Role of simulation in safe tunnel ventilation design

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Abstract: *Fire safety is of greatest concern when designing tunnel ventilation facilities. The first part of the paper deals with the difference of the roles of one-dimensional and three-dimensional simulation of ventilation. The authors establish the operation policy with the aid of a 1-D simulator, and are constructing a simulator which can be used via the Internet. With this simulator, users planning an emergency ventilation system can use the 1-D simulator to create a stable safety design for various tunnels.*

Nomenclature

A Cross-sectional area of the tunnel [m^2]

C Concentration of smoke [illegible]

D Diffusion coefficient [illegible]

d Hydraulic diameter of the tunnel cross section [m]

F Total force imposed on tunnel air [N]

[illegible] Piston force [N]

m Mass of air in tunnel [kg]

[illegible] Flow rate of fresh air per unit length [illegible]

q_e Flow rate of exhaust air per unit length [illegible]

t Time [s]

u Longitudinal air flow velocity [m/s]

x Distance from the entrance portal [m]

λ Coefficient of pipe friction loss [-]

ξ_s Coefficient of momentum transfer by fresh air supply [-]

ξ_e Coefficient of momentum transfer by exhaustion [-]

Q Smoke generation rate [illegible]

ρ Air density [kg/m^3]

Introduction

The concept of fire safety in road tunnels has drastically changed during the past several years due to severe accidents in Europe. It is no doubt that one of the key factors for securing safety during a fire accident is the ventilation facilities and its operation or control. The authors have been carrying out the numerical simulation of ventilation for a variety of road tunnels for more than 20 years. It started with longitudinal ventilation system for the Kan-etsu Tunnel (for normal operation[1] and emergency operation[2], followed by the Trans-Tokyo-Bay Tunnel[3].

Later work was done for the emergency ventilation control for a transverse ventilation system for model tunnels[4-5]. Here it was confirmed that the imbalance ventilation strategy is effective in controlling the longitudinal velocity of air, where the supply and exhaustion flow are intentionally differed. The equation of motion used in these works turned out to be doubtful, and a thorough consideration was made to establish a new expression of the equation of motion[6]. The analysis based on this new equation was carried out for a simulation for the Higashiyama Tunnel[7]. The actual test was carried out for transient ventilation for the Higashiyama Tunnel in early 2003, and the simulation results were found to agree with the real phenomena pretty well.

One of the authors insisted that safety measures had to be a thoughtful combination of various necessary issues needed for an emergency case[8].

Based on the experience of safety studies with a series of numerical simulations mentioned above, the authors attempt to reconsider and establish safety judgment criteria from the viewpoint of securing evacuation during a road tunnel fire. Discussion in this paper is limited to the judgment of adequacy in the capability of the ventilation facility and its control logic.

When fire breaks out in the tunnel it is necessary that a safe environment is secured while the road users try to move into a safe location (a cross passage or a refuge shelter) under appropriate guidance by the operator, It means that the ventilation control has to be switched to emergency mode as soon as the fire breaks out, and is maintained for 5 to 10 minutes to allow the tunnel users to evacuate. In the emergency mode, top priority has to be to provide a safe environment for evacuation. The most simple and important process for studying evacuation is a one-dimensional (1-D) simulator. When the 1-D simulation gives a negative result, 2-D or 3-D analysis is recommended because the density of smoke at human height may be at an allowable level.

When a tunnel has branches or mergings, there are a large number of unknown variables of air velocities and pressures which make the calculation quantity much larger. In order to avoid this complication, the authors use graph theory where pressure terms can be eliminated[9]. With this method an efficient scheme of calculation is attained.

In the last part of the paper, the authors describe their intention to establish a simulation service via the Internet so that everyone who is interested can use it from everywhere in the world.

Criteria of fire safety in road tunnels

The criteria for judging safety of human lives in a road tunnel fire depends on whether all of the users can evacuate properly. It is therefore necessary to confirm safety from this viewpoint during the planning and construction stage. Consideration has to be made for avoiding the occurrence of an accident/fire. In the event of an incident the management is important so that notification is made to the operator quickly, and the users are guided by emergency broadcast to ensure a rapid evacuation.

The ventilators have to be operated so that the evacuation environment is secured using an appropriately prepared control sequence. One of the authors insisted the necessity of the systematic configuration of these safety measures[8]. The ventilation system plays a major role in a safe environment while the tunnel users seek refuge. Under the assumption that the cross passages or the refuge shelters are properly situated, the necessary time duration for the users to evacuate the tunnel is considered to be 5 to 10 minutes, based on the walking speed or the delay of evacuation at the start of the fire.

The safety criterion is therefore that smoke thicker than the permissible level does not exist in the region of human height during the evacuation period. This condition has to be maintained under all possible situations.

Role of one-dimensional simulator

Judgment of safety by 1-D simulation

The authors' proposal for the criteria for confirming safety in case of a tunnel fire is basically carried out by airflow analysis, followed by one-dimensional simulation. The airflow simulator has to be capable of describing the whole aerodynamic phenomena in the tunnel, which can affect the air velocity at the fire site. It means that the simulator includes models for ventilator dynamics and its control logic.

According to the authors' experience, they recommend an incompressible analysis of airflow. Even a 10 km long tunnel can be reasonably dealt with as being incompressible[1-2]. Fundamental equations of motion for longitudinal or transverse ventilation systems are presented in the following section. The equation of motion for the object tunnel is solved numerically to give the time dependent air velocity at the fire location and any other place of concern.

Based on the air flow velocity solved above, the 1-D convection diffusion equation for smoke density c,

$$-\frac{\partial c}{\partial t}+D\frac{\partial^2 c}{\partial x^2}-\frac{\partial (cV)}{\partial x}+\Omega_e=0, \qquad (1)$$

is analyzed in the difference form. Ω_e is the smoke generation due to fire.

In the 1-D convection diffusion equation, the smoke density is hypothesized to be uniform in a cross-section of the tunnel. In reality, however, smoke tends to be in the region close to the ceiling due to the buoyancy effect, which results in the fact that the 1-D analysis tends to give more severe results, especially in the vicinity of fire.

The calculated distribution of smoke in space and time is illustrated in Figure 1. The inclined line denotes the movement of the evacuating people. If this line does not touch the dense region in the figure, it can be judged that the users can evacuate safely. The smoke density is defined with the variable C_s, which is related with visibility[a].

Difference in role between 1-D and 3-D simulation

The speed of technological innovation in computer performance is enormous. Following this fact, there is discussion like: "Three-dimensional analysis of heat and smoke distribution in tunnel fire has become possible, one-dimensional analysis does not make sense any more. It is obvious that three-dimensional results gives more realistic phenomena to one-dimensional ones."

Although many people may think so, it is not necessarily correct. The crucial information regarding the possibility of evacuation is the longitudinal air velocity in the vicinity of fire. In order to analyze the air flow, it is

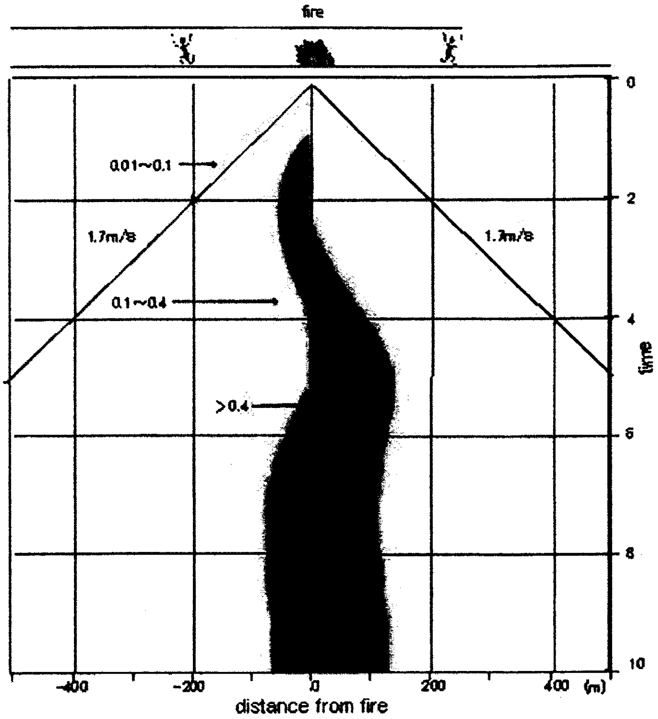

Figure 1: A sample illustration of space-time variation of smoke density.

necessary to take all components into account, including ventilator performance, as well as operation and control of the ventilators. The behavior of smoke is analyzed according to the result of the airflow analysis

As has already been stated, 1-D analysis generally gives a more severe result regarding smoke density than the real phenomena. Therefore, when a 1-D result shows that it is safe it can be judged that a safe evacuation environment is secured. If the 1-D analysis does not give a positive result that the users can evacuate safely under the smoke density less than 0.4, it is recommended that a three-dimensional analysis be conducted with the boundary condition of the longitudinal air velocity obtained through the one-dimensional analysis. The region of 3-D analysis for this purpose is limited to within several hundred meters including the fire site.

It is probable that the 3-D analysis will indicate that the smoke density is in the permissible level for evacuation at the height of human being, and the facility is all right. If it is not the case, the facility is considered not sufficiently safe, and a re-design is necessary in the ventilation facilities and/or its control logic.

Adaptation to various ventilation systems

Aerodynamic model for longitudinal ventilation system

For the analysis of the air flow in a longitudinally ventilated tunnel, Newton's second law of motion is applied.

$$m\frac{dV}{dt} = F, \tag{2}$$

where m is the mass of air in the tunnel, V is the air velocity. F is the summation of all forces, which are traffic force, friction force, meteorological force, ventilation force, etc. Explanation in detail of these forces is described in other works[1-2].

Aerodynamic model for transverse ventilation system

In the transversely ventilated division, the equation of motion of the longitudinal airflow is described as:

$$\frac{\partial p}{\partial x} = -\rho\left\{\frac{\partial V}{\partial t} + \frac{\lambda}{2d}V|V| + 2V\frac{\partial V}{\partial x} + \frac{\xi_b q_b - \xi_e q_e}{A}V\right\} + \frac{1}{A}\frac{\partial F_t}{\partial x}. \tag{3}$$

from consideration of momentum conservation in an infinitesimal control volume[6], where incompressibility is supposed. The uniformity of the fresh air supply and exhaust along the ventilation division is also hypothesized. This equation is valid for any combination of q_b and q_e values, including semi-transverse ventilation system, where one of them vanishes.

Supposing that the moving fresh air does not bring any longitudinal momentum, $\xi_b=0$. And if the velocity distribution is uniform enough and $\xi_e=1$ can be supposed, then Eq. (3) can be rewritten as:

$$\frac{\partial p}{\partial x} = -\rho\left\{\frac{\partial V}{\partial t} + \frac{\lambda}{2d}V|V| + 2V\frac{\partial V}{\partial x} + \frac{q_e}{A}V\right\} + \frac{1}{A}\frac{\partial F_t}{\partial x}. \tag{4}$$

This equation is integrated along x and the pressure difference at both portals is related to acceleration, which is the equation of motion for the transverse ventilation system. A more concrete sample of usage of this equation is exemplified in the application to the Higashiyama Tunnel[7].

Structure of the 1-D simulator

The one-dimensional simulator described above is used for confirming the safety in a fire emergency for the case of a road tunnel. It is a set of mathematical models with each function, as shown in Figure 2.

- *Aerodynamic Model:* Under a set of given conditions for ventilator operation and traffic data, the longitudinal air flow velocity is calculated as a function of time by solving the equation of motion. The user has to be capable of solving the equations for various ventilation systems; longitudinal, transverse and their combination. In the transverse system, supply and exhaust airflow can be controlled independently, so that longitudinal airflow can be manipulated.
- *Convection Diffusion Model:* Intensity of smoke

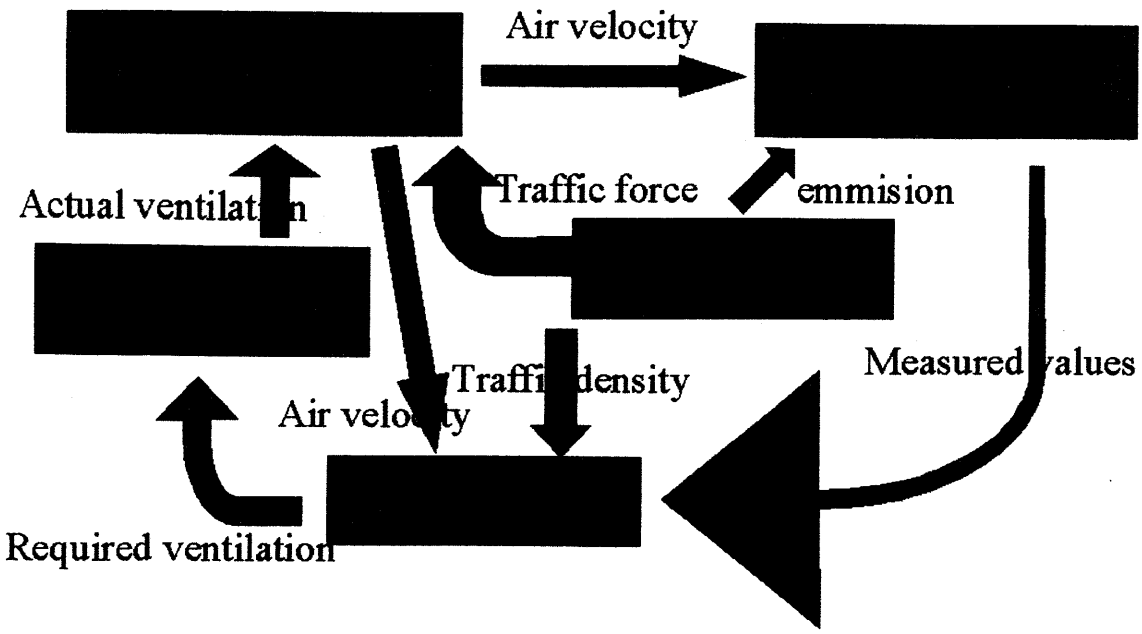

Figure 2: Configuration of the simulator.

generation is hypothesized as a function of time, and the convection diffusion equation (1) is solved numerically. Although diffusion can affect the results, it is usually neglected. It may be meaningful to use any finite diffusion coefficient D based on certain theoretical or experimental background. With these considerations, the fundamental behavior of smoke can be understood through the analysis by means of a 1-D convection equation. However, this model deals with uniform smoke density in any cross section, and cannot describe the stratified flow due to buoyancy caused by heat. This fact means that the result from a 1-D analysis gives more severe results in comparison to actual phenomena, in which dense smoke stays at the ceiling and the region at human height is rather free of smoke. When the longitudinal airflow is very slow, smoke travels with a speed larger that the cross sectional mean, and it is not guaranteed that the 1-D result always gives a safer result.

- *Traffic Model:* Traffic model is necessary both for one-way and two-way traffic. The phenomena has to be described where the accident hinders the traffic flow and the vehicles approaching from behind are accumulated, while the vehicles leave the incident without being disturbed. Either a macro model or a micro model is used. The macro model deals with the movement of vehicles as distributed in each cell with a difference form, while in the micro model the movement of each vehicle is described. In the emergency case, the algebraic model is also reliable and reproductive, where traffic density and speed is defined as function of time and space.
- *Controller Model:* When a fire is recognized in the tunnel, the ventilation control is turned over into emergency mode, which is quite different from the ordinary one. In the first 5 to 10 minutes, the control logic has to be aimed at safety for evacuation as top priority. Then the purpose of ventilation control is shifted, so that rescuing and fire-fighting activity can be smoothly carried out.
For the longitudinally ventilated tunnel with jet fans, the ON-OFF operation of JFs to bring the air velocity to the target value is started, as is the case described in the paper for the Kan-etsu Tunnel[2]. For the transverse ventilation, on the contrary, it is considered to be difficult to control the longitudinal air flow. One of the authors has proposed a strategy named 'imbalance control'[4-5], in which the air flow can be manipulated by posing the imbalance of supply air and exhaust oppositely between upstream and downstream of the division of fire. As this sometimes does not work as effective as JFs do, it is strongly recommended that one confirm the effectiveness in advance. The fundamental equation is slightly modified[6] from the former work[4-5] so that the convective term of momentum is described more exactly.
- *Ventilator Model:* In reality, the measured data of air velocity is given to the controller model. In simulation the aerodynamic model gives it to the controller. From the given data, the controller executes certain calculations, and outputs the requirement of ventilation. The ventilator model receives it, and adjusts it, so that the ventilators behave as being real. The function includes delay of start-up of fans, limitation in number of JFs, which can be started due to rush current.

The simulator consists of these models combined organically, and the calculation is advanced on a time step, which gives the air flow velocity and smoke density in time and space. The distribution of smoke is used for the judgment of safety in evacuation.

Applicability to complex tunnels

The ventilation systems for road tunnels vary from a simple single shaft to a complex one with branches and mergings. For a longitudinal tunnel with a single shaft, the transient air flow can be analyzed by solving equation (2) as a function of time. On the other hand, the longitudinal air flow for the transverse ventilation can be simulated by solving the equation of motion based on equation (3).

For the complex ventilation system, where branches and/or mergings (for traffic/ventilation) are included, a set of differential equations has to be solved simultaneously. In this process air velocities and pressures are unknown variables, which makes the situation complex. The simulators developed by the authors for complex ventilation system with longitudinal[10] or transverse ones are capable of efficient calculation by eliminating the pressure terms[9].

Simulation service through the Internet

In the preceding sections the authors have discussed the capability of the 1-D ventilation simulator for providing the criteria of fire safety with regard to ventilation facilities and its control scheme. Considerable effort is required to construct a simulator, and additional work is needed in confirming the validity of the code.

In order to solve this problem, the authors are considering the establishment of a Internet-based venture-business which enables the simulation of the behavior of airflow and smoke (see Figure 3). It can be used both designing new tunnels and for the safety confirmation of the tunnels which are already in service.

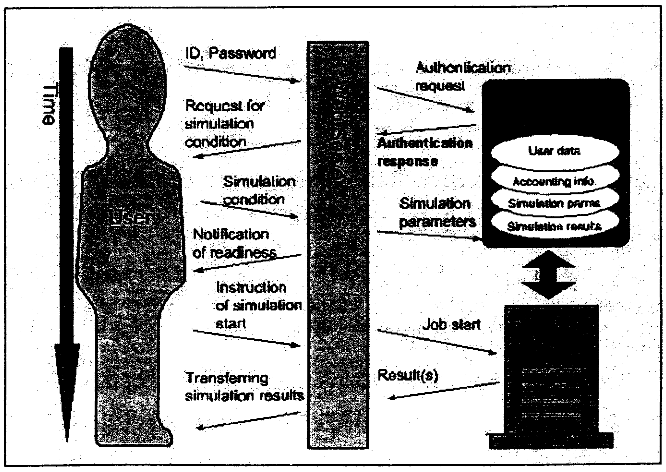

Figure 3: Simulation service through the Internet.

Conclusion

Various facilities are installed for road tunnel safety, such as a notification system, refuge guidance, fire extinguishers, etc. Among those, the ventilation system has a crucial role. Under such recognition, the authors proposed a criteria for confirming fire safety by means of one-dimensional simulation. The authors hope that this discussion is extended worldwide, and a new global standard for tunnel fire safety is established.

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(a) Visibility in the extension of l[m] in the smoke density of C_s is $C_s = -(1/l)\log\tau$, where τ is the rate of light penetrating through certain density of smoke with the distance. Ordinary criteria is: At $C_s = 0.01$ smoke can be noticed, at 0.1 smoke is thicker but one can walk, over 0.4 smoke is thick and walking is disturbed.

Nomenclature

A	: Cross sectional area of the tunnel [m^2]
c	: Concentration of smoke [1/m]
D	: Diffusion coefficient [m^2/s]
d	: Hydraulic diameter of the tunnel cross section [m]
F	: Total force imposed to tunnel air [N]
F_t	: Traffic force [N]
m	: Mass of air in tunnel [kg]
q_b	: Flow rate of fresh air per unit length [m^3/s m]
q_e	: Flow rate of exhaust air per unit length [m^3/s m]
t	: time [s]
V	: Longitudinal air flow velocity [m/s]
x	: Distance from the entrance portal [m]
λ	: Coefficient of pipe friction loss [-]
ξ_b	: Coefficient of momentum transfer by fresh air supply [-]
ξ_e	: Coefficient of momentum transfer through exhaustion [-]
Ω_c	: Smoke generation rate [1/s m]
ρ	: Air density [kg/m^3]