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Numerical analysis of pollutants dispersion in urban roadway tunnels

Yao Tao[1,2], Jingliang Dong[1,2] Yimin Xiao[1] and Jiyuan Tu[2]
1 College of Urban Construction and Environmental Engineering,
Chongqing University, Chongqing, 400045, China
2 School of Engineering,
RMIT University, Bundoora, Victoria, 3083, Australia

Abstract

Vehicular toxic emissions can easily contaminate the air quality of the enclosed tunnel environment especially during rush hours with traffic jam events or low vehicle speeds, which would pose serious health hazards to road utilizers. The piston effect generated by moving vehicles was normally considered adequate to discharge vitiated air out of short tunnels based on the typical driving speeds. However, complex traffic conditions may yield unexpected results of in-tunnel air quality. This study numerically investigated the in-tunnel contaminant dispersion by identifying the CO_2 concentration under three traffic conditions including the severe congestion and vehicle motion under low speeds. Fan conditions were considered to generate mechanical winds and to compare with the motion-induced airflow. Elevated CO_2 concentration were found at the vicinity of near-ground region and downstream the tunnel. Despite that the piston effect induced by a higher vehicle speed that could sufficiently controlled the in-tunnel CO_2 concentration, the conditions that cars were idling and moving under a lower speed still encountered with accumulation problems of vehicular emissions. The ceiling mounted mechanical ventilation had a limited contribution to the discharging of emissions when integrated with the motion-induced wind.

Introduction

Roadway tunnels are increasingly being constructed worldwide as an alternative way to reduce commute time and alleviating traffic congestion. However, vehicular toxic emissions, such as CO, NOx, and smoke, can easily contaminate the air quality of the enclosed tunnel environment and bring hazardous respiration issues to drivers and commuters, especially during severe traffic events. The pollutants concentration within road tunnels depends on factors that determine vehicle emissions (e.g. traffic volume, speed, fuel quality and tunnel length) and the rate of dilution (affected by the tunnel ventilation system, traffic volume and speed). For short roadway tunnels, the piston effect induced by the moving vehicles can drive fresh air in and discharge vitiated air out of tunnels. While for relatively long roadway tunnels, mechanical ventilation approaches such as jet fans are needed in addition to the piston effect to remove toxic gases emitted by vehicles in the tunnels and keep the vehicular toxic emissions within safety limits, especially during traffic jams.

Studies of the piston effect and mechanical jet fans have received extensive research attention for decades. Chen et al. [1] experimentally studied the piston-effect and jet fan-effect based on a rotating-belt model vehicle tunnel. Their results demonstrate that the vehicle speed plays a more important role on the flow velocities distribution inside the tunnel than the vehicle spacing and vehicle size. Although a larger fan velocity can generate a higher flow velocity inside the tunnel, a worse exhaust concentration in the lower region of the tunnel may occur. Chung et al. [2] numerically modelled the turbulent flow and pollutants dispersion in a road tunnel. Their results reveal that cross-sectional concentrations of air pollutants are non-uniformly distributed and the concentrations rise in proportion with downstream distance. Bari et al. [3] built a computational model based on a real tunnel case to study the air flow and pollutants levels under traffic congestion and fan power failure conditions, and a detrimental condition of in-tunnel air quality was captured. Ashrafi et al. [4] simulated the air pollution dispersion inside tunnels and obtained the spatial distribution of air pollutants for evaluating the ventilation efficiency, and obtained a good agreement between modelling and measurement data. Meanwhile, the air pollution near road tunnel portals also generates potential health hazards to residents living nearby. Matsumoto et al. [5] developed an air quality simulation model combining the effect of the jet stream from the tunnel portal and the ambient wind field, and good conformity was obtained between the numerical results and the air tracer experimental data. Eftekharian, Dastan, Abouali, Meigolinedjad and Ahmadi [6] conduced a numerical investigation into the performance of jet fans in an urban tunnel under severe congested traffic condition. Their results show that the average CO concentration under traffic jam condition was higher than the permissible level in the vicinity of human breathing zone. Eftekharian, Abouali and Ahmadi [7] also obtained a correlation for pressure drop due to stopped cars inside the tunnel as a function of tunnel average air velocity and tunnel length from CFD simulation results, to optimize the estimation of pressure drop due to vehicles. With the advantage of visualization to provide details that hard to obtain from on-site measurement, and cost-less than running scaled models, CFD techniques have been widely used to study pollutant transport and distribution in the tunnel under severe traffic jam conditions.

However, most researches focused on the effects on severe traffic congestions that vehicles were idling, while in real situations of traffic congestions, vehicles often moved under a low velocity that dynamically influenced the airflow and contaminant transport around the vehicles. Solazzo, Cai and Vardoulakis [8] simulated the flow and turbulence induced by atmospheric wind and vehicle motion within an idealised street canyon. Moving wall conditions were set at the street facets to generate the relative motion. They proposed the simplified methodology that could analyse the transport and dilution of pollutants emitted by vehicles at street level. López González, Galdo Vega, Fernández Oro and Blanco Marigorta [9] numerically analysed the influence of the piston effect in the longitudinal ventilation system of subway tunnels using a dynamic mesh technique. They quantified the different parameters influencing the sub-way ventilation system and addressed the impact of the piston effect on the global ventilation performance for the system studied.

The piston effect induced by the vehicle motion is a highly complex, three-dimensional and unsteady process. Whether the flow patterns associated to the piston effect under low speeds could be adequate to discharge air pollutants, and how it could incur risks of exposure to in-tunnel hazards remains unclear. This study aims to investigate the influence of piston effect resulted from the vehicle motion on the spatial distribution of pollutants inside the tunnel and out of the exit portal. The interaction between motion-induced airflow and mechanical ventilation was also considered. Numerical simulations using dynamic mesh method were performed on three road tunnel traffic condition (i.e. idling, 10km/h and 40km/h), under fan on and off conditions respectively. CO2 concentration was used to represent vehicular emissions under those scenarios.

Numerical Modelling

Governing equation

For a three-dimensional time-dependent turbulent and buoyant flow of an incompressible fluid, the Reynolds-average Navier-Stokes equations (RANS) are solved for the fluid phase, using the commercial CFD package ANSYS Fluent. The general transport equation where continuity, momentum equations, turbulent quantities and energy are given is stated as equation (1):

$$\frac{\partial \rho\phi}{\partial t} + \frac{\partial(\rho u_i \phi)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S_\phi \quad (1)$$

where, Φ represents the general variables, Γ represents the diffusion coefficient and S_Φ represents the source term, u_i is the velocity component in i direction. The expressions for Φ and S corresponded to each transported variable. The standard k-ε turbulence model is adopted to predict the air flow pattern, and the transport of the vehicular pollutants is governed by the mass-fraction equations. All transport equations are discretised using second-order upstream scheme. The SIMPLE algorithm was used for pressure-velocity coupling. The vehicle motion was achieved by integrating dynamic mesh technique using laying method to update the deformed meshes before every time step in the unsteady process.

Model Geometry and Boundary Conditions

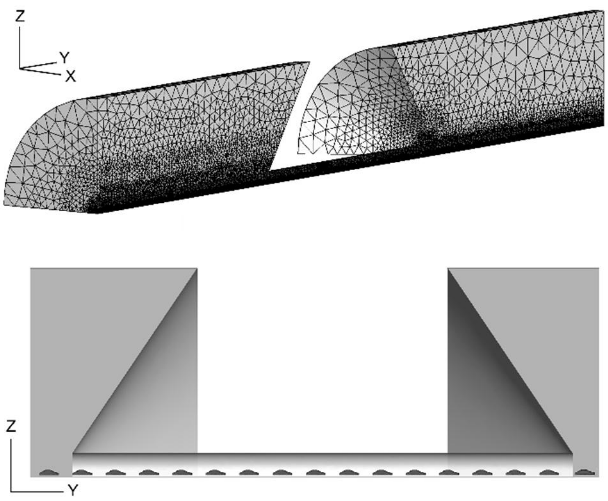


Figure 1. The computational domain and mesh generation

The fluid domain of the current numerical model consisted of a one-way tunnel, upstream and downstream open roadway extensions, and atmosphere sections at the tunnel entry and exit where hillsides were simulated (Figure 1). Here we assumed a roadway tunnel with two traffic lanes and a semi-circular roof. The tunnel had a radius of 5m and a length of 120m, so as the length of each open road extensions. The open roadway sections were modelled as a half cylindrical shape with a radius of 10 times of the road tunnel's radius.

In order to save computational time, the whole system was split from the YZ-plane where symmetric flow features were assumed. The semi-circular tunnel was then built as a quarter of a circular roof with one traffic lane. The whole computational domain was meshed into hybrid meshed of tetrahedral volumes for moving vehicles set as the moving mesh, and hexahedral control volumes for the rest of the tunnel as the fixed mesh. The moving part and stationary part of meshes in the model were matched as interfaces. A mesh independence study was conducted by consecutively reducing cell spacing by a factor of 1.2 and plotting the velocity magnitude along a vertical line which was 1.0 meters behind the centre of a vehicle in the middle of the tunnel (Figure 2). We started with a grid of 0.9 million and subsequent grids of 1.7 million, 2.8 million and 4.8 million were made. The velocity profiles showed convergence between mesh size 2.8 million and 4.8 million and for computational efficiency and accuracy, the 2.8 million model was chosen for the remainder of the study.

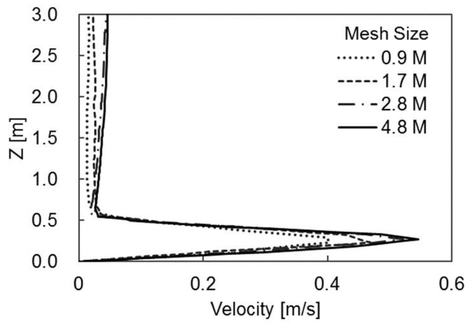


Figure 2. Mesh independence study: comparisons of velocity simulation results of four grids on a vertical line behind a vehicle

The no slip stationary wall boundary condition was used for the tunnel walls and car bodies. Three different traffic condition under vehicle velocities of 0 km/h (car idling), 10km/h (low speed) and 40 km/h (medium speed) were considered to simulate possible scenarios when traffic congestion happened. Distances between vehicles were calculated according to the safe following distance that allowed 2 seconds for vehicles to stop, thus 6 meters for 0 km/h and 10 km/h and 12 meters for 40km/h. Symmetry boundary was set at the mid-plane for the whole system. Despite that for short tunnels the airflow driven by the movement of vehicles (the 'piston-effect') is normally adequate to manage in-tunnel air quality, the fan condition was designed in this study to generate an in-tunnel wind velocity to interact with the piston effect. The fan was located 0.5 m to the ceiling of the tunnel, horizontally 40m to the entrance and 80m to the outlet, met the requirement of fan installation in long tunnels. A pressure jump of 150Pa in the driving direction was prescribed for the fan boundary, which generated a fan outlet velocity of 10m/s and an average in-tunnel wind velocity of 1.47m/s according to the simulation results. Opening boundary conditions were imposed on the atmosphere region as pressure-inlet and pressure-outlet. In order to control the flowing direction for all the cases, a slight pressure value of 0.1Pa was imposed on the pressure-inlet for all the cases, to generate a negligible velocity of around 0.3m/s according to our simulation results.

The exhausts were released at the outlet vent with a diameter of 0.06m at the back of every vehicle. In the real condition, the tailpipe was located at the left, the right or both sides of the car. For simplicity, our study assumed the locations of tailpipes were in the middle for all the vehicles, set as a velocity inlet with a speed of 3 m/s under the traffic conditions. CO_2 was chosen as the indication of in-tunnel air quality. The mass fraction of air components released from gasoline engines were: O_2 = 0.02, CO_2 = 0.17, CO = 0.005, and the other component was regarded as N_2, with an air temperature of 30 C. The air intake of the tunnel had a CO_2 mass fraction of 0.006, corresponding to an approximate concentration of 400ppm, with a temperature of 20 °C.

The severe traffic jam with no vehicle motion was calculated under the steady state. While for the vehicle motion, given the process of exhaust dispersion from running vehicles was time-dependent, we regarded the vehicles running through a tunnel length (120m) as a baseline cycle during which vehicles were still fully occupying the tunnel. Once the vehicles finished a cycle, the results of the whole flow domain were interpolated as the initial condition for the original case to run again. In that way the continuous running was approximated. The area-averaged CO_2 concentration at tunnel outlet was monitored to find the time for the whole system to reach equilibrium. The time for different traffic conditions to became nearly steady are shown in Figure 3. Vehicle speeds of 10km/h and 40 km/h with fan-on and fan-off conditions achieved nearly steady state at the fifth cycle. Therefore, the results after running for 5 cycles were used for the comparisons (results were obtained at t = 200 s for 10km/h and t = 50s for 40km/h)

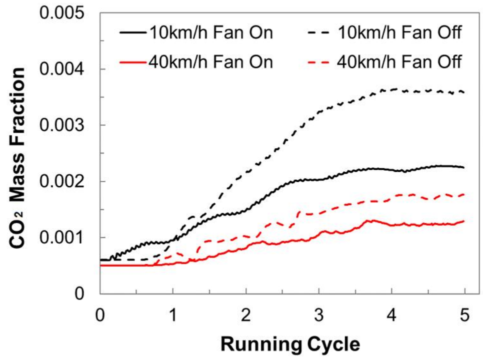
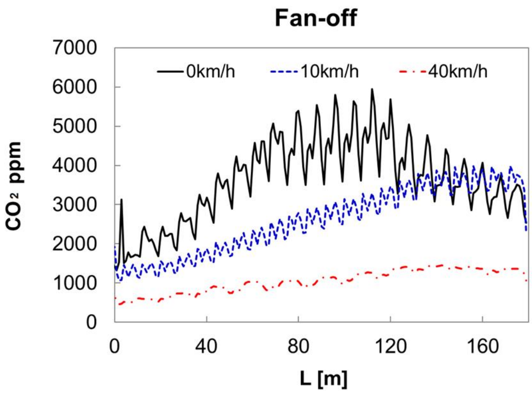


Figure 3. The area-weighted CO_2 mass fraction at the tunnel exit against the calculation cycle. One cycle equals to the duration for vehicles to run through 120m under corresponding vehicle speeds.

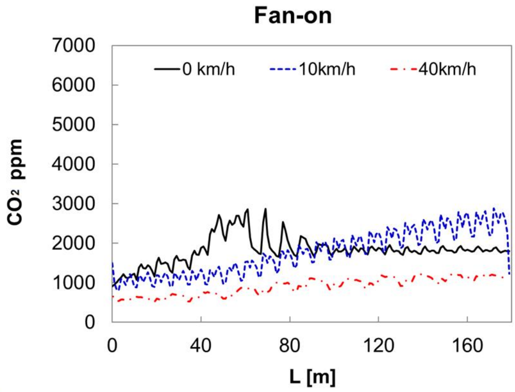
Results and Discussion

Influences of the vehicle speed

The average CO_2 concentration at the height of 1.0m under three traffic conditions with the fan turned off are plotted in Figure 4(a). Under the severe traffic congestion (0 km/h), the average CO_2 concentration increased notably along the tunnel length since no piston effect or mechanical ventilation was introduced to the tunnel. The highest CO_2 concentration went up to 3000 ppm at the location about 40m downstream, and reached the highest level of 6000 ppm inside the tunnel near the tunnel exit. as vehicles occupying the tunnel increased blockages to the in-tunnel airflow and led to more vitiated air accumulate inside the tunnel at the lower height (1.0 m) downstream the tunnel. Coming out of the tunnel exit (120m), the CO_2 concentration gradually diminished due to the diffusion to the ambient air on the open roadway.



(a)



(b)

Figure 4. The area-weighted CO_2 concentration (ppm) at the height of 1m under 3 traffic conditions. the calculation cycle. The distance started from the tunnel entry (1m).

When vehicles started to travel along the tunnel, the in-tunnel airflow was pushed to flow which was referred to as the piston effect. The average velocities at the tunnel exit were 1.37 m/s and 4.49 m/s under vehicle speed of 10km/h and 40km/h respectively, at the nearly steady state (t = 200s) discussed above. With the piston effect, the in-tunnel concentration notably decreased. The vehicle speed of 10 km/h pushed contaminants to move downstream rather than the accumulate inside the tunnel that idling cars yielded. Under this low vehicle speed, the CO_2 concentration at the height of 1.0 m reached about 3000 ppm at the exit, which were also a hazardous level for the environment. Air flow induced by vehicle speed of 40km/h showed a higher capability to discharge emissions due to higher in-tunnel wind speed induced by higher vehicle speed, and also due to the halved number of vehicles running thus reduced the total emissions under the higher vehicle speed. Generally, the pollutant discharging under vehicle moving conditions showed an increasing trend along the downstream distance, even kept the same concentration level of CO_2 after coming out of the portal. The piston effects obviously produced the jet stream from the tunnel exit portal into the ambient, for which the CO_2 concentration continued the emission level out of the portal rather than a dilution as the idling cars experienced. The vitiated air came out to the open roads with the running of vehicles might bring issues to the surroundings.

When the fan was turned on, an additional wind velocity alleviated the CO_2 concentration level. At the exit portal of the tunnel, the CO_2 concentration reduced by 53%, 34% and 16% when the vehicles were running under 0km/h, 10km/h and 40km/h respectively. Under the severe congestion, the average velocity at the tunnel outlet was 0.30m/s under the fan-off condition and 1.47 m/s under the fan-on condition. The mechanical ventilation kept the CO_2 concentration under around 3000 ppm comparing to the highest 6000 ppm under the severe traffic condition. But high emission concentrations still accumulated in the downstream part of the tunnel. Out of the portal the concentration maintained in a lower level. This was related to the different airflow features that induced by vehicle motion and mechanical fans, that fans induced airflow in the upper part of the tunnel while vehicles pushed the airflow at the lower height near the vehicles.

CO_2 Concentration and Velocity Distribution

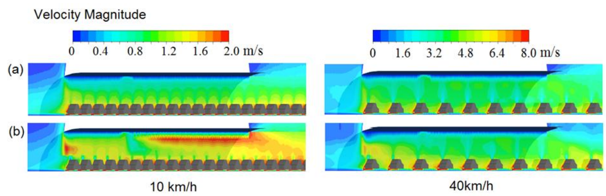


Figure 5. Velocity field at the plane through the centre of car bodies (X = -2.1m) under vehicle speeds of 10 km/h and 40 km/h at (a) fan-off; (b) fan-on conditions.

The velocity and concentration distribution through the middle plane of the cars (X = -2.1m) under vehicle moving conditions are shown in Figure 5. The view focused on the tunnel section and was rotated to shorten and clear the picture. The natural wind pushed by moving vehicles showed high velocities around the bodies, while the wind at the upper part of the tunnel were relatively stagnant. With an outlet velocity of 10m/s, the fan-induced airflow generated confined jet-like airflow with high wind velocities at the ceiling but the velocities were lower around the vehicles. While as the vehicle speed increased, the fan-induced airflow showed minor effects on the whole tunnel's velocity distribution.

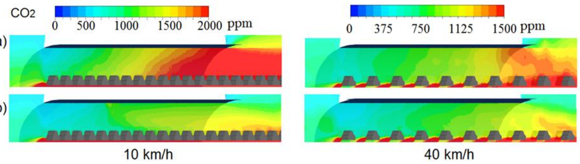


Figure 6 Contour of CO_2 concentration at the plane through the centre of car bodies (X = -2.1m) under vehicle speeds of 10 km/h and 40 km/h at (a) fan-off; (b) fan-on conditions.

The CO_2 distribution at the plane X = -2.1m is shown in Figure 6. When the discharging of vehicle emissions depended merely on the piston effect (Figure 6(a)), the higher velocities around the moving vehicles pushed the exhausts to flow downstream the tunnel. However, vitiated air gradually accumulated at the downstream ceiling due to the thermal buoyancy and the low wind speed at the upper part of the tunnel. A higher vehicle speed (40km/h) also occurred the same problem that high concentration of CO_2 gathered at the outlet, but it discharged the contaminants considerably well and only small regions with high CO_2 concentration were found at the portal.

With the fan turned on and generated higher wind velocities near the roof, the high level of CO_2 concentration at the ceiling was discharged and the ascending due to buoyancy effect was overwhelmed. Finally, the contaminants were controlled within a lower concentration at the exit portal and the surrounding environment. Under a higher vehicle speed of 40 km/h that the fan-induced airflow was comparatively weak compared to the motion-induced wind, the piston effect was already adequate for keeping the in-tunnel CO_2 concentration within an acceptable range. The mechanical ventilation effects showed significance in assisting the discharge when it was comparable to the average piston wind generated by the vehicle motion. While the piston wind became larger (at 40km/h), the mechanical ventilation became dispensable.

Conclusions

The distribution of CO_2 concentration inside a short tunnel was numerically investigated to identify the air quality under traffic conditions of car idling and slow motion. Under the idling condition that no piston effect or mechanical ventilation was introduced, vitiated air in the downstream region identified as a risky CO_2 levels. The piston effect helped the elimination of emissions adequately under a vehicle speed of 40 km/h. But a lower vehicle speed of 10km/h still encounters the high CO_2 concentration levels at the downstream part and the exit portal of the tunnel.

With the additional mechanical ventilation, the CO2 level under idling condition was controlled at a lower level however still showed a higher concentration at the middle of the tunnel. As an additional wind speed to the piston effects, it helped the discharge of emissions at the upper part of the tunnel that came from the thermal buoyancy, and kept the remained CO_2 at the exit portal an acceptable level around the vehicles. But for higher vehicle speeds (40 km/h) the fan was dispensable. Although normally the forced ventilation is not required for the short tunnels, it showed a significance to eliminate emissions when piston effect is not sufficient under complex traffic conditions.

Acknowledgements

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