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Development of Guanyin Road Tunnel Ventilation Solver

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ABSTRACT

A computer program has been developed to analyze the aerodynamics and ventilation system in the Guanyin Road Tunnel currently under construction in the northern part of Taiwan. The computational models employed in this program include the aerodynamics modeling of the internal airflow inside the road tunnel and the transport equations of the pollutants for prescribed traffic data. The solver is based on the Fortran programming. Through the program, the ventilation characteristics in the tunnel can be determined and proper adjustments on various operating parameters associated to the tunnel ventilation system can be identified so that the smoke and carbon monoxide concentrations within the tunnel can be kept at satisfactory levels. Although this program was specifically developed for the Guanyin Road Tunnel, this program does not lose its generality in the sense that it can be adjusted for any other tunnel with similar design as long as the input parameters are properly set up. The computation algorithms, the program features and its basic characteristics are presented in this paper, along with demonstrations of its computational results. The plots of air velocity, smoke and CO concentrations allow one to further understand the combined effect of longitudinal and transverse ventilation.

Keywords: *Guanyin Road Tunnel, air velocity, smoke concentration, CO concentration, traffic data, simulation*

1. INTRODUCTION

In additiaonal to the 12.9-km Hsuehshan Road Tunnel, the 7.9-km Guanyin Road Tunnel is one of the most recently built road tunnel. It belongs to the Taiwan No. 9 Su-Hua Highway, as shown in Fig 1. The tunnel consists of two single-bore unidirectional tubes designated for one-way traffic. There are two lanes in each tube. Since all road tunnels in Taiwan are unidirectional, longitudinal ventilation is clearly the most economic means of ventilation which takes full advantage of the air flow induced by the single-directional moving traffic. However, this newly designed Guanyin Road Tunnel is more complicated in the sense that its ventilation system combines longitudinal and transverse ventilation schemes, i.e., it consists of the longitudinal jet fan system and the transverse smoke extraction vents installed along the tunnel ceiling. Once opened, these vents allow air and smoke in the tube to enter the smoke removal passage right above the tube separated by a ceiling, as shown in Fig. 2. On each tube, this passage is eventually connected to the north portal machine rooms and an exhaust shaft, as shown in Fig. 3. In regular operation, only the longitudinal ventilation mechanism will be activated supplying sufficient fresh air and thrust to keep the tunnel inner condition favorable for all tunnel users. Only in heavy traffic or emergency conditions, the transverse ventilation system will be activated in complimentary to the longitudinal ventilation scheme. In additional to the activation of smoke extraction system, the intake shaft will also inject fresh air into the southbound and/or northbound tubes where fresh air is needed. As a matter of fact, the effect of smoke removal passage has been investigated last year [1]. Unfortunately, this study is mostly reported in Korean language.

Depending on the purpose of study, some might model a long road tunnel system as one-dimensional [2-3] whereas the others were more interested in the local phenomena within the tunnel and simulated the tunnel using 3D CFD approach [4-6]. Quite recently, Colella, et al. [7-9] have literally combined these two approaches and developed a multi-scale approach to model the ventilation flow in tunnels. This approach is capable of providing detailed local flow conditions at selected sections with a remarkable reduction in computational requirement.

Although the one-dimensional modeling of a road tunnel may introduce some errors, it is particularly advantageous when dealing very long road tunnel. Since the Guanyin Raod Tunnel is very long, it is more reasonable and practical to emply this approach to grasp a whole picture of the tunnel ventilation. The purpose of this work is to develop a one-dimensional model for the integrated ventilation system in the Guanyin Road Tunnel. This model is then programmed in Fortran language to facilitate the investigation on the outcomes when different components of the overall ventilation system are activated.

2. MATHEMATICAL MODEL

This program was developed mainly based on the aerodynamics in the tunnel and the emission rates of CO and smoke from the vehicles traveling within the tunnel. In additional to the tunnel geometry and ventilation information, traffic data has to be included to take into consideration the piston effect established by the moving vehicles as well as the contaimination the vehicles produce.

2.1 Aerodynamic Analysis of Tunnel Air

In general, the air in the tunnel can be reasonably assumed continuous, incompressible, and one-dimensional as long as the road tunnel is long enough and the air speed in it is much slower than the speed of sound. Also, it is further assumed that the curvature of the tunnel is negligible, the tunnel cross-sectional area is constant, the wind motion mechanically induced is steady and uniform, and the traffic condition is uniform along the tunnel. The entire computational domain of the tunnel was divided into 24 finite control volumes and 23 literally fictitious control volumes, as shown in Fig. 4. According to the principle of mass conservation, the average velocities in these control volumes are inter-related. For this reason, the forces acting within can be modeled using the Newton's Second Law. In general, there are five kinds of forces acting on these sections [10-12]:

$$M\frac{dV_r}{dt} = \sum F = F_n + F_t + F_s + F_j + F_f \tag{1}$$

where the five forces appeared in the equation above are

(a) the force due to pressure difference between the entrance and exit portals:

$$F_n = \frac{\rho}{2} A_r \left(\varepsilon + \zeta + f\frac{L}{D_H} \right) V_n \left| V_n \right| = A_r \left(P_{in} - P_{out} \right) \tag{2}$$

(b) the force due to vehicle piston effect [13]:

$$F_t = N\frac{\rho}{2} A_e C_D \left(V_t - V_r \right)^2 \tag{3}$$

(c) the force due to thrust by shaft ventilation:

$$F_s = \rho Q_s\left(\frac{Q_s}{A_b}\cos\beta - V_r\right) + \rho\left(Q_e - Q_s\right)\left(V_r - \frac{Q_s}{A_r}\right) \tag{4}$$

(d) the force due to thrust by operating jet fans:

$$F_j = n\eta_m \rho Q_j\left(\frac{Q_j}{A_j} - V_r\right) \tag{5}$$

(e) the force due to wall friction:

$$F_f = -\frac{\rho}{2}A_r f\frac{L}{D_H}V_r\left|V_r\right| \tag{6}$$

A more complete explanation of these forces were presented by Jang and Chen [11-12].

2.2 Modeling of Vehicle Emissions

Among all the comtaminants emitted from a vehicle, the smoke and CO (carbon monoxide) are the two most significant ones. The smoke concentration is used to ensure sufficient visibility in the tunnel whereas the CO concentration normally indicates the highest toxic level among all contaminants. As a matter of fact, the emission rate of these two contaminants depend on many factors. For example, trucks produce smoke whereas passenger cars do not. Other factors including the engine capacity; the fuel; the age, the mileage, and the brand of the vehicle; the driver's driving habit; the road conditions; and so on. According to a technical report by PIARC [14], the emission rates of smoke and CO from a vehicle can be estimated as

$$q_{smoke} = q_{smoke,veh}\cdot f_{iv}\cdot f_h\cdot m\text{, and} \tag{7}$$

$$q_{CO} = q_{veh}\cdot f_i\cdot f_v\cdot f_h, \tag{8}$$

where the q's are the emission rate of average vehicles whereas the f's are the factors associated with the road and vehicle conditions.

2.3 Transport Equation of Contaminants

Although contaminants emitted from a moving vehicle will propagate due to diffusive and convective mechanisms, the diffusive effect is basically ignored due to its insignificance in comparison with the convective effect. Thus, the propagation of smoke and CO particles can be modeled using the following simplified rule [10]:

$$\frac{\partial C}{\partial t} = -V\frac{\partial C}{\partial x} + Q_{veh} - \frac{C}{A_r}\frac{Q_{ex}}{\Delta x}, \tag{9}$$

where C represents smoke or CO concentration, V is the air speed, Q_{veh} is the vehicle emission rates for smoke or CO, Q_{ex} is the amount of exhaust air, and A_r is the tunnel cross-sectional area

2. 4 Algorithm of the Solver

Since the dispersion of smoke and CO in the tube depends strongly on the air velocity, it is the first task for the solver to determine the velocity distribution along the tunnel. The program solves simultaneousy for the velocities based on the 24-coupled Newton's Second Law, eq. (1), using the Gauss iteration method. Once the velocity distribution is known, the distributions of smoke and CO along the tunnel can be calculated. The algorithm for this computational scheme is shown in Fig. 5. In the beginning, the solver reads in the basic parameters. After that, ventilation-related settings, such as jet fan settings, smoke extraction vent settings, flow rate settings, etc., were entered. Then, the solver solves for the distributions of velocities, smoke and CO concentrations.

3. SIMULATIONS AND DISCUSSIONS

Although this program was developed specifically for the Guanyin Road Tunnel, the geometric parameters, including the tunnel length, height, slope, elevation, cross-sectional area, and hydrodynamic diameter, can be changed to suit other road tunnels. The ventilation parameters, such as the flow rates of the exhaust and intake facilities, can also be changed. The aerodynamics parameters related to the forces acting on the air along the tunnel are the wind speed difference between the north and south portals, the momentum loss coefficient associated with the entrance and exit of the tunnel, the coefficient of frictional loss due to the tunnel wall surface, the flow rates, and the moment loss coefficient of the jet fans. The piston effect, on the other hand, depends on the traffic condition within the tunnel. As a matter of fact, the traffic data is so dynamic that it can only be estimated. In real situation, the average numbers of trucks and passenger cars entering the tunnel are collected in the traffic control center located right in front of the tunnel entrance while the average vehicle speed is measured by the sensors installed in the tunnel.

For the conditions listed in Table 1, we can see that the traffic condition in the southbound tube is normal whereas the one in the northbound tube is congested. Therefore, it would be sufficient enough in the sounthbound tube just to activate some jet fans, i.e., 2 out of the 6 jet fans (JF501S~JF506S) and 2 out of the 6 jet fans (JF507S~JF512S). On the other hand, the large volume of vehicles in the northbound tube has a higher requirement for ventilation. For this reason, 3 out of the 6 jet fans (JF501N~JF506N), 1 out of the 2 jet fans (JF507N~JF508N), and 2 out of the 4 jet fans (JF509N~JF512N) are activated. Not only so, intake shaft injects fresh air into the northbound tube at a flow rate of 150 m3/s while 3 ventilation vents (SD520N~SD522N) are opened to remove contaminated air through the passage at a flow rate of 210 m^3/s. These three vents are highlighted with red boxes in Fig. 6. The flow rate settings are listed in Table 2.

The air velocity, smoke and CO variation along the Guanyin Road Tunnel is shown in Fig. 7. As shown in Fig. 7(a), the air velocity is constant everywhere within the tunnel. In real situations, the air velocity varies in accordance to localized factors, such as tunnel layout, facility installation, nonuniform traffic conditions, and so on. Since the overall nature of the tunnel ventilation is more important in this study, these relatively less important localized factors are not considered. The smoke and CO concentration is found to increase linearly along the traffic direction. Their maximum concentrations are obviously slightly greater than 0.4 which is way lower the standard value. This suggests that the ventilation setting solely based on jet fans is more than enough to handle the southbound traffic condition listed in Table 1. On the other hand, the air velocity in the northbound tube is much more complicated. At the section closed to the south portal, the air velocity is the highest while the smoke and CO concentrations are the lowest. It is observed that there exist several reduction in air velocity immediately downstram of the ventilation valves (SD520N~SD522N) when the air stream experiences a loss in momentum. At the same locations, the smoke and CO concentrations experience increases in concentration gradient. At roughly 8 km on the highway, there is an immediate increase in air velocity downstream caused by the fresh air injected into the tunnel through the intake shaft. With the additional fresh air, the smoke and CO concentrations in the air downstream of the intake shaft reduce dramatically. After this point, the smoke and CO concentrations keep on increasing until the air reaches at the north portal of the tunnel. Also noticed is that the smoke production rate is greater than the CO production rate in the nouthbound tube. In this case, the ventilation scheme is barely good enough to keep the contamination of the tunnel air under standard value.

4. CONCLUSIONS

A computer program has been successfully developed to investigate the ventilation characteristics of the Guanyin Road Tunnel. Based on the prescribed tunnel geometric parameters, ventilation parameters, and traffic data, the program is capable of estimating the air velocity within the tunnel and the distributions of smoke and CO concentrations. However, there are still a great deal of improvements to be incorporated in near future. The current version of the program has shown its abilities in fulfilling the basic capabilities to gain better understanding of the Guanyin Road Tunnel. However, more complicated functions and more general settings should be encompassed in future version of this program.

5. FIGURES AND TABLES

Fig.1 The geographical location and elevation of the Guanyin Road Tunnel (觀音隧道) in the Taiwan No. 9 Su-Hua Highway.

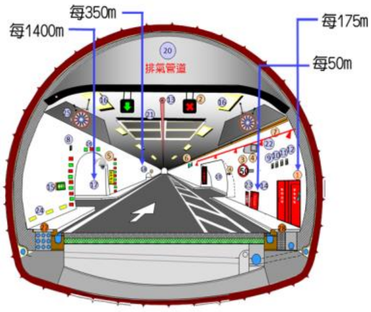


Fig.2 Illustration of the tube, the smoke extraction vents (no. 21), and the smoke removal passage (no. 20).

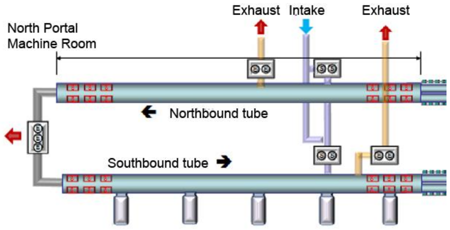


Fig.3 Schematic of overall ventilation system with its exhaust and intake shafts.

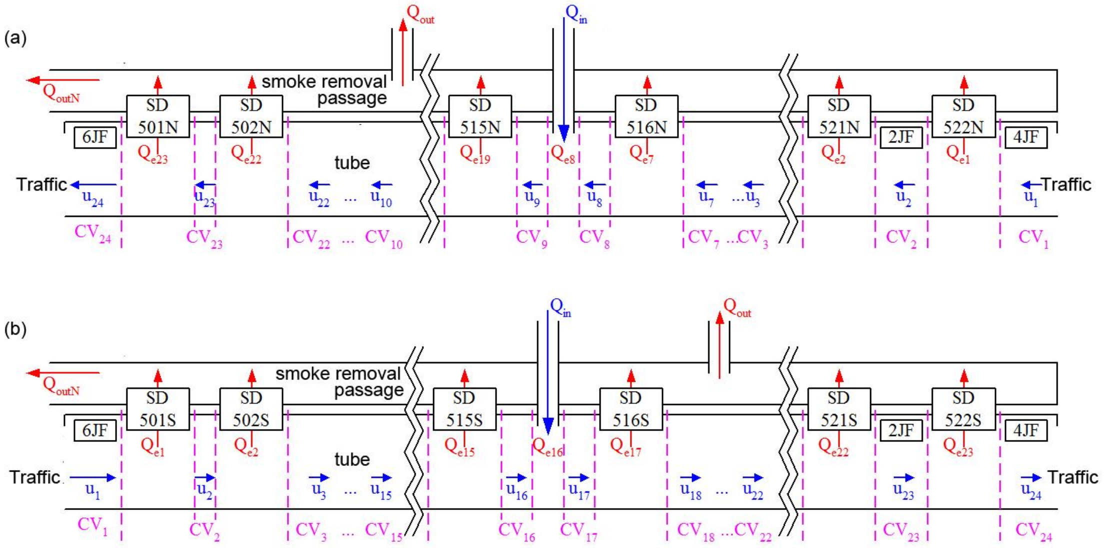


Fig.4 The schematic of the ventilation scheme along with the control volumes: (a) northbound, and (b) southbound.

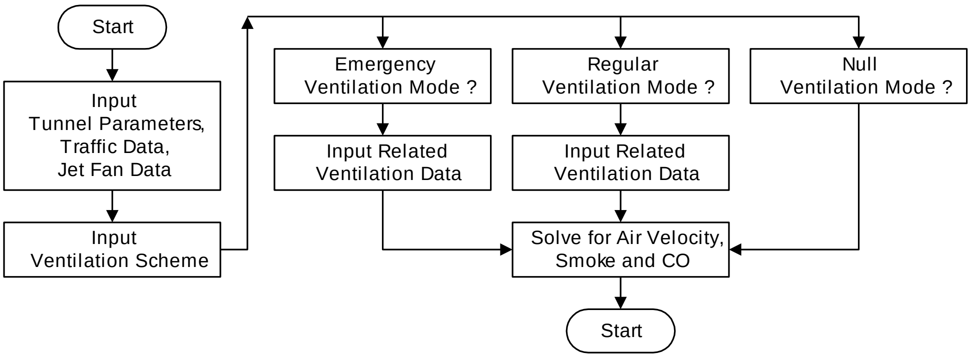


Fig.5 Algorithm of current solver.

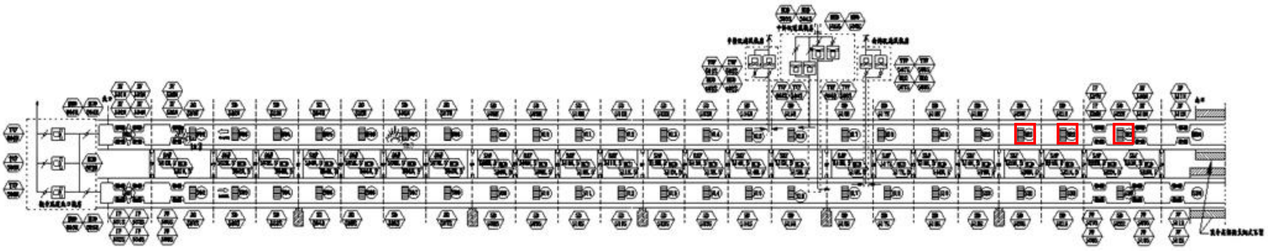
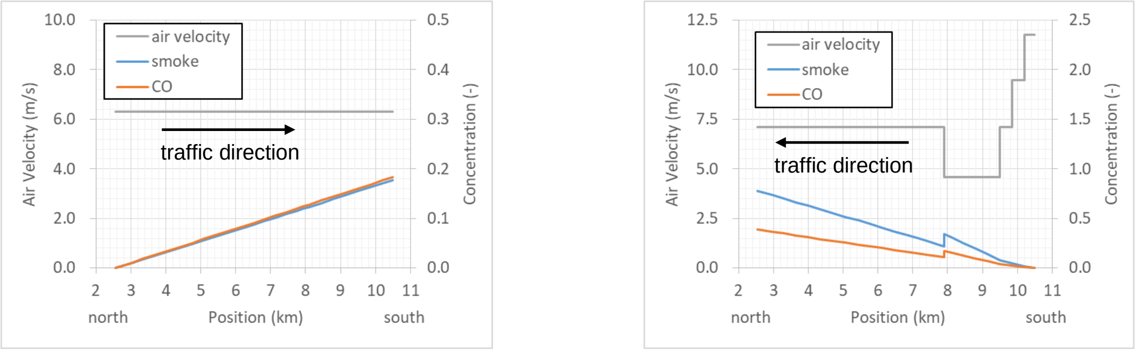


Fig.6 The numbering scheme for jet fans, smoke extraction vents, and other facilities.



(a) southbound tube (b) northbound tube

Fig.7 The schematic of the experiment: (1) sunlight; (2) collector; (3) funnel; (4) regulator; and (5) lightpipe.

Table 1. Traffic conditions

	Number of vehicle per hour		Average vehicle speed (km/hr)
	Passenger cars	Trucks	
Northbound tube	2,000	250	50
Southbound tube	1,100	150	70

Table 2. Shaft Ventilation Flow Rates

	North Portal	Exhause	Intake
	Flow rate at Regular Ventilation Mode (m^3/s)		
Northbound tube	210	210	150
Southbound tube	215	215	150
	Flow rate at Emergency Ventilation Mode (m^3/s)		
Northbound tube	340	340	150
Southbound tube	340	340	150

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