=1}^{n}\left\{\left(\frac{l_j}{2} + \sum_{k=j+1}^{n} l_k\right)\frac{d}{dt}(Q_{bj} - Q_{ej})\right\} \\ &- \frac{1}{2l}\left[\left\{\sum_{j=1}^{n}\frac{(Q_{bj} - Q_{ej})}{A_r}\right\}^2 + 2V_{r1}\sum_{j=1}^{n}\frac{(Q_{bj} - Q_{ej})}{A_r}\right] + \frac{1}{\rho l}\sum_{j=1}^{n} I_j + \frac{1}{\rho l}(L_1 + L_n),\end{aligned} \tag{11}$$

in which it is defined as $\sum_{k=r}^{s} l_k = 0$ when $r > s$. The eqn. (11) is numerically integrated in terms of Runge-Kutta method.

2.3 Simulation Models
The numerical simulator for *solving the behavior of longitudinal air flow in a transversely* ventilated tunnel with multiple ventilation divisions is constructed based on the above mentioned aerodynamic model accompanied by the following models;

Traffic model
The speed and density of traffic are kept constant in prescribed values before the accident at $t = t_a$. It is set to be $t_a = 0$ s in the current simulation. When the accident occurs, it is assumed that the vehicles toward the point of accident stop at once, while the

vehicles leaving from the point run away without being disturbed. According to this model, a strong imbalance force can be exerted after the accident, which is the case in the actual phenomena. The delay time from the accident to the inception of traffic control is neglected in the current study, although arbitrary values of t_a and t_c can be set in the simulator.

Controller model
Before the accident, all the ventilators are in full operation in all cases. Three controller models for emergency are prepared, and it is to be switched over to one of them at time t_c. ($t_c = 0$.)

(1) Constant operation is kept after the accident.

(2) Stepwise operation is done at the time of accident.

(3) Feedback control is performed after the accident.

In the last model, it is supposed that the point of accident is detected, so that the longitudinal air flow velocity at the point can be calculated by eqn. (1) from the measured data V_{rj}.

Ventilator model
The model represents the delay of ventilators in changing flow rate. The required flow rates of the ventilators Q^*_{bj} and Q^*_{ej} are imposed to the model and it gives the actual values of the flow rate Q_{bj} and Q_{ej} at each time step.

Sensor model
Anemometers are supposed to be placed at each node between divisions and at both portals to give the longitudinal air flow velocity at each location. The fire detectors are installed in proper interval so that the point of fire (accident) can be identified in a certain accuracy.

3. MODEL SIMULATIONS

3.1 Model Tunnels and Hypothesized Conditions
For the model simulation to demonstrate the performance or the controllability of the longitudinal air flow in the transversely ventilated tunnel, two model tunnels are considered.

- *Tunnel A*: The model tunnel with two ventilation divisions, as in figure 3.
- *Tunnel B*: The model tunnel with four ventilation divisions, as in figure 4.

Each ventilation division has the length of 1,000 m, and the design values of flow rate of fresh air and exhaustion for each division are 150 m^3/s respectively. The accident is supposed to occur at $x = 200$ m (for Tunnel A/B) or at $x = 1,800$ m (for tunnel B). In all cases traffic is set to 1,000 vehicles an hour in each direction respectively, and ventilation is operated in full load before the accident, that is $Q_{bj} = 150 m^3/s$, $Q_{ej} = 150 m^3/s$ for $j = 1,2$, or $j = 1,2,3,4$. The cases are limited in which the natural wind is be nonexisting in the current study.

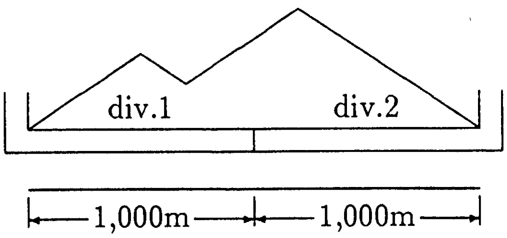

Figure 3: Tunnel A; the model tunnel with two ventilation divisions

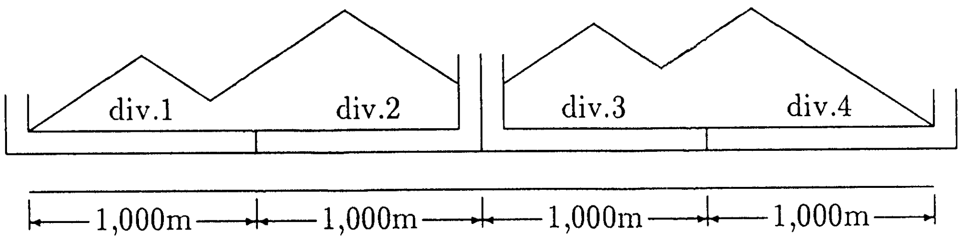

Figure 4: Tunnel B; the model tunnel with four ventilation divisions

3.2 Transient Characteristics

The simulation cases for observing the transient characteristics are summarised in table 1. If no countermeasure is taken against the accident at $x = 200$ m in the model tunnel A, the longitudinal air flow behaves like figure 5. Positive flow is induced by a strong imbalance force by traffic, which continues until the vehicles go out of the tunnel several minutes later. On the other hand, if the fresh air supply is kept in full load in the second division while the exhaustion is shut down, V_{ra} takes lower value, although it does not reach zero for more than three minites due to traffic imbalance (See figure 6). In the first division, Q_{b1} and Q_{e1} remain in full load operation. This result shows that controllability is rather limited for the tunnel with two ventilation divisions, although one can expect a better performance if the point of accident is closer to the center of the tunnel.

Table 1: Simulation Cases for Stepwise Operation

	Model Tunnel	Point of Accident	Ventilator Operation after the Accident							
			Q_{b1}	Q_{e1}	Q_{b2}	Q_{e2}	Q_{b3}	Q_{e3}	Q_{b4}	Q_{e4}
case 1	Tunnel A	200m	150	150	150	150				
case 2	Tunnel A	200m	150	150	150	0				
case 3	Tunnel B	200m	150	150	150	150	150	150	150	150
case 4	Tunnel B	200m	150	150	150	0	150	0	150	0
case 5	Tunnel B	1,800m	0	150	150	150	150	0	150	0
case 6	Tunnel B	1,800m	150	0	150	150	0	150	0	150

Q's in m^3/s

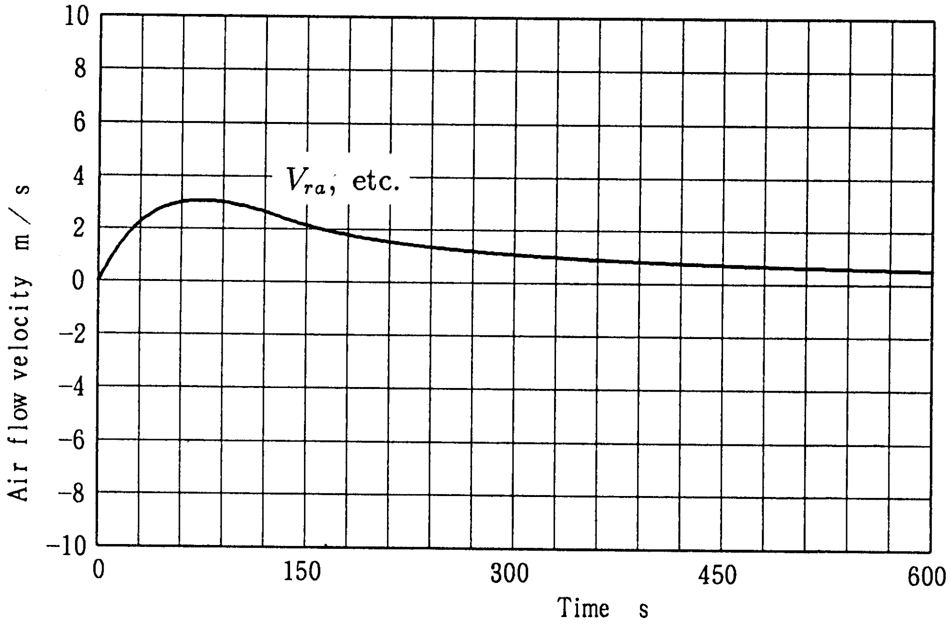

Figure 5: Air Flow Velocity (case 1): Tunnel A; $x_a = 200$ m, $Q_{b1} = 150$ m^3/s, $Q_{e1} = 150$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 150$ m^3/s

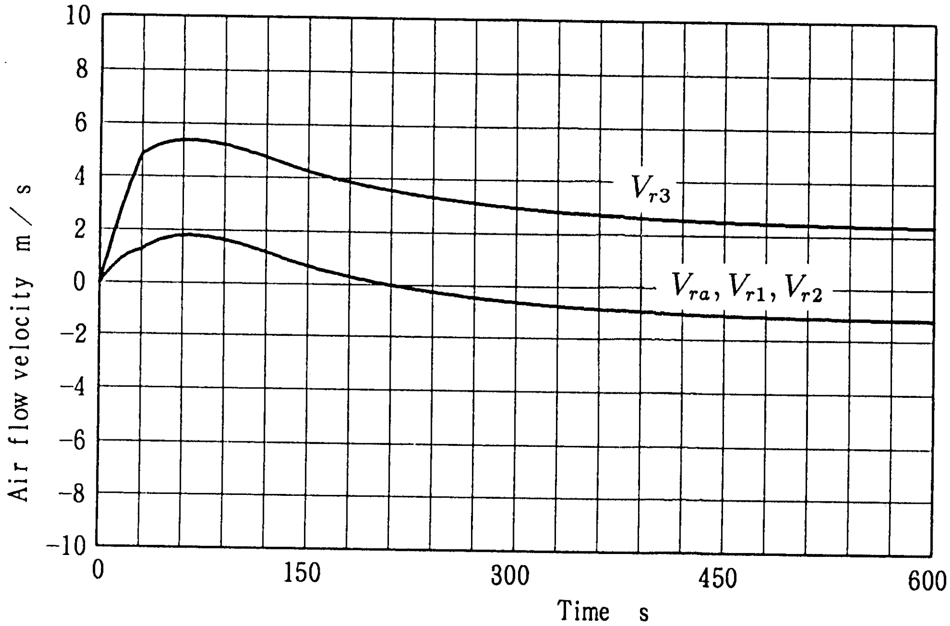

Figure 6: Air Flow Velocity (case 2): Tunnel A; $x_a = 200$ m, $Q_{b1} = 150$ m^3/s, $Q_{e1} = 150$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 0$ m^3/s

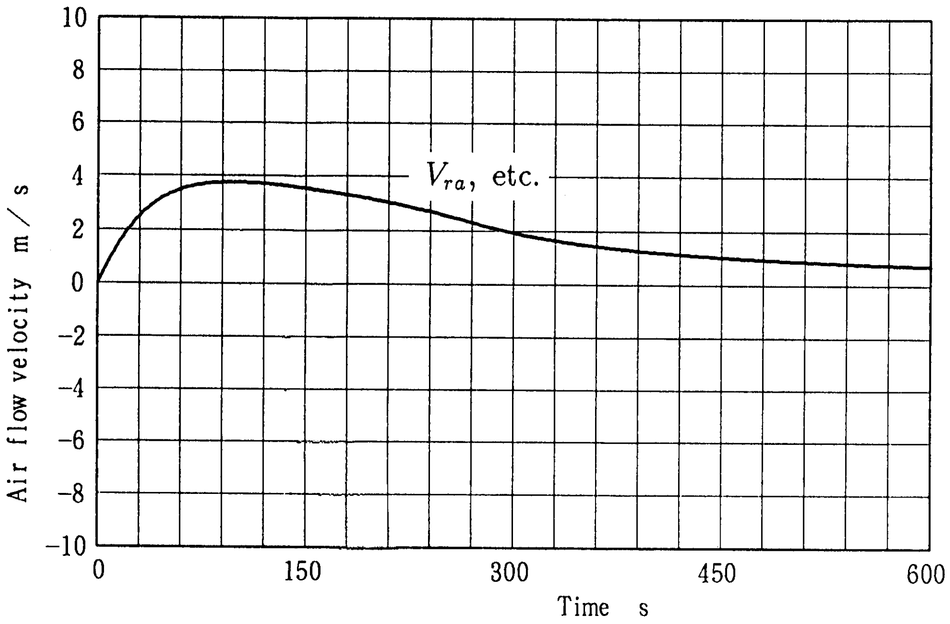

Figure 7: Air Flow Velocity (case 3): Tunnel B; $x_a = 200$ m, $Q_{b1} = 150$ m^3/s, $Q_{e1} = 150$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 150$ m^3/s, $Q_{b3} = 150$ m^3/s, $Q_{e3} = 150$ m^3/s, $Q_{b4} = 150$ m^3/s, $Q_{e4} = 150$ m^3/s

In the cases for the tunnel with four ventilation divisions the situation is different. Case 3 in figure 7 is the result in which constant operation for all ventilators is kept even after the accident at $x_a = 200$ m. The air flow velocity reaches nearly 4 m/s due to imbalance of the traffic force. The imbalance operation of ventilators after the accident is much more effective for the Tunnel B. Figure 8 is the most extreme operation so that the air flow comes to negative values. Due to the blockage effect of the blowing flow in the other divisions than the first one, the flow at the point of accident comes to negative value from the beginning and never comes above zero. This result, together with the former one, means that there is enough possibility of controlling the longitudinal air flow velocity to keep the value of zero with proper control algorithm.

In the cases in which the point of accident is at 1,800 m which is closer to the center of the tunnel, the situation is different. Because the traffic imbalance is smaller, the air flow velocity can be easily manipulated toward negative (figure 9) or positive (figure 10) direction, which suggests higher controllability with proper operation.

3.3 Feedback Control of the Longitudinal Air Flow

As fundamental concept of controllability is obtained in the last section, two of the applications of feedback control are demonstrated here. Model simulations are performed for the tunnel B.

In order to bring the longitudinal air flow velocity at the fire point to the target value $V_{r0} = 0$, the controller generates a set of instructions to the ventilators at the beginning of each control period. The difference between the blowing (Q_{bj}) and the exhausting flow rate (Q_{ej}) in division j is defined as $\Delta Q_j \equiv Q_{bj} - Q_{ej}$, where $-Q_{ejd} \leq \Delta Q_j \leq Q_{bjd}$. At

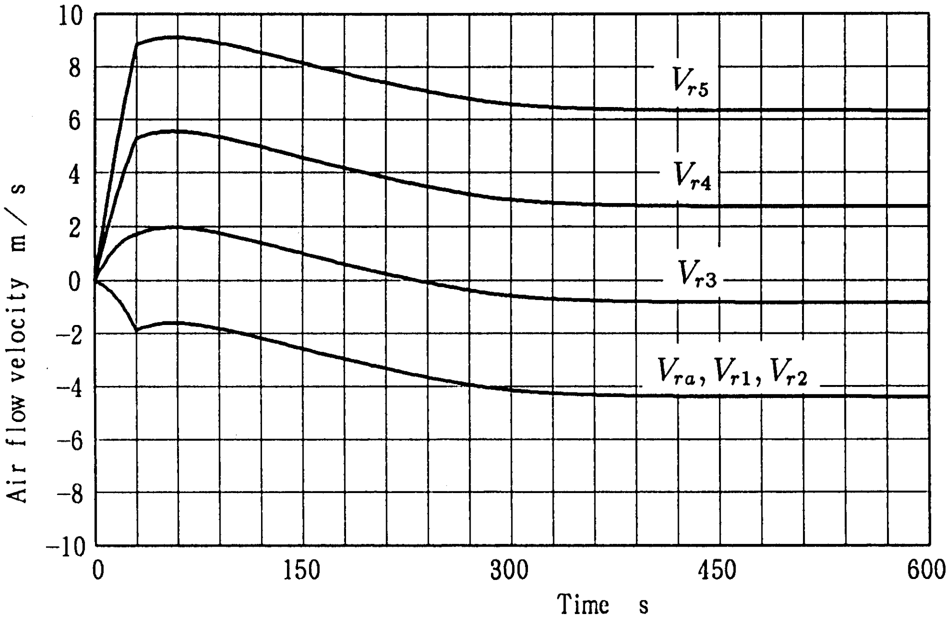

Figure 8: Air Flow Velocity (case 4): Tunnel B; $x_a = 200$ m, $Q_{b1} = 150$ m^3/s, $Q_{e1} = 150$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 0$ m^3/s, $Q_{b3} = 150$ m^3/s, $Q_{e3} = 0$ m^3/s, $Q_{b4} = 150$ m^3/s, $Q_{e4} = 0$ m^3/s

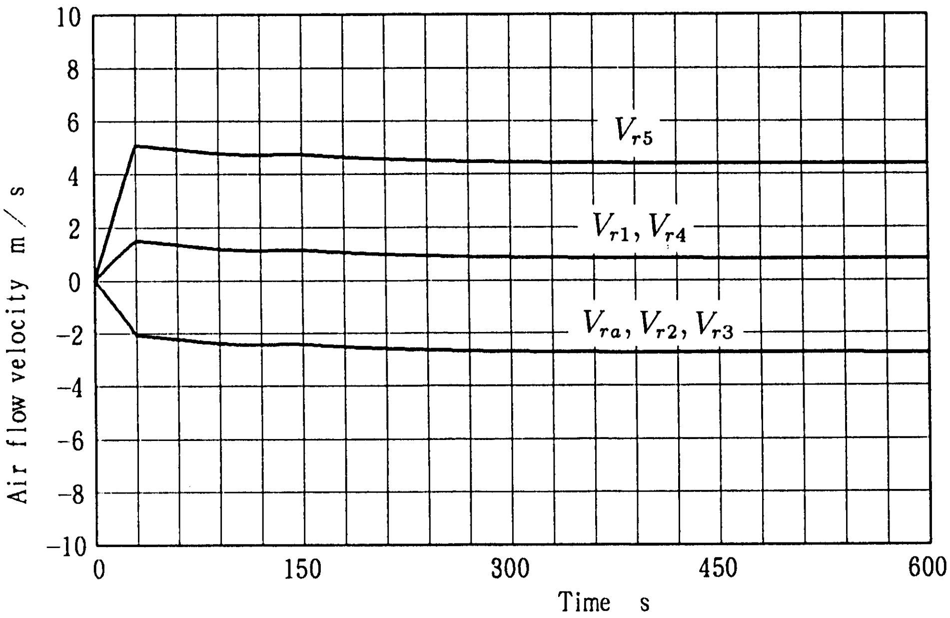

Figure 9: Air Flow Velocity (case 5): Tunnel B; $x_a = 1,800$ m, $Q_{b1} = 0$ m^3/s, $Q_{e1} = 150$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 150$ m^3/s, $Q_{b3} = 150$ m^3/s, $Q_{e3} = 0$ m^3/s, $Q_{b4} = 150$ m^3/s, $Q_{e4} = 0$ m^3/s

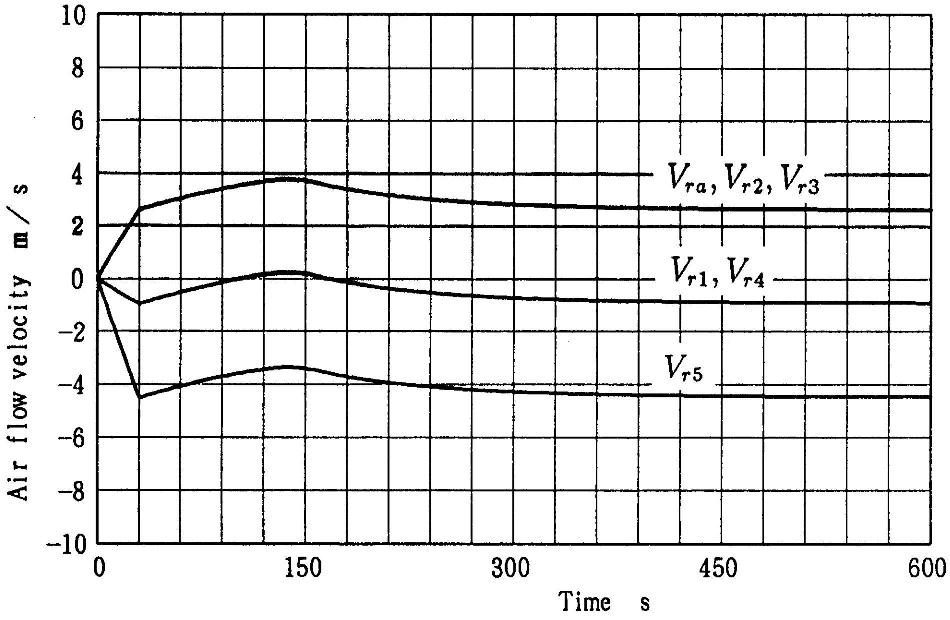

Figure 10: Air Flow Velocity (case 6): Tunnel B; $x_a = 1,800$ m, $Q_{b1} = 150$ m^3/s, $Q_{e1} = 0$ m^3/s, $Q_{b2} = 150$ m^3/s, $Q_{e2} = 150$ m^3/s, $Q_{b3} = 0$ m^3/s, $Q_{e3} = 150$ m^3/s, $Q_{b4} = 0$ m^3/s, $Q_{e4} = 150$ m^3/s

the end of a certain control period, ΔQ_j^* for the next control period is determined by

$$\Delta Q_j^* = \Delta Q_j - K_p (V_{ra} - V_{r0}), \tag{12}$$

where K_p is a constant propotional gain and V_{r0} is the target value of the air flow velocity. In the current simulations, $K_p = 20$ m^2 and $V_{r0} = 0.0$ m/s, and the control period is $T = 10$ s.

Once the value ΔQ_j^* is determined according to eqn. (12), the controller generates a set of instructions as follows:

(1) The ventilators in the division including the point of accident are operated in full load in spite of the controller output.

(2) The ventilators in the right side divisions are instructed to operate so that the relation $Q_{bj}^* - Q_{ej}^* = -\Delta Q_j^*$ is satisfied.

(3) The ventilators in the left side divisions are instructed to operate so that the relation $Q_{bj}^* - Q_{ej}^* = \Delta Q_j^*$ is satisfied.

In the simulation delay of the ventilator response is also taken into account in the way that the blade angle can be changed in full span in the period of $T_Q = 30$ s. In addition, in each control period, the summation of Q_{bj} and Q_{ej} is shifted toward their mean design value $(Q_{bjd} + Q_{ejd})/2$, within the extent that the effect of control is not disturbed.

Two examples are shown here, corresponding to the conditions of $x_a = 200$ m and $x_a = 1,800$ m for tunnel B. In the case of $x_a = 200$ m, the flow rates of the ventilation divisions

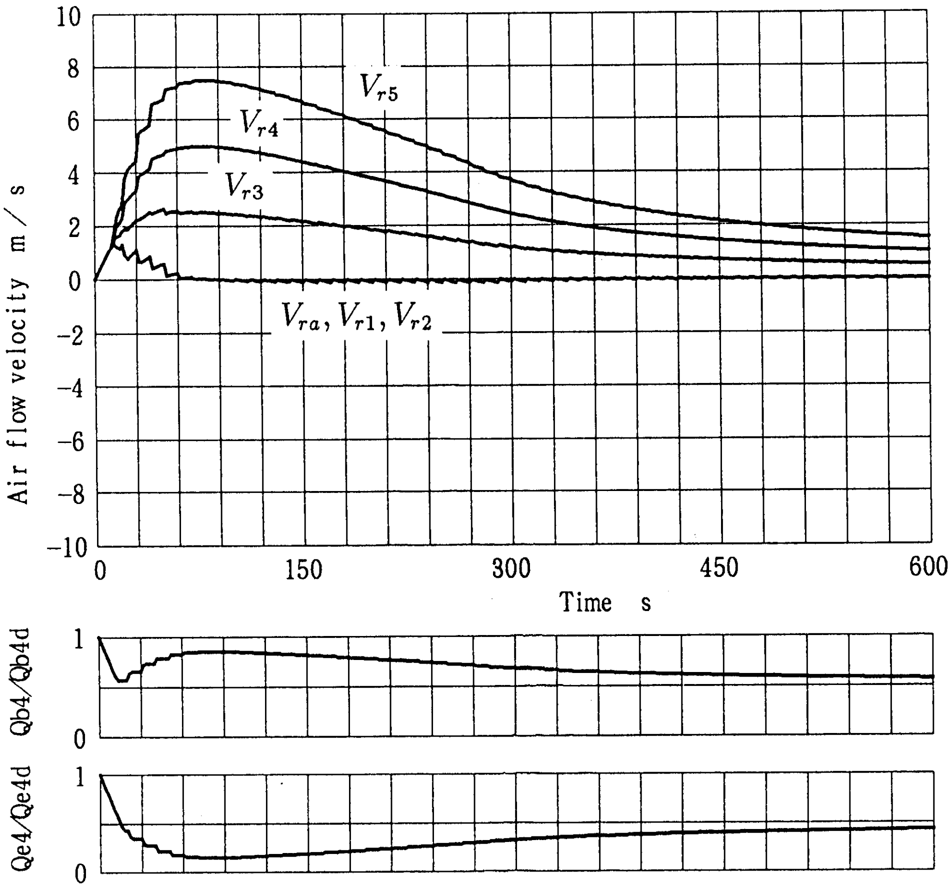

Figure 11: Air Flow Velocity (feedback): Tunnel B; $x_a = 200$ m

2,3,4 are in phase, that is

$$Q_{b2} = Q_{b3} = Q_{b4}, \tag{13a}$$
$$Q_{e2} = Q_{e3} = Q_{e4}. \tag{13b}$$

The result (figure 11) shows excellent performance that the air flow velocity at the point of accident is brought to the target value ($V_{r0} = 0$) quickly, and stable control is attained. The velocities in the down stream divisions take higher values with which the air flow in the division 1 is suppressed. For the case of $x_a = 1,800$ m, the effect of traffic imbalance is less strong and a reasonable result is obtained as in figure 12. In this case the flow rates are confined in the following manner.

$$-Q_{b1} = Q_{b3} = Q_{b4}, \tag{14a}$$
$$-Q_{e1} = Q_{e3} = Q_{e4}. \tag{14b}$$

4. CONCLUSION

The aerodynamic model is proposed for the numerical simulation of unsteady air flow in the longitudinal direction in transversely ventilated tunnels with multiple ventilation divisions. According to the model, the simulator is developed for arbitrary number of

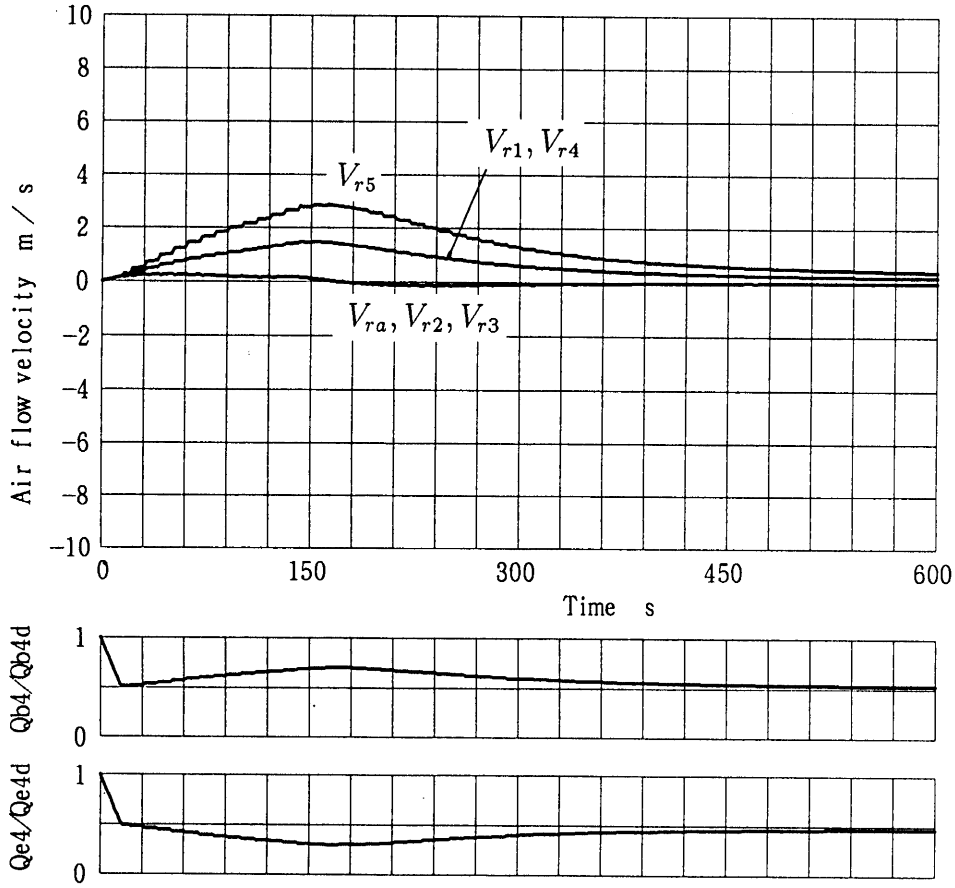

Figure 12: Air Flow Velocity (feedback): Tunnel B; $x_a = 1,800$ m

divisions. Although it is mainly for the tunnel with two way traffic, it is also possible to adapt to one way traffic tunnel. Numerical simulations for examining the controllability of the air flow velocity in two and four ventilation divisions have been performed. The main results obtained through the study are:

(1) For the tunnel with two ventilation divisions, it is made clear that there exist cases in which it is difficult to suppress the air flow velocity at the point of accident if it is close to the tunnel portal.

(2) For the tunnel with four ventilation divisions, on the other hand, the effect of imbalance operation of the ventilators is much more stronger in disregard of the location of fire that a pretty large force induced by the traffic can be suppressed.

(3) The air flow velocity at the fire point can be controlled to keep zero by a rather simple feedback control algorithm in the tunnel with four (and more) ventilation divisions.

REFERENCES

- Mizuno, A. and Ichikawa, A. (1991) "Possibility of controlling longitudinal air flow velocity in emergency for a transversely ventilated tunnel", *Proc 7th int symp on the Aerodynamics and ventilation of Vehicle Tunnels*, BHR Group, Brighton, UK, 349-364.