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The impact of traffic-flow patterns on air quality in urban street canyons

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A B S T R A C T

We investigated the effect of different urban traffic-flow patterns on pollutant dispersion in different winds in a real asymmetric street canyon. Free-flow traffic causes more turbulence in the canyon facilitating more dispersion and a reduction in pedestrian level concentration. The comparison of with and without a vehicle-induced-turbulence revealed that when winds were perpendicular, the free-flow traffic reduced the concentration by 73% on the windward side with a minor increase of 17% on the leeward side, whereas for parallel winds, it reduced the concentration by 51% and 29%. The congested-flow traffic increased the concentrations on the leeward side by 47% when winds were perpendicular posing a higher risk to health, whereas reduced it by 17–42% for parallel winds. The urban air quality and public health can, therefore, be improved by improving the traffic-flow patterns in street canyons as vehicle-induced turbulence has been shown to contribute significantly to dispersion.

1. Introduction

Traffic-flow in urban systems is dynamic. In urban centers, frequent interruption to traffic flows due to intersections and changes in street layout lead to a frequent change in traffic-flow patterns. Free-flow induces more turbulence in the lowermost portion of the canyon, which reduces pollutant concentrations and improves air quality in the breathing zone compared with congested conditions. Further street canyons in which buildings limit the dispersion of pollutants emitted by the vehicles often tend to be poor in air quality (Kumar et al., 2008) as buildings themselves tend to prevent simple advection from transporting pollutants from their source. Rapidly increasing urbanization and accompanied number of vehicles may further accentuate the exposure leading to even higher risks. A few studies on urban traffic-flow patterns (Gokhale and Pandian, 2007; Gokhale, 2011, 2012) reported that urban traffic flow is often interrupted resulting in frequent stop-go and congested-flow conditions. This is one of the main causes of higher emissions and poor air quality in urban traffic corridors. In case of street canyons, additionally, the buildings surrounding the street help create pockets of higher pollution. These studies, however, used analytical methods. The computational fluid dynamics (CFD) based modeling may provide better insight into the dispersion, wind-flow vectors and the resulting pollutant levels in street canyons. Vardoulakis et al. (2003) and Li et al. (2006) have presented extensive reviews of street canyon air quality modeling using CFD. CFD modeling of wind flows and pollutant dispersion generates the wind flow and concentration fields in street canyons of any configuration. It, therefore, improves the understanding of the behavior of urban systems. It may not be used for direct comparison with regulatory standards of pollutant concentration (Vardoulakis et al., 2003). RANS models with standard, RNG and Realizable k-ε turbulence closure schemes are widely used to study the wind flow and pollutant dispersion in street canyons due to their computational robustness and efficiency (Li et al., 2006). These schemes are also well validated for engineering application flows. However, difficulty is in the validation against field data in real urban configurations. Therefore, standardizing CFD modeling practice is essential to assure the quality of results.

Franke et al. (2007) have detailed the guidelines for conducting CFD simulations in an urban environment, to improve the results of modeling studies. Most studies considered 2D representation of street canyons simulated with perpendicular winds. May be

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because the perpendicular wind is worst for pollutant dispersion (Gromke and Ruck, 2012). The 2D representation does not adequately capture the wind-induced flow pattern in street canyons, making 3D modeling the only recourse (Li et al., 2006). Tsai and Chen (2004) carried out 3D simulations for a street canyon of 0.8 aspect ratio for perpendicular winds and found that the leeward side concentration was 64–107% higher compared to the windward side. This indicates that the perpendicular winds are more critical to air quality in street canyons. Another study supported this, as Soulhac and Salizzoni (2010) by an analytical model showed that parallel winds ventilated pollutants better. Besides wind flows, turbulence generated due to vehicular movement is significant for pollutant dispersion, particularly when wind velocity drops below 1.5 m s^{-1} (Solazzo et al., 2007). Murena et al. (2009) found better agreement between the measured and modeled concentrations when vehicle induced turbulence (VIT) was included in the CFD model. Several studies thereafter incorporated VIT in the air quality models and reported the increase in prediction accuracy (Gallagher et al., 2013; Solazzo et al., 2011). It, however, increases the computation time as it adds an equation (Gallagher et al., 2013). In low-winds (<1.5 m s^{-1}), the VIT becomes a significant driver of pollutant dispersion in street canyons (Sini et al., 1996). A few studies (Gallagher et al., 2013; Murena et al., 2009; Solazzo et al., 2011) reported that it improves accuracy in the modeled concentrations, however, the influence of wind flows on the VIT is not studied.

These studies primarily focused on the parameterization of traffic turbulence and the method of inputs to the numerical models (Solazzo et al., 2008, 2007). The dependence of VIT on wind-flow angles (direction) has not been studied. As the wind induced turbulence for different wind-flow angles is significantly different, the influence of VIT during different wind-flows may also not be same. This understanding calls for the study of the behavior of VIT under different wind-flows as well as free, interrupted and congested traffic-flow patterns, and its influence on the dispersion and the reduction in pollutant concentrations in street canyons.

In this study, therefore, the impact on pollutant concentrations in a real asymmetric urban street canyon during different traffic-flow patterns and wind-flows with and without the influence of VIT has been investigated using 3D numerical modeling. The focus has been on two aspects, one the influence of VIT under two principal wind-flows – parallel and perpendicular; and two, the influence of the traffic-flow patterns – free, interrupted and congested on pollutant dispersion and reduction in pollutant concentrations. The comparison of with and without VIT pollutant concentrations has been done in order to evaluate the percentage change in pollutant concentrations. The present study used Realizable k-ε turbulence closure scheme for a real asymmetric street canyon. The modeling was conducted in accordance with COST guidelines (Franke et al., 2007).

2. Method

2.1. Study site

A street canyon, located in the urban center of Guwahati, India, on the AT Road at 26.10N and 91.45E coordinate, 200 m long and oriented along NW–SE was selected for the study. The street canyon is asymmetric with the surrounding buildings 4–30 m high (Fig. 1). The street is 24 m wide, including sidewalks each of 5 m with a clear 14 m wide carriageway. The site is in proximity of the railway station, which ensures heavy flow of pedestrians. The average traffic flow in the canyon has been 2176 veh h^{-1}. The street canyon experiences varied traffic-flow patterns with frequent interruption and congestion.

2.2. Field study

The CO concentrations and the meteorological observations were measured daytime from 10 am to 5 pm on December 23–27, 2013 with the CO Analyzer (Delta Ohm model, HD37AB17D). The CO measurements were taken at a height of 2.2 m at one location on Side A of the canyon and the meteorological observations (wind speed and wind direction) were taken on the rooftop of a building near air quality station. The location of the air quality monitoring was on the leeward side for perpendicular (from West) winds. The CO concentrations were hourly averaged to correspond with the meteorological parameters. The wind speed was in the range of 0.3–2.2 m s^{-1} and the predominant direction of wind was from South, which was parallel to the street canyon. The traffic-flow rate and the various traffic-flow patterns were recorded at the site and observed with the videotapes. The traffic count was done in four categories – two-wheeler (scooter, motorcycle), three-wheeler (auto-rickshaw), four-wheeler (passenger car, MUV) and diesel-driven four-wheeler HDV/LDV (bus, minibus, truck) for the purpose of estimating emissions for modeling. The amount of emission changes with the traffic speed and the level of traffic congestion. Therefore, three traffic-flow patterns – free-flow (FF), interrupted-flow (IF) and congested-flow (CF) were observed from the traffic data and studied. The average speeds for the vehicles of each category during these patterns were estimated from the videotapes (Table 1).

2.3. Methods for emission calculation

The COPERT-IV methodology, which employs speed-dependent equations, was used to estimate the emissions for different traffic-flow patterns. Traffic speed varies with the traffic flow rate, interruption, and the degree of congestion on the road, which results in the change in traffic-flow patterns and accordingly the change in emissions. Therefore, three scenarios were developed for the modeling study, viz. free-flow (uninterrupted traffic, FF), interrupted-flow (stop-and-go traffic, IF), and congested-flow traffic (CF). Table 1 shows the speeds corresponding to each pattern, used to estimate the traffic density. In order to account for the heterogenous traffic (mixed), the traffic-flow rate was expressed in terms of passenger car units per hour (PCU/h) and the density as PCU/km. The PCU values suggested by IRC (1990) for urban Indian roads were used, viz. 0.7 for two-wheeler, 2.0 for autorickshaw and 3.7 for bus.

2.4. The CFD modeling

2.4.1. Numerical model

The numerical simulations were carried out by the Ansys Fluent v14, a widely used CFD code for flow and pollutant dispersion studies (Garcia et al., 2013; Murena et al., 2009; Sabatino et al., 2008). A steady-state Realizable k-ε turbulence model was used, the most advanced model and best for the flows involving separation and complex flow features. e.g. streamline curvature, vortices and rotation (AnsysFLUENT, 2011). The pollutant transport was modeled by the conservation equation for species transport solved together with the equations of the mean-flow characteristics, as given by the governing Equations (1)–(5).

The continuity equation:

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

The momentum conservation equation: