A numerical evaluation of the effect of portal exhaustion system

K Ishida, A Iida, A Mizuno
Kogakuin University, Japan

ABSTRACT

In recent years, exhaust gas emission out of tunnel portal has been a problem. In order to maintain the environment around the tunnel portal, concentrated exhaustion system is installed in some tunnels. In the area between the suction port and the portal, the air flows in the opposite direction to the traffic, so that the pollutant is sucked toward the exhaustion port. Evaluation and prediction have been performed using experiment or theory. However, there are many factors which affect carrying out of exhaust gas, such as a disturbance by automobile run and influence of a side wind. In order to grasp the detailed phenomena, the authors investigated quantitatively the extent of pollutant, which is brought out of tunnel portal, in terms of three-dimensional numerical analysis. This simulation system include sliding mesh algorithm in order to express the movement of vehicles. A typical result of the suction velocity of 3.0 m/s showed that almost no emission out of the tunnel is observed.

1 INTRODUCTION

In recent years, as environmental preservation measures, there are more one-way traffic automobile tunnels which install a concentrated exhaustion port before the exit portal (see figure 1) in order to reduce the exhaust gas that diffuses from tunnel portal. This concentrated exhaustion system allows to suppress the exhaust gas diffusion generated inside the tunnel, by bringing the fresh air from outside the tunnel, and by directing the ventilation flow in the opposite direction to the traffic between the concentrated exhaustion port and tunnel portal. Nevertheless, it is necessary to develop a highly accurate estimation method, as the environmental effect around the tunnel portal is viewed as a problem, caused by the partial emission of exhaust gas accumulated in the tunnel along with vehicle travel.

Traditionally, the evaluation and prediction of exhaust gas carried out along with vehicle travel was examined by the experiment with a model and by one-dimensional theory [1) 2)]. Still, the definitive evaluation method is not yet established, as the experiment machine examination simulating vehicle travel has problems such as measurement error and difference in Reynolds numbers.

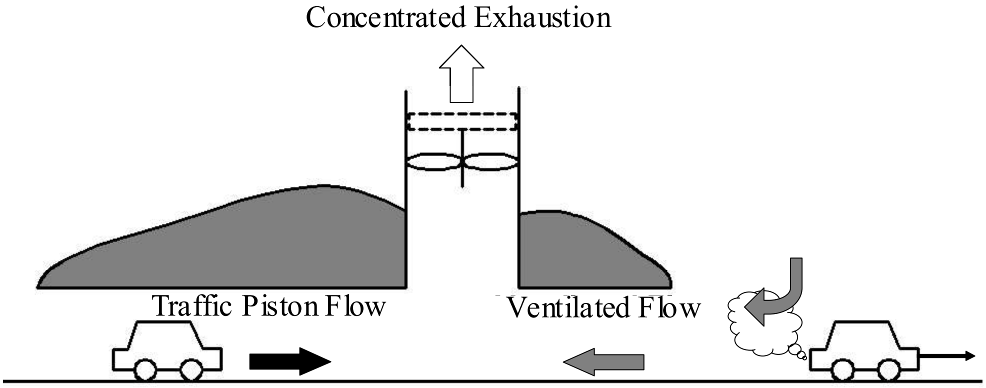

Figure 1. Schematic of Concentrated Exhaustion System

In this study, we would like to examine three-dimensional incompressible non-stationary fluid analysis to quantitatively evaluate the carrying-out of exhaust gas, along with the in-depth understanding of the phenomena of carrying-out of exhaust gas at the tunnel portal by the vehicle travel. Also, we examine the effect of natural wind (cross wind) outside of the tunnel to the carrying-out of exhaust gas.

2 ANALYSIS METHOD

In this study, we used STAR-CD, fluid analysis software that can deal with fluid, analysis of turbulent dispersion and the problem of moving boundary of vehicle. Vehicle travel is simulated by relatively moving the so called sliding mesh including the vehicles to the part of static mesh. After the vehicle travels to the ending point of analysis area, it is returned to the original point. By repeating this, we simulated the situation of infinite vehicle travel.

3 CONDITIONS OF ANALYSIS

This study is examined at the one-way, 2,000m length model tunnel, described in figure 2. To narrow the analysis size and to analyze precisely around the tunnel portal, the areas of analysis used for numerical analysis are both the zones of 200m before tunnel portal, and 60m from tunnel portal. The flow at the upstream side of the tunnel (1,800m zone from the inlet portal) and exhaust gas concentration distribution are calculated based on the technical standard of the tunnel[2)], and given as inlet boundary condition at 1,800m section (flow rate: 5m/s, exhaust gas (CO) concentration: 16.1ppm). Cross-sectional area of tunnel and exhaustion port area are 50m^2 respectively. The target of this analysis is standard-sized car and we determine the head to head distance of vehicles on a lane at 50m, running speed at 16m/s (57.6km/h). In this condition, the traffic volume is 1,152 vehicles/h.

In this study, we analyzed on the premise that the gas exhausted from the travelling vehicle is carbon monoxide (CO). The amount of exhaust gas emission is μ_{car}=1.1×10^3 ℓ/km [3)], and the CO present in the exhaust gas is μ_{co}=7 ℓ/km [3)]. Based on the above, the concentration of CO discharged from a vehicle is 6363ppm, and the mass flux of CO is M_{car}=1.3×10^{-4} kg/s. This analysis is conducted by using the vehicles which discharges constant quantity of mass flux of CO.

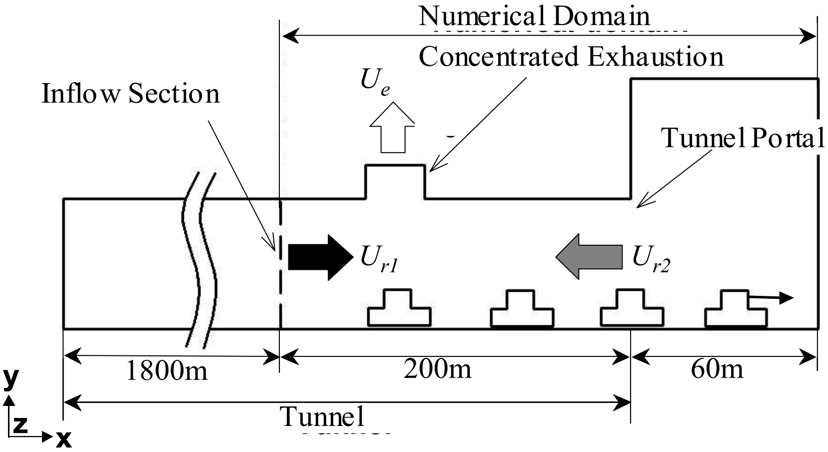

Figure 2. Schematic of Analysis Area

The number of total mesh in analysis area is approximately 350,000 grids. The number of mesh in the fixed part is around 250,000 grids and the sliding mesh including those of vehicle counts around 100,000 grids. The minimum mesh range in the neighbourhood of vehicle is 0.02m.

4 ANALYSIS PARAMETERS

Table 1 describes the analysis of cases. In the concentrated exhaustion system, the flow velocity U_{r2} between concentrated exhaustion port and tunnel portal is used as main parameter, as the flow velocity of suppression gives substantial effect to the carry-out of exhaust gas. The velocity of tunnel U_{r1} is 5m/s in all cases.

First, we analyse the case without concentrated exhaustion (case 0). Second, we changed the flow velocity of suppression U_{r2} by altering concentrated exhaustion flow velocity U_e for the purpose to examine the degree of change in suppressant effect of the carry-out of exhaust gas in case of concentrated exhaustion (case 1, case 2). Also, we examined the effect that natural wind gives to carry out the exhaust gas, by changing the cross wind (perpendicular to the tunnel) without altering the flow velocity parameters inside the tunnel (case3, case 4).

Table 1. Analysis of Cases

	Case0	Case 1	Case 2	Case 3	Case 4
Velocity of tunnel: U_{r1}	5 m/s	5 m/s	5 m/s	5 m/s	5 m/s
Velocity of concentrated exhaustion: U_e	0 m/s	8 m/s	6 m/s	6 m/s	6 m/s
Velocity of tunnel: U_{r2}	5 m/s	-3 m/s	-1 m/s	-1 m/s	-1 m/s
Velocity of cross wind: U_n	0 m/s	0 m/s	0 m/s	0.5m/s	2.5m/s

5 DEFINITION OF CARRYING OUT OF EXHAUST GAS FROM TUNNEL PORTAL AND THE CARRY-OUT RATE

In this study, the mass flux of exhaust gas in cross-section of tunnel portal M_{portal}[kg/s] is defined as:

$$M_{portal} = \sum_{n=1}^{N} (\rho_{co} dA\, U_{dim} C_{dim})_n \quad \text{[kg/s]} \qquad (1)$$

We define N as the number of partitions in the tunnel cross-section, ρ_{co} as the density of CO, dA[m^2] as minimal cross-sectional area at the tunnel portal cross-section, U_{dim}[m/s] as flow velocity (considering the direction of traffic as positive), and C_{dim}[ppm] as exhaust gas concentration at the minimal cross-section. In this study, the amount of exhaust gas carried out at the tunnel portal $\overline{M_{portal}}$ is defined as the time average of M_{portal} at the transit time of four vehicles, when the fluctuation of exhaust gas concentration field in the tunnel is considered to converge.

Traditionally, the ratio of exhaust gas carried out is equal to the amount of exhaust gas carried out at the tunnel portal divided by total exhaust gas generated in the entire tunnel length. In this case, the amount carried out becomes unclear in case the carry-out ratio is equivalent although total amount of exhaust gas differs based on the various tunnel extensions. Therefore, we use exhaust gas yield per 1km as benchmark, and defined E[-] as the ratio of exhaust gas carried out at the tunnel portal to the exhaust gas yield per 1km.

$$E = \frac{\overline{M_{portal}}}{M_{1\mathrm{km}}} \qquad (2)$$

In this equation, the $M_{1\mathrm{km}}$ is the exhaust gas yield [kg/s] per 1km in the entire tunnel. Based on the condition of the traffic volume and exhaust gas in this study, it is defined that: $M_{1\mathrm{km}} = 2.57$g/s

6 RESULTS OF NUMERICAL ANALYSIS

6.1 Suppressant effect by concentrated exhaustion at the tunnel portal

In case 0, case 1, and case 2, the exhaust gas concentration field (cross-section of 0.5m from the ground) around the tunnel portal is respectively presented at a, b, and c in figure 3. Figure 4 shows the time and field average of exhaust gas concentration distribution in respective area at the cross-section of tunnel. In case 0, the exhaust gas concentration in the tunnel come up to the maximum of 17.77ppm at the point 1m before tunnel portal, then diffuses outside the tunnel. Therefore, the exhaust gas concentration around the tunnel portal becomes significantly high. On the other hand, in case 1 and case2, where concentrated exhaustion are taken place, exhaust gas concentration around the tunnel portal was very low, thus may conclude that enough suppressant effect was achieved. Also, we confirmed that the diffusion of exhaust gas is successfully suppressed at a stronger flow velocity of suppression.

Table 2 shows the quantitative evaluation of exhaust gas carry-out from tunnel portal and its ratio. In case 0, at the tunnel of 2km long, almost all exhaust gas is carried out. Also, we found out that the carry-out value becomes negative in case of no cross wind, as the exhaust gas generated by vehicles outside the tunnel is blown back to the tunnel.

6.2 Effect on carry-out by cross wind

The exhaust gas concentration field around the tunnel portal (cross-section of 0.5m from the ground) in case 3 and case 4 is respectively presented at d and e on figure 3. Figure 5 shows the exhaust gas concentration distribution. When there is a cross wind, the exhaust gas is flown out of the tunnel, thus the exhaust gas concentration around the tunnel portal diminishes. Besides, we noticed that a strong cross wind may influence the flow inside the tunnel; therefore it helps to diminish the exhaust gas concentration around the tunnel portal. Figure 6 shows the iso-surface equivalent surface of exhaust gas concentration(0.5ppm), velocity vector, and the streamline at 5m before the tunnel portal. As shown in the figure, the eddy generated around the tunnel portal suppresses the carry-out of exhaust gas outside the tunnel.

Table 2 shows the quantitative evaluation of the carrying out of exhaust gas and its ratio. In case 3, we found out that the diminution of the exhaust gas yield outside the tunnel reduces the exhaust gas blown back to the tunnel, thus the amount to be carried out becomes larger, which makes the carry-out value positive. In case 4, the diminution of exhaust gas concentration around the tunnel portal results the carry-out value near 0.

Table 2. Comparison of Exhaust Gas Carried Out from Tunnel Portal and the Carry-out Ratio

	Case0	Case 1	Case 2	Case 3	Case 4
Amount carried out: $\overline{M_{portal}}$ [g/s]	5.05	-0.037	-0.023	0.013	0.069×10^{-3}
Carry-out ratio: E [%]	196.8	-1.44	-0.88	0.50	0.28×10^{-4}

7 CONCLUSION

Insights below are the results of examination of three dimensional numerical analysis on suppressant effect of exhaust gas carried out under the concentrated exhaustion system in the road tunnel.

- In case of no cross wind, the carry-out rate is negative, as not only the exhaust gas generated within the tunnel is not carried outside the tunnel, but also the exhaust gas generated outside the tunnel is blown into the tunnel.

- In case of cross wind, the carry-out rate is positive. The larger the cross wind velocity is, the more effect to the flow inside the tunnel, and the less exhaust gas concentration around the tunnel portal, therefore the less exhaust gas carried out.

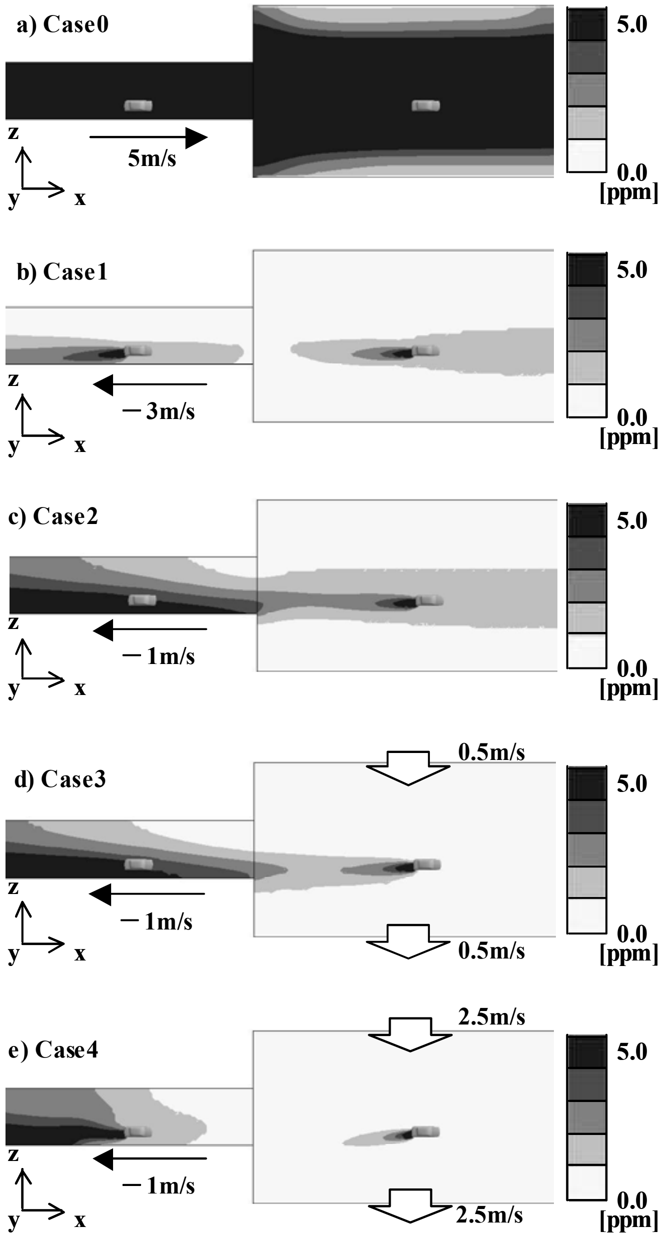

Figure 3. Exhaust Gas Concentration Field (0.5m from the ground)

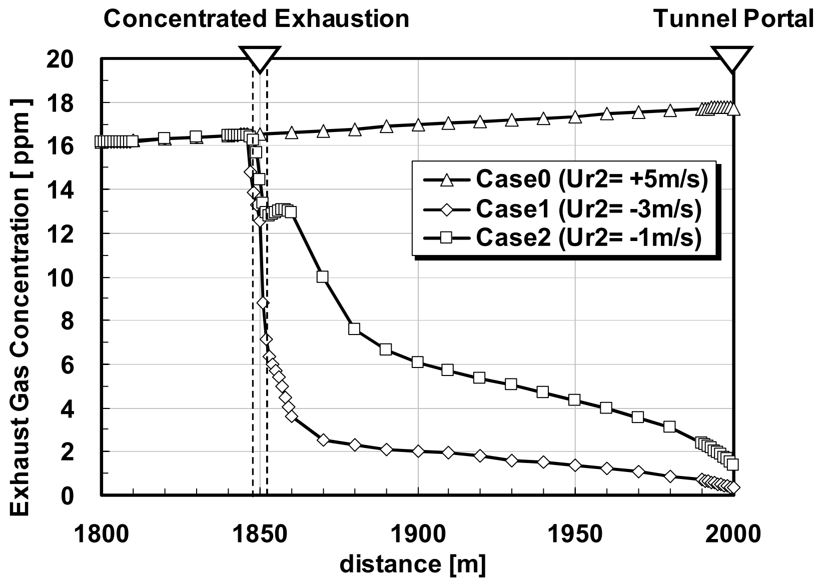

Figure 4. The Relation between Flow Velocity of Suppression and Exhaust Gas Concentration Distribution

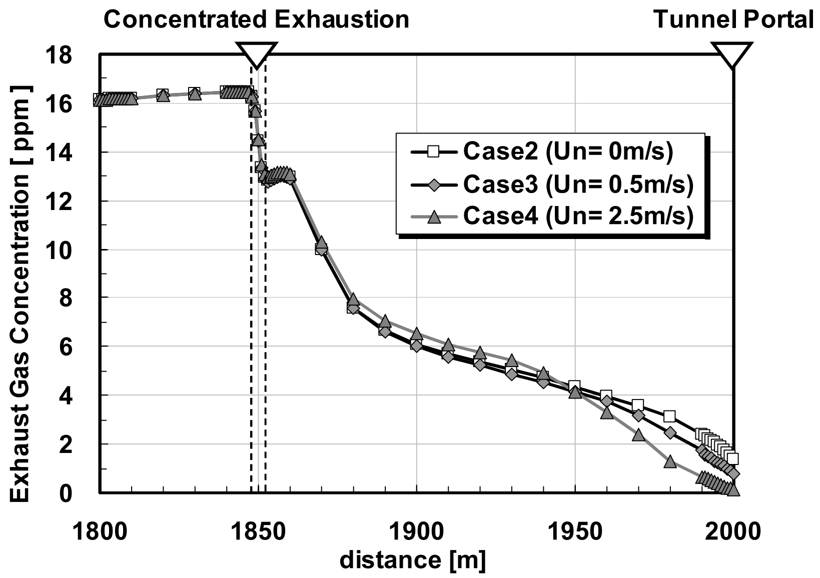

Figure 5. The Relation between Cross-wind Flow Velocity and Exhaust Gas Concentration Distribution

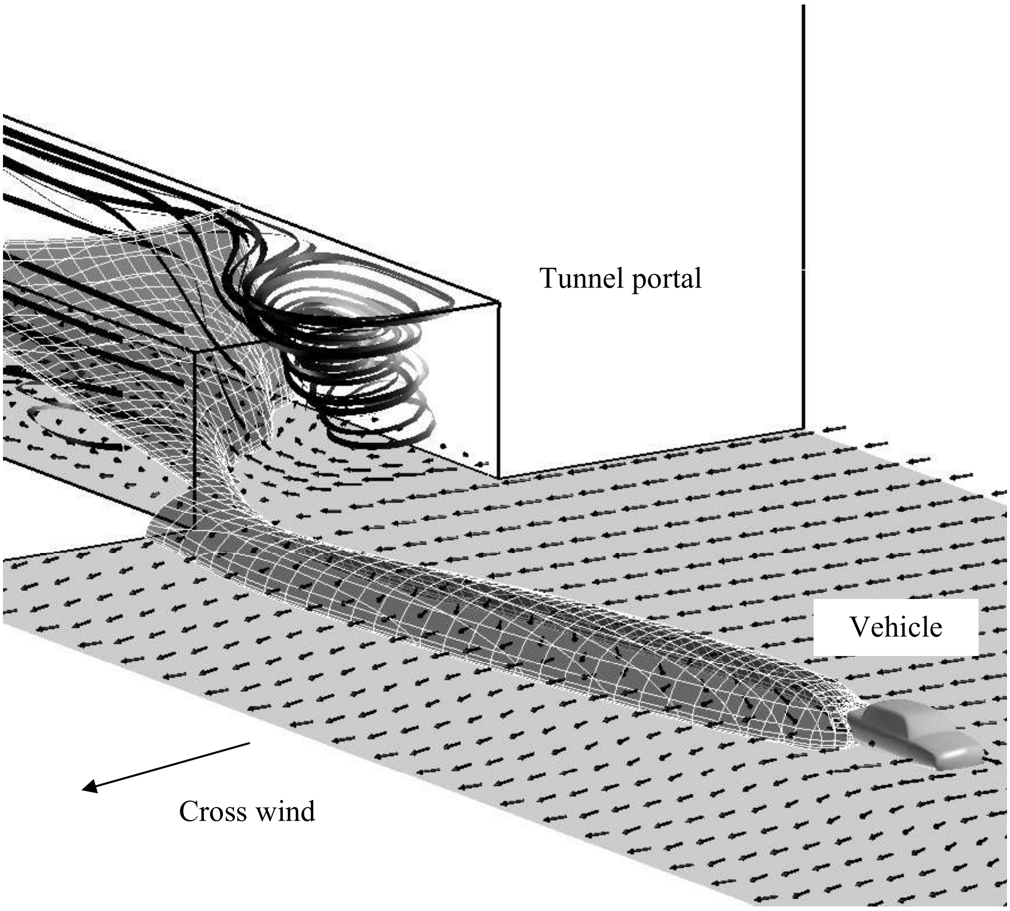

Figure 6. The Suppression of Carrying Out the Exhaust Gas by the Effect of Eddy

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