Physical modeling of vehicular pollution dispersion in an isolated urban street canyon under heterogeneous traffic conditions and its simulation by Artificial Neural Network (ANN) technique

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ABSTRACT: Wind tunnel modeling technique has been extensively used to investigate air pollution dispersion phenomena in the urban street canyon(s). These studies have shown that the vehicle-induced effects can be adequately simulated in the wind tunnels under different ‘control’ conditions. However, most of these studies have been carried out under homogeneous traffic conditions and only a few studies have been reported for mixed traffic conditions which are typical of most of the developing countries. In the present study, experimental data have been obtained at the Environmental Wind Tunnel (2mx2mx16m) facility at the Indian Institute of Technology (IIT) Delhi (India), to evaluate the effects of traffic parameters on the pollutant concentrations in the urban street canyon. Recently, Artificial Neural Networks are being increasingly used for vehicular exhaust emissions modeling under the complex urban conditions. The present investigation also demonstrates the ability of these ANN models to simulate, the complex non-linear interaction between various variables and predict the pollutant concentrations in an urban street canyon under mixed traffic conditions dominated by vehicle-induced effects.

KEYWORDS: Vehicular pollution, Exhaust dispersion, heterogeneous traffic, Urban street canyon, Environmental wind tunnel, Artificial neural networks

1 INTRODUCTION

Air pollution from motor vehicles is one of the most serious and rapidly growing problems in various urban centers of the world. Predicting the distribution of pollutants under various urban conditions such as urban street canyon is extremely complex involving a variety of physical and meteorological factors including vehicle emissions, wake effects, canyon wind flows and turbulent dispersion [1]. Over the past two decades, significant progress has been made in understanding and modeling vehicular pollution dispersion phenomena within urban street canyons by using Environmental Wind Tunnel (EWT) technique. These studies have greatly helped in determining the pollutant concentrations within the street canyon as a function of building dimensions, upwind building configuration, wind direction with respect to building configuration and roof geometry [2]. Recently, various studies have shown that the vehicle-induced turbulence (or mixing) is an important factor of pollutant dispersion in these urban street canyons, particularly under low wind conditions which are typical of urban street canyons [3,4]. Moreover, most of these studies have been carried out under homogeneous traffic conditions. As a result, most of the models (empirical or semi-empirical) developed on the basis of these studies
do not adequately account for the vehicle-induced mixing, leading to inaccurate and unreliable predictions, and sometimes even misleading conclusions under these heterogeneous traffic and low wind speed conditions. Only a few studies have been carried out and reported in literature, to know the effect of vehicle-induced mixing on pollution dispersion phenomena in the urban street canyons under heterogeneous traffic and low wind speed conditions. The present study is aimed at enhancing our understanding regarding the complex dispersion phenomena in urban street canyons under these conditions.

In recent years, feed-forward ANN trained with the back-propagation have become a popular and useful tool for modeling various environmental systems, including its application in the area of air pollution and vehicular exhaust emissions modelling under the complex urban conditions [5,6]. The multilayer ANN or Multilayer Perceptron (MLP) can be trained to approximate virtually any smooth measurable function. The ability of the ANNs to ‘learn by example’ makes it an important tool to simulate dispersion phenomena in complex urban environmental situations where complete understanding of the dispersion mechanisms including the interaction between various influencing variables still does not exist (black-box approach). The present investigation also demonstrates the ability of these ANN models to simulate and predict the pollutant concentrations in an urban street canyon under mixed traffic conditions dominated by vehicle-induced effects.

2 METHODOLOGY AND EXPERIMENTAL SET UP

2.1 Simulation of atmospheric boundary layer

The experiments were conducted in the EWT facility located at IIT Delhi. It is an open circuit, low speed and suction type Boundary Layer Wind Tunnel (BLWT), having a 2m ×2m cross-sections with the boundary layer development-cum-test section of 16m length. The mean velocity profile throughout the entire depth of the boundary layer is represented by the power law equation \( u/U_\infty = (z/\delta)^\alpha \). An artificially thickened boundary layer with \( U_\infty = 1.23 \text{ m/s}, \delta = 800 \text{ mm} \) and power law index (\( \alpha = 0.35 \)) typical of ‘large city centers’ has been produced. Based on the value of ‘\( \delta \)’ = 600 m, the simulated ABL is represented to a scale of 1:750.

2.2 Street canyon model

A simple geometry represented by two building blocks (L x B x H; 1.25m x 0.25m x 0.25m) spanning the width of wind tunnel at the turntable section has been used to model the street canyon. The present configuration ensures systematic study of pollution dispersion phenomena within the urban street canyon with varying aspect ratio (ratio of street width W to building height H), as a function of different traffic (volume, speed) and meteorological conditions (wind direction) without any effect of surrounding buildings and other building configurations. The difference in model scale, determined from the approach flow profiles i.e., ABL (1:750) to that of street canyon model (1:100) will not have any significant effect, as under all experimental conditions the model is always completely submerged in the simulated and fully developed ABL. The street canyon model was placed at the centre of the turn-table at equal distances on both the sides of precisely designed line-source [7].

2.3 Simulation of traffic in the EWT

A model traffic movement system has been designed and made used in the EWT [7]. Plate’s criteria was employed to simulate the vehicle-induced turbulence in the EWT. The modelling criteria for vehicle-induced turbulence is based on the condition that the ratio of the energy production caused
by the moving traffic ($P_T$) to the energy production caused by the wind ($P_W$) (referred to as the scaling factor in the literature) should be the same in the model and prototype of a street canyon, based on the Plate’s criteria, Kastner-Klein et al \[3,4\] derived the equation which converted the actual traffic / meter to traffic / meter in the EWT. The same methodology was also employed in the present study to simulate the vehicle - induced turbulence.

Heterogeneous (mixed) traffic conditions with traffic composition consisting of 55% two wheelers, 30% four wheelers (mostly cars), 10% buses and 5% commercial vehicles (mostly trucks) (typical of traffic composition generally observed on the Indian urban roads). Vehicle models in the form of rectangular blocks scaled (1:100) as per their actual sizes and attached to MVMS. For simplicity, all vehicles were represented by their respective rectangular block shapes, instead of actual shapes, as it will not have any significant effect in terms of the turbulence generated by these vehicles.

2.4 Tracer dispersion experiments

Dispersion experiment in the EWT was carried out by releasing a neutrally buoyant tracer gas mixture of 5% acetylene in grade I nitrogen through the line source. For tracer gas concentration measurements, a Flame Ionisation Detector (FID) type of Gas Chromatograph (GC) was used. Tracer measurements were carried out for 2 walls (windward and leeward) x 4 wind angles (0°, 30°, 45°, 90°) x 3 aspect ratios (1.2, 1.0, 0.8) x 5 sampling locations along the length of the street canyon x 6 sampling locations along the height of the street canyon at $Z/H=0.06, 0.2, 0.4, 0.6, 0.8, 0.95$ x 4 (traffic volumes - no vehicular movement or no traffic conditions, 1500 vehicles/h, 2200 vehicles/h and 3000 vehicles/h). They correspond to 2880 measurements (1440 each for windward and leeward sides/walls of the street canyon model).

3 MODELLING OF EWT DATA USING ARTIFICIAL NEURAL NETWORK (ANN) TECHNIQUE

In the present study ‘Stuttgart Neural Network Simulator’ (SNNS, Version 3.1) has been used to train and model the EWT data. This software is freely available via the internet (ftp://ftp.informatik.uni-stuttgart.de). As a first step towards training of the network, separate pattern files, consisting of 1080 training data (inputs and corresponding output) corresponding to three-wind flow directions (0°, 45°, 90°) have been made separately for leeward and windward walls of the street canyon model. Training data consisting of 9 inputs (aspect ratio, wind angle, three space coordinates x, y, z indicating the positions of the sampling points, traffic volume, traffic speed, wind speed, and length of the street canyon and one output (non-dimensionalised pollution concentration term K). During training, MLP is repeatedly presented (i.e., batch training) with the training data (i.e., supervised learning or training) and weights in the network are adjusted until the desired input-output mapping (in terms of average mean square of errors) occurs. As there is rule of thumb to determine the number of the hidden layers and neurons, their number is determined by adopting trial and error method in combination with learning rate, no of cycles and transfer function to achieve desired level of accuracy (in terms of MSE). Remaining 25% of the data (360 measurements corresponding to 30° wind angle case) have been used for verification (i.e., validation) of the trained network in the terms of given output. The validation of the ANN predicted results and EWT data were compared by using the model performance evaluation criteria in terms of $R^2$ and d (coefficient of determination and degree of agreement respectively) \[6,8\].
4 CONCLUSIONS

Pollutant concentration on the leeward wall was found to be 1 to 1.5 times more than that of windward wall indicating the presence of weak recirculating vortices at lower wind speed. Moreover, pollutant concentrations inside the street canyon were found to be significantly affected by the direction of the wind flow. Under perpendicular wind direction the pollutant concentrations were found to be maximum at the mid point and decreased towards the edges however, under the parallel wind flow conditions due to the ‘chanelling of flow’ accumulation of pollutant concentrations along the downwind side of the street canyon has been observed. The spatial variations in pollutant concentrations at 30° and 45° were found to be between the parallel and perpendicular wind flow conditions. The study has also indicated that, depending upon the approaching wind direction, the maximum concentrations (i.e., hot spots, where pollution levels are likely to exceed the air quality standards prescribed by the regulatory agencies) can be expected either at the center or at the edges of the urban street canyon(s). Under ‘no traffic conditions’ (similar to stationary vehicles at red lights) the concentration in the street canyon was found to be maximum. But, as movement of the vehicles starts, the pollution concentration starts decreasing (for the same level of vehicular emissions) due to traffic - induced mixing of the pollutants. Thus, while increase in the traffic volume increases the pollutant levels in the street canyon, the effect of increased pollution level to a certain extent, is offset by the increased traffic - induced mixing generated by these vehicles. Further, the statistical evaluation of the experimental EWT data and ANN predicted values were found to have values of $r^2$ (>0.83) and ‘d’ (>0.81) for leeward and windward walls, indicating that the ANN model can predicted the pollutant concentrations in the simulated urban street canyon with good accuracy.

The present study enhances our understanding regarding the complex dispersion phenomena in urban street canyons under low wind speed and mixed traffic conditions. Further, the study is of practical application as the findings can be used for siting ambient air pollution monitoring stations and devising air pollution control strategy in any urban street canyon. Another major contribution of the present study is the demonstration of the applicability of Artificial Neural Network (ANN) technique to predict the pollution concentrations in the urban street canyons(s) under varying traffic and meteorological conditions.

REFERENCES