Influence of Moving Vehicles on Pollutant Dispersion in Street Canyon: A Numerical Study

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ABSTRACT

The occurrence of "crazy bad" air pollution in many cities of China often hits the international headlines. In Hong Kong, the outdoor air quality faces great challenges as well. According to the report released from the Environmental Protection Department of the Hong Kong Government, vehicular emissions and street canyon effects are the two main contributing factors to roadside air pollution. This paper outlines the findings from our numerical investigation of the dynamic pollutant dispersion as induced by moving vehicles within the street canyon environment of Hong Kong. The integrative computational fluid dynamics (CFD) models, including the standard k-ε model for airflow turbulence, the species transport model for gaseous pollutants, and the dynamic mesh model for moving vehicles, were validated by wind tunnel measurements as well as reported data from published literatures. Our findings confirm that moving vehicles could generate secondary airflow, and hence introduces additional ventilation effects. This leads to continuous interaction between the wind flow and the wake of vehicles, and in addition, promotes the mixing and transportation of the vehicle exhausted pollutants. Dynamic impacts of the moving vehicles on the airflow field (such as the flow velocity) and the pollutant dispersion (such as the concentrations of CO from a stationary line source and NO_2 from the moving point source) were found highly dependent on: (i) The geometrical configuration of the street canyon; (ii) The mode of vehicular movements, such as in single- or multi-lanes and their travelling directions, and (iii) The position of the monitoring site, i.e. near the leeward/windward wall, at the middle of the street canyon, or near the two street end openings.

Keywords: *micro-climate, sustainable neighbourhood, roadside air quality*

1. INTRODUCTION

The occurrence of "crazy bad" air pollution in many cities of China often hits the international headlines. In Hong Kong, the outdoor air quality faces great challenges as well. According to the report released from the Environmental Protection Department of the Hong Kong Government, vehicular emissions and street canyon effects are the two main contributing factors to roadside air pollution, which is often associated with high pollutant concentrations exceeding current air quality standards. Therefore, air quality in urban street canyon has garnered great interest and numerous studies have been conducted to enrich our understanding of the airflow field and the mechanisms of pollutant transport, dilution and removal in street canyon. Several parameters that dominate the pollutant dispersion process can be classified as geometrical, meteorological related, and traffic related.

It is undeniable that traffic is one most dominating risk for the urban atmospheric environment. However, the influence of on-road vehicles on the air quality of urban canyon is far more complicated than just simply considers it as the source of diverse atmospheric pollutants. Previously, theoretical studies, field measurements, wind tunnel experiments, as well as computational fluid dynamics (CFD) techniques were used to interpret the detailed processes of airflow and pollutant distribution under the influence of moving vehicles. In general, the rapid running vehicles on-road can themselves introduce secondary airflow and additional ventilation effect due to the continuous interactions between the natural wind and vehicle wakes. Consequently, in the presence of moving vehicles, the normal airflow pattern and pollutant distribution profile within a street canyon will be broken up, and both micro- and large-scale mixing and dispersion processes will take place. The complexity in predicting the pollution distribution and in the assessment of air quality will considerably increase.

In this present work, dynamic impact of the moving vehicles on the airflow and pollutant dispersion within the idealized deep and uniform canyons were investigated by innovatively adopting the dynamic mesh model based on the FLUENT software platform. As to the model validation, the wind tunnel test section was modified to incorporate the Moving Model Rig for the vehicle movement. Research outcomes are expected to help narrowing the knowledge gap in understanding the influence of traffic on the transport characteristics of pollutants, and to help identifying spots vulnerable to be polluted.

2. NUMERICAL METHODOLOGY

2.1 Studied cases

The size of the computational domain in all studied cases is X = 600m, Y = 290m, and Z = 150m (Figure 1). The idealized urban street canyon is formed by two parallel aligned blocks—the upstream and downstream building blocks. Each has the dimensions of LB = 90m, WB = 30m, and HB = 30m. Both the deep (aspect ratio=3) and the uniform (aspect ratio = 1) street canyons were investigated. The approaching wind was set perpendicular to the long axis of the street canyon. The double-decker-bus model (Lv = 12.5m, Wv = 2.5m, and Hv = 4.5m) run through the street canyon at a moderate speed of 36 km/h. Each bus model has a 0.1m diameter exhaust tail-pipe at its rear end. Traffic pollutants from the constant traffic fleet and from the moving vehicles were investigated separately. The vehicular emissions from the steady traffic fleet are simplified as: (i) a ground-level continuous pollutant area source of Carbon Monoxide (CO) in the deep street canyon, and (ii) the line source(s) of CO in the uniform street canyon. The emission from the exhaust tail-pipe of a moving vehicle is taken as a moving point source of Nitrogen Dioxides (NO_2). The dynamic impact of the moving vehicles are studied in four different scenarios: (i) Scenario#1: Single vehicle runs on the one-lane street of the deep canyon (Figure 2a); (ii) Scenario#2: Two vehicles run in the same direction of the two-lane street of the deep canyon (Figure 2b); (iii) Scenario#3: Two vehicles run in the opposite directions of the two-lane street of the deep canyon (Figure 2c); and (iv) Scenario#4: Four vehicles run on the four-lane street (two-way traffic) of the uniform canyon (Figure 2d).

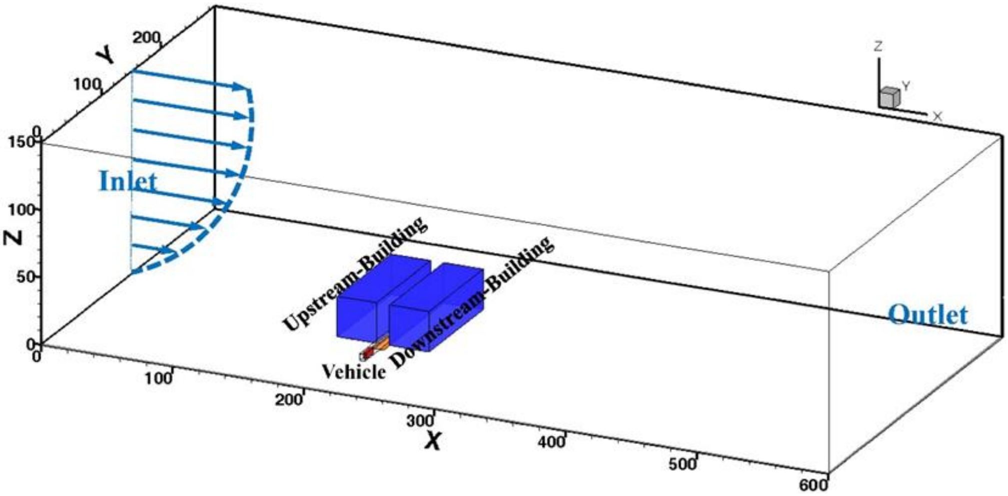

Figure1: Geometrical layout of the computational domain (Scenario#1)

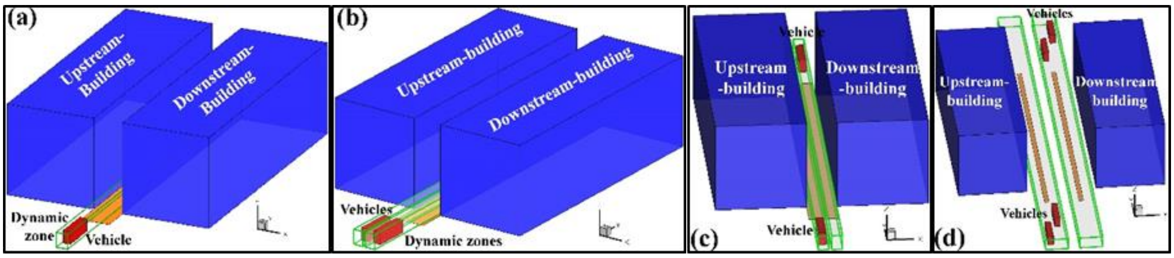

Figure 2: Core region of the computational domain in four different scenarios

2.2 Numerical models

The standard k-ε model was used in this airflow study due to its simplicity, low computational cost, robustness and relatively good accuracy. The species transport model was employed to simulate the dispersion and distribution of the tracer gases. The dynamic mesh model was adopted to deal with the influence from a moving object on the airflow field and the pollutant concentration field. The integral form of the conservation equation for a general scalar Φ, on an arbitrary control volume V with moving boundary can be written as:

$$\frac{d}{dt}\int_{V} \rho\Phi dV + \int_{\partial V} \rho\Phi(\vec{u} - \overrightarrow{u_m}) \cdot d\vec{A} = \int_{\partial V} \Gamma\nabla\Phi \cdot d\vec{A} + \int_{V} S_{\Phi} dV$$

Equation 1

where ρ is the fluid density, $\vec{u}$ is the flow velocity vector, $\overrightarrow{u_m}$ is the grid velocity of the moving mesh, ∂V represents the boundary of the control volume, Γ is the diffusion coefficient, S_{Φ} is the source term of Φ. The computational domain should be divided into two separate sections: (i) the dynamic mesh zone for the moving vehicle model, and (ii) the static mesh zone for the rest domain. The interface data exchange between the two sections was implemented by the grid interface principles of sliding mesh theory. The dynamic layering method was employed to update mesh only in the dynamic mesh zone. User-Defined Functions (UDFs) served to define and track the motion of vehicle model. In our previous studies, the dynamic influence of human walking movement on the airflow and particle concentration in ventilated room have been successfully modelled and investigated. On this technical basis, the linear movement of on-road vehicles can be appropriately modelled.

Accordingly, the inlet of the computational domain was set as velocity inlet with a power-law wind profile. The mean velocity u_H at the top of the building was set 2.5m/s and with the exponent α at 0.4 for urban terrain. The temperature of the approaching wind was 303.15K. The outlet, the top and two side surfaces of the computational domain were defined as the Outflow Boundary Condition and Symmetric Condition. The bottom of the computational domain, and all surfaces of the two buildings as well as the vehicle models were defined as No-slip Wall. After the time step independent tests, the time step of 0.02s for Scenario#1 and 0.01s for Scenario#2-#4 are selected for dynamic simulation. The SIMPLE algorithm was used to solve the Pressure-Velocity coupling equations. The Pressure was discretised using the second order scheme. For the discretization of the governing equations, the second-order upwind scheme was used for the convection terms, and the central differences scheme with second order accuracy was for the diffusion terms. The scaled residual criteria for all the flow properties were set at 10-5.

Extensive tests on the independence of the meshes were carried out with increasing mesh numbers until further refinement was shown to be insignificant. Finally, the Moderate Mesh for each scenario (about 2 million cells) was adopted for the following simulation.

2.3 Model validation

Good performance of the standard k-ε model coupled with the species transport model in modelling the airflow pattern and the tracer gas concentrations within street canyons was demonstrated by comparing the computer outputs with the wind tunnel database of CODASC. The competence and performance of the adopted models for capturing the initial pollutant dispersion from a diesel vehicle were also validated by comparing with the measured data from Chan et al., 2001.

To validate the dynamic mesh model for vehicular movement, a series of tests was carried out in the wind tunnel laboratory of the City University of Hong Kong. The wind tunnel was modified to accommodate a moving model rig, which allowed the scaled vehicle model to be fired across the test-section of the wind tunnel. A gas supply system was specially designed for the continuous releasing of tracer gas (Propane) during the forward movement of the vehicle model. SWEMA03 Anemometers and HRF 400 fast FID systems were appropriately installed and tuned preceding to the measurement of the transient and time average features of wind flow and tracer gas concentrations. Close agreements were found between the measured and modelled data (results are not shown here), which strongly indicates that the integrative model adopted in this study can provide a reasonable description of the transient flow physics under the dynamic influence of vehicular movement.

3. RESULTS AND DISCUSSION

For the convenience of making comparisons amongst the different scenarios, airflow velocity, concentrations of CO and NO_2, and time series were normalized to become Vel*, CO*, NO_2*, and Time* respectively. Time* = 0 stands for the start of the vehicle movement; Time* = 0.5 represents the arrival of vehicles at the middle of the street canyon, and Time* = 1.0 indicates that the vehicle reaches the terminal end of the moving path and stops moving forward. Moreover, the sampling time is much longer than the whole moving duration of the vehicle in order to include the recovery process after the pass of moving vehicle. In this study, the contours of Vel* and CO* are first presented to help capturing the general features and rules of the dynamic influence. Then, detail effects of the potential influencing factors are discussed by analysing the temporal variation of NO_2*.

3.1 General characteristics of dynamic impact

Dynamic impacts on the Vel* and CO* distributions at the adult breathing height (z/Hv = 1/3) within the deep street canyons (Scenario#1 - #3) when the vehicles are at the mid-point of the street canyon (Time* = 0.5) are illustrated in Figure 3 and Figure 4 respectively.

Take Scenario#1 in Figure 3 as an example: the most striking features of the dynamic influence on the airflow pattern are the generation of the "Propelling effect" in the form of a relatively high Vel* in front of the head of the moving vehicle, and the "wake effect" characterized by a stripe of high Vel* following its rear end. Within the semi-confined space (i.e. the train tunnel), the train movement would generate the "piston effect". For the street canyon environment, the combined effect of "propelling effect" and "wake effect" of each individual vehicle can be taken as the equivalent "piston effect". Similar dynamic impacts on pollutant (CO*) distribution within the deep street canyon can be found in Figure 4, where the polluted air in front of the vehicles is pushing forward due to the "Propelling effect" and the relatively clean air is entrained into the vehicle wake due to the "Wake effect". Moreover, we expected that vehicles running in the same direction (Scenario#2) would enhance the combined influence of "piston effect". Such influence would be attenuated when the vehicles running in the opposite directions (Scenario#3).

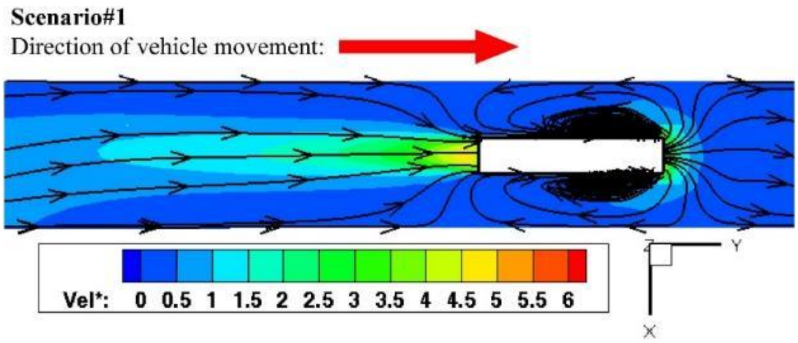

Figure 3: Contour of Vel and airflow streamlines at the height of adults' breathing zone (z/Hv=1/3) for Scenairo#1 within deep street canyon*

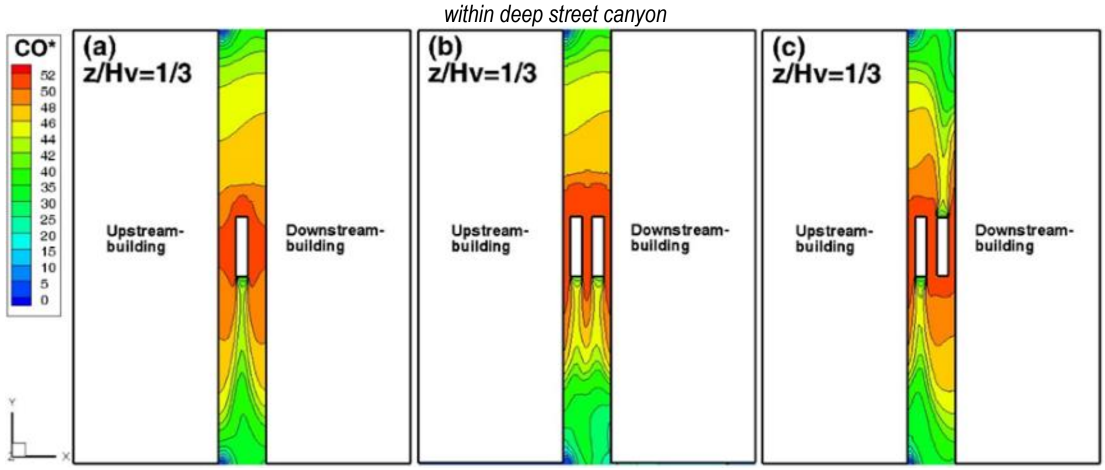

Figure 4: Contours of CO at the adult breathing height (z/Hv = 1/3) within deep street canyon*

3.2 Effects of influencing factors

In this section, the temporal variation of NO_2* is analysed to help figuring out the detailed effects of potential influencing factors.

Figure 5(A) presents the time series of NO_2* at the adult breathing height near the leeward and windward walls for the above four scenarios. The dynamic variation pattern and magnitude of NO_2* in the deep canyon (Scenario#1 - #3) are found quite different from that in the uniform street canyon (Scenario#4), even though Scenario#3 shares similar mode of vehicle movement with Scenario#4. This indirectly demonstrates that geometrical configuration of the street canyon has an important role on the influencing range and the extent of the dynamic impact induced by the moving vehicles. Compared with the uniform street canyon, air ventilation is less effective in the deep street canyon, leading to a relatively stronger transient influence of vehicle movement. Secondly, the dynamic impact is found in close association with the mode of the moving vehicles — the number and the travelling direction. Take the deep canyon (Scenario#1 - #3 in Figure 5A) as an illustrating example. NO_2* in Scenario#1 is much lower than those in Scenario#2 and #3, which strongly indicates that single moving vehicle would release less amount of pollutant, while multiple moving vehicles would generate stronger dynamic influence on the transportation and dispersion of vehicular pollutants. Moreover, vehicles running in the same direction (Scenario#2) would reinforce the combined "piston effect", enhance the disturbance on the airflow, and promote the transport of pollutant. However, individual "piston effect" would offset by one another when the vehicles run in the opposite directions (Scenario#3). This results in a reduction of dynamic disturbance at the far field, but at the same time, generates a "mixing effect" which would promote the dilution and mixing of local pollutant around the moving vehicles. Therefore, NO_2* in Scenario#2 is relatively higher than that in Scenario#3. Thirdly, the difference in transient distribution of pollutant can be observed between the leeward and windward sides due to the joint effect of vehicle induced airflow and the ambient wind field. Generally speaking, in the deep street canyons (Scenario#1 - #3), the variation trends of NO_2* near both sides share the similar pattern but carry remarkable different peak values. For the uniform street canyon (Scenario#4), NO_2* peak value on the windward side is much higher than that on the leeward side. However, long-lasting influence is actually found near the leeward wall.

Dynamic variations of NO_2* at the adult breathing height at different horizontal positions near the windward wall in Scenario#2 is shown in Figure 5(B), where 0 LB, 1/4 LB and 1/2 LB are at the opening, the quarter, and the centre of the street canyon, respectively. It can be seen that NO_2* at the street openings (0 LB) is lower than that in the internal space of the street canyon (1/4 LB and 1/2 LB), due to the outside clean air fills in through these two openings. Also, the occurrence time of the NO_2* transient variation is found in tight relationship with the time instance when the moving vehicle passes by the adjacent monitoring site.

Figure 5(C) gives the temporal variations of NO_2* at different vertical heights of the street canyon (z = 1/6 HB, 1/3 HB, 2/3 HB and 1 HB) for Scenario#2. NO_2* at the lower level of the street canyon is found much higher than that at the upper level, and the occurrence time of concentration peak at the lower level is prior to the upper level. However, certain amount of pollutants can still reach the upper height of the street canyon. Such enhanced vertical dispersion of vehicular pollutant induced by the moving vehicles might call for extensive research efforts on dynamic simulation, because there might be unexpected exposing risks at some places (i.e. higher level of the street canyon), which may not be predictable by the conventional steady state simulation.

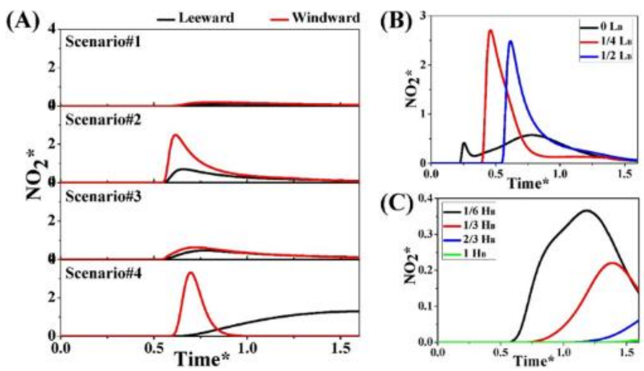

Figure 5: Time series of NO2 (A) Near the leeward and windward wall for the four different scenarios; (B) At different horizontal positions for Scenario#2; and (C) At different vertical heights for Scenario#2*

4. CONCLUSION

Dynamic impacts of the moving vehicles on the airflow and pollutant dispersion within both the deep and uniform street canyons were numerically investigated under four different scenarios. This was by employing the standard k-ε model for the airflow turbulence, the species transport model for the dispersion of tracer gas, as well as the dynamic mesh model for the vehicle movement. These adopted numerical models were validated by wind tunnel measurements and reported data from the published literatures. Dynamic simulation results clearly confirm that moving vehicles could generate secondary airflow and hence introduce additional ventilation effects, in the form of the combined effect of "Propelling effect" and "Wake effect". This leads to a continuous interaction between the wind flow and the wake of vehicles, and also promotes the mixing and transport of vehicle exhaust pollutant. Dynamic impact of the moving vehicles on the airflow field and the pollutant dispersion are found highly dependent on: (i) The geometrical configuration of the street canyon; (ii) The mode of vehicular movements, such as in single- or multi-lanes and their travelling directions, and (iii) The position of the monitoring site, i.e. near the leeward/windward wall, at the middle of the street canyon, or near the two street end openings. Finally, a deductive conclusion can be made based on this dynamic simulation study. There might be unexpected exposing risks at some places (i.e. at higher level of the street canyon), which may not be predicted by the conventional steady flow simulation. Hence, more research efforts are needed for investigating the urban air quality under dynamic impact of moving vehicles.

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