Physical Simulation of Automobile Exhausts Dispersion at an Urban Intersection – Part I: Concentration Fields and Dispersion

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Abstract

The major sources responsible for deterioration of urban environments are automobiles. The case at urban intersection may become more critical due to variable modes of vehicular movement and their emissions, especially at low wind conditions. In this paper, the line source dispersion and concentration fields at an urban intersection under low wind conditions have been investigated and discussed. The atmospheric boundary layer (ABL) flow equivalent to urban terrain category, is reproduced using passive type of roughness generating devices with appropriate similarity criteria. The line source is simulated and tracer gas concentrations at various locations of the intersection are measured using online Flame Ionization Detector (FID) type of gas chromatograph. The experiments are carried out for 0^0, 30^0 and 60^0 approaching wind directions. The experimental results show various critical locations, where pollutant concentrations become twice or even more. The approaching wind directions of 30^0 and 60^0 carry more dispersion of pollutants than 0^0. However, the pollutants concentrations at inner corners of building blocks are more than at other locations.

Keywords: *Wind tunnel, urban intersection, line source dispersion, low wind condition*

1.0 Introduction

The automobile exhaust emissions continuously deteriorate urban environment. The situation at the urban street canyons and intersections, where ventilation is insufficient, becomes more critical. The air within the street canyons/congested intersections is 'trapped', leading to the build-up of pollutants [1]. At intersections, the accelerations, deceleration and idling of vehicles result in more complex dispersion behavior of exhaust emissions than at roadways [2]. Further, each mode of vehicular operation has its concomitant emissions. Typically, 'idling' emissions are higher than the 'accelerating/decelerating' emissions, which in turn, are higher than 'cruise' emissions [3, 4]. The challenge is compounded by the complexity of kinematics and the difficulty in making concentration measurements [5, 6]. A weak mixing of pollutants with the external flow (resulting long residence time for exhaust emissions) takes place at poorly ventilated regions of the intersection, especially under 'calm/low' wind conditions. Hoydysh and Dabberdt [7] have reported the formation of intermittent vortices at the corners of the building in the close vicinity of intersection. These corner vortices are responsible for creating 'convergence zone' in the mid-block region of the street canyon/intersections. Additional low-pressure areas and wind circulations near the intersections, result in creation of horizontal corner vortices. In relatively short canyons, corner vortices might be strong enough to inhibit a stable vortex, perpendicular to the street in the mid section. Hoydysh and Dabberdt [5] and Dabberdt et. al. [6] have carried out wind tunnel simulation studies evaluating the effects of nearby buildings on exhaust dispersion at different locations of intersection. They have reported pedestrian level concentrations and its variability at regular array of rectangular low-rise urban blocks with wide avenues and narrow streets. There exists a gap in systematic understanding of exhaust dispersion mechanisms in the close vicinity of urban intersection at various locations and vertical heights and pollutant concentration variability across streets and corners under low wind conditions. Further, Traffic-induced turbulence plays a significant role in the dispersion of automobile exhaust emissions, especially, at urban street canyons/intersections at low wind conditions. However, the nature of traffic - induced effect is poorly understood so far and the existing air pollution models adopt various empirical schemes that are difficult to verify. The present study carries out in-depth experimental investigations of the exhaust dispersion behavior in the close vicinity of urban intersection including the influence of nearby buildings blocks and wind – intersection orientations (0^0, 30^0 and 60^0) under low wind conditions. The traffic-induced effects on exhaust dispersion have been experimentally investigated and discussed elsewhere [8].

2.0 Experimental setup

The experiments have been carried out in an open circuit, low speed and suction type environmental wind tunnel (EWT). The overall length of EWT is 26 m, out of which 16 m length is test section with cross-section of 2 m x 2 m. The detailed constructional features and operational characteristics of the EWT has been described in Khare et. al. [9] and Ahmad et. al. [10].

2.1 Simulation of atmospheric flow

The atmospheric boundary layer has been simulated by using cubical blocks of 30 mm x 30 mm x 30 mm size with uniform spacing of 75 mm placed on the floor of the entire test section of the EWT along with a set of six elliptic vortex generators (Counihan's type of spires) designed as per Counihan [11], each of 1 m height placed at the entrance of the test section. The design of cubical blocks has been carried out as per Counihan [12], Wooding et. al. [13] and Gartshore and De Cross [14]. The characteristics of the simulated flow has been described below:

Mean velocity profile

The longitudinal mean velocities have been recorded at selected heights above the tunnel floor using hot wire anemomaster. The velocity recordings have been taken at 12 m from the entrance to the test section (before the turntable). The mean velocity profile in the simulated ABL, is be represented by well known power – law form (equation 1):

$$\frac{u}{U_\infty} = \left(\frac{z}{\delta}\right)^\alpha \quad \ldots\ldots \quad (1)$$

The normalized profile of observed longitudinal mean velocity u/U_∞ versus normalized depth z/δ follows the power law as shown in Fig. 1(a). The power law index (α) and boundary layer depth (δ) are 0.333 and 800 mm (i.e., the point where u / U∞ = 0.995), respectively. The power law exponent (α) value is in the range as quoted by Snyder [15], Davenport [16] and Counihan [17] for urban terrain categories. Davenport [16] has reported boundary layer depth (δ) as 457 m corresponding to α value of 0.333 (towns, suburbs, outskirts of large cities). Further, the ASCE Standard 7 – 95 [18] recommends α = 0.33 for exposer A (defined as "large city centers with atleast 50% of the buildings having a height in excess of 70 feet").

Log law profile

The lowest 10 – 15 % of the ABL (surface layer/canopy layer) has been characterized by the sharpest variations of wind speed and other meteorological parameters with height. In this layer, the adiabatic equation is as follows:

$$\frac{u}{u_*} = \frac{1}{\kappa}.\ln\left[\frac{(z-d_0)}{z_0}\right] \ldots \qquad (2)$$

in equation (8), three parameters u_*, z_0 and d_0 have been evaluated using the least square analysis, based on quality of fit of observed velocity profiles as recommended by Schaudt [19]. The evaluation of these parameters has been carried out within the logarithmic height range. For the selection of logarithmic height range, the criteria suggested by Raupach et. al. [20] and Bottema [21] have been adopted. The recommended logarithmic height range for evaluating the surface roughness parameters are Z_{min} > 2h (where, h, is the roughness element height) and Z_{max} < 0.25 δ. Table 1 gives the roughness parameters in the simulated ABL. The values of σ_d and σ_{z0} in table 1 shows the deviations in the best estimated values of d_0 and z_0.

Table 1: Estimated roughness parameters for the simulated flow

u_*, m / s	d_0, mm	z_0, mm	Q	χ^2	σ_d, mm	σ_{z0}, mm	u_*/U_∞
0.127	29.27	6.59	0.76	0.54	1.65	0.29	0.085

Comparison of roughness parameters with full scale data

The full scale values of z_0 and d_0 have been compared with the recommended values of EPA [22] and ESDU [23] (Table 2). It is observed that the value of z_0 well represents the situation of the apartment (residential) or central business district land use types. Further, the comparison of the values of d_0 with recommended value of ESDU for city centres also shows good agreement.

Table 2: Comparison of roughness parameters with the values of EPA and ESDU: 85020

Present study			EPA recommended values		ESDU: 85020 values	
z_0 m	d_0 m	Scale	Land use type	z_0 m	Terrain	d_0 m
3.76	16.68	1:570	Apartment residential	3.7	City centres	15 to 25

Turbulence Profile

The longitudinal component of fluctuating velocities has been measured at the center span (12 meter from the entrance of the test section) at selected heights above the tunnel floor using hot-wire anemo-master. Fig. 1(b) shows the variation of turbulence intensity with normalized height. It is observed that the turbulence intensity is maximum (38%), near the ground surface, which further decreases with height. The turbulence intensities (at full scale of 1:570) are compared with Robins [24] at the scale 1:300, Counihan [25] at the scale 1:400, Lee [26] at the scale 1:350, Reinhold et. al. [27] at the scale 1:600, Akins – Cermak [28] at the scale 1:250 and Farrel and Iyengar [29] at the scale 1:500 (Fig. 1c). The comparison shows good agreement.

2.2 Simulation of the urban intersection

An urban intersection has been simulated in the turntable of EWT using four blocks of 300 mm x 300 mm x 250 mm. The distance between two building blocks is 370 mm (Fig. 2). The Snyder's [15] and Cermak [30] guidelines have been used for the selection of the scales for both building blocks as well as model vehicles. The scales of building blocks and model vehicles have been taken as 1:100. These blocks of 250 mm (25 m high in field) represent six storey buildings in the close vicinity of the urban intersection. Further, to ensure the similitude between the full scale and model, the building Reynolds number has been calculated using following relationship:

$$\mathrm{Re}_H = \frac{u_H H}{\nu} \quad \ldots \qquad (3)$$

where, H is the building height, u_H, the wind speed at that height and ν, the kinematic viscosity of the air. In the present study, the building Reynolds number is 18150 which is more than the critical value of 11000.

2.3 Simulation of line source

The line source simulation for urban intersection is achieved more or less similar to that as recommended by Meroney et. al. [31] by placing small tubes of 1mm internal diameter with spacing of 3 mm center to center in the plenum of 470 mm each. A thin metal strip of 48 mm width and 470 mm long is placed 5 mm above the tube holes so that any initial vertical gas momentum is deflected laterally to release the tracer gas along its edge. Further, this metal strip represents the divider of the road into two-way simulation and also helps in the exhaust emissions either side of the road [10].

3.0 Sampling and analysis of tracer gas

The sampling points are located at normalized distances of 0, 0.2, 0.4, 0.6, 0.8 and 1.0 from centers of inner wall to inner wall making streets (Fig. 2a). The sampling is also carried out at the normalized heights (z/Z) of 0.08 (receptor height), 0.16 (I-floor), 0.32 (II-floor), 0.48 (III-floor), 0.64 (IV-floor) and 0.96 (VI-floor) from the EWT floor (Fig. 2b). Further, the sampling points are also located at interior corners of all four blocks and extended diagonally from each corner.

The tracer gas used in the experiment is a mixture of laboratory grade acetylene (95.5 % pure) and grade–I nitrogen (99.9 % pure). Pre-calibrated rotameters are used to maintain flow rate of the gases into the mixing unit. The tracer gas mixture is then fed to a common multiple outlet container. The container is connected with a multiple rotameter assembly, which feeds the tracer gas to various inlet ports of the line source. The flow rate is maintained at 2 litres/min to ensure low discharge velocity at the tips of 1 mm internal diameter of tubing of the line source. A set of six copper tubings is laid for the online sampling of tracer gas from EWT. One end of the tubings is connected with sampling probes (inside the EWT) and the other side is connected with a diaphragm type suction pump. During sampling of the tracer gas, the 'isokinetic condition' is maintained. The schematic of experimental set up is shown in Fig. 3.

The sampling of tracer gas is carried out on line after establishing the stable flow (sudden opening and closing of the EWT door creates disturbance in simulated flow, which is stabilized after few minutes) inside the EWT. Sampling probe tips are placed at pre-selected locations and sample is sucked using diaphragm type suction pump. The flow of sucked sample through copper tubes is made online from EWT to GC as discussed earlier. At an interval of one minute sample is injected into the column of GC through manual sampling valve. Then, the online sample has been analyzed using GC with flame ionization detector (FID). At every sampling location, 3 samples have been taken with a time difference of 1 min and averaged.

The tracer gas concentration data have been normalized using the following relationship:

$$K = \frac{K_0 U_{ref} LH}{Q} \quad \ldots \quad \ldots \qquad (4)$$

Where, K is non dimensionalized concentration, K_0, the measured concentration, U_{ref}, the free stream velocity, L, the length of line source, H, the characteristic height and Q, the strength of the line source. Then, the variation of the tracer gas concentration with height and vertical concentration gradients in windward/leeward directions as well as inner corners of building blocks is visualized. The contours of concentration are used to visualize the concentration reduction and their pattern in horizontal as well as vertical directions in streets joining at intersection and diagonally at intersection.

4.0 Results and discussion

4.1 Effects of building blocks at 0^0 approaching wind direction

Line source dispersion across street A to B

Fig. 4(a) shows the spatial distribution of normalized concentration from the building block A to B in both horizontal and vertical directions. The color bar [at right hand side of Fig. 4(a)] shows the intensity of normalized concentration at various locations. The isocontours show relatively higher values of concentration ($K = 2.32*10^6$), near the source and in the 'lower' portions of the street. However, the concentration decreases as the distance from the line source increases in horizontal as well as vertical directions and attains the minimum value, i.e., $K = 0.68*10^6$ at the VI-floor ($z/Z = 0.96$) of the building. It is due to the 'uplift' of the wind-induced turbulence along the street wall, which causes dispersion of tracer gas [7, 32, 33, 34, 35, 36 and 37]. Fig. 4(b) shows the vertical concentration profiles at six sampling locations between A and B. The maximum concentration occurs at the receptor height and thereafter decreases exponentially and attaining the minimum value at the VI-floor ($z/Z = 0.96$) of the building block.

Line source dispersion across street B to C

Fig. 5(a) shows the spatial distribution of normalized concentration from the building block B to C in both horizontal and vertical directions. The normalized concentration at leeward direction is approximately twice than that at windward direction. The maximum concentration, i.e., $K = 4.44*10^6$, is observed at receptor height, $2/5^{th}$ of the street width ($w/W = 0.6$, from B) and the minimum, i.e., $K = 0.86*10^6$, at the VI-floor ($z/Z = 0.96$) of the building block C. It is due to the 'skimming flow' inside the street that carries the tracer gas towards leeward side that results in the increase in concentration. Similar observations have been reported by Dabberdt et al. [32], Wedding et al. [33], Hoydysh and Dabberdt [7] and Hunter et. al. [37] in their experiments. Fig. 5(b) shows vertical concentration profiles at different locations between B to C. The maximum values of normalized concentration have been observed at the receptor height. It decreases exponentially, and attains the minimum value at VI-floor ($z/Z = 0.96$) of building block C.

Line source dispersion across street C to D

The spatial distribution of normalized concentration from the building block C to D in both horizontal and vertical directions is similar to that of A to B. The concentration at each location of the street C to D is approximately twice than that at the upwind locations i.e., A to B. It may be due to the accumulation of the tracer gas in the downwind direction and the contribution from the adjacent streets. Further, higher values of concentration, ($K = 4.68*10^6$) are observed at receptor heights. However, it decreases with increase in distance from the line source in horizontal as well as vertical directions and becomes minimum ($K = 1.51*10^6$), at the VI-floor ($z/Z = 0.96$).

Line source dispersion across street D to A

The spatial distribution of tracer gas concentration across the street D to A is similar as observed across the street width C to B due to similar configuration and wind flow direction.

Line source dispersion across the corners A to C and B to D

Fig. 6(a) shows the spatial distribution of normalized concentration across inner corners of the building blocks A to C. The concentration at upwind corners (corners DAB and ABC), are observed less than that at downwind corners (corners BCD and CDA). The maximum concentration, i.e., $K = 3.39*10^6$, has been observed at receptor heights of downwind corners BCD and CDA. Further, the values of K at all corners have been observed less than that at other locations of the intersection. It is due to the formation of corner vortices, which decreases the concentration of tracer gas and prevents its accumulation [5]. Fig. 6(b) shows the vertical normalized concentration profiles, across corners A to C. The concentration decreases exponentially with height and becomes minimum at VI-floor ($z/Z = 0.96$). The behavior of tracer gas distribution across corners B to D is similar to that as corners A to C.

4.2 Line source dispersion at 30^0 approaching wind direction

Line source dispersion across street A to B

Fig. 7(a) shows the spatial distribution of normalized concentration from the building block A to B in both horizontal and vertical directions at 30^0 approaching wind. The isocontours show the accumulation of tracer gas towards the wall of building block B. It may be due to the low pressure, generated in that region that carries the tracer gas towards B. Further, the sharp convergence of isocontours along the height of the street shows the induction of 'spiral vortices' with a cork screw type of action [7, 32, 33, 34, 35, 36 and 37]. Fig. 7(b) shows the vertical profiles of normalized concentration at six locations between A and B. The maximum concentration, $K = 3.34*10^6$, has been observed at the receptor height ($z/Z = 0.08$)) and $w/W = 0.6$. The concentration decreases exponentially and attains the minimum value i.e., $K = 1.49*10^6$, at the VI-floor ($z/Z = 0.96$) of the building block A.

Line source dispersion across street B to C

Fig. 8(a) shows the spatial distribution of normalized concentration from the building block B to C in both, horizontal and vertical directions. The isocontours show that the normalized concentration at 'leeward' direction is more than that at 'windward' direction. The maximum concentration, $K = 3.44*10^6$, is observed at receptor height, $2/5^{th}$ of the street width ($w/W = 0.4$) and the minimum, i.e., K =

$0.78*10^6$, at the VI-floor (z/Z = 0.96) of building block C. Fig. 8(b) shows the vertical concentration profiles at different locations between B to C. The maximum values of normalized concentration have been observed at the receptor height (z/Z = 0.08). It decreases exponentially and attains the minimum concentration at VI-floor (z/Z = 0.96) of the building block C.

Line source dispersion across street C to D

Fig. 9(a) shows the spatial distribution of normalized concentration from the building block C to D in both horizontal and vertical directions. The concentration at each location of the street C to D is approximately two times more than that at corresponding locations in the 'upwind' direction. It may be due to the accumulation of the tracer gas in the downwind direction and the contribution from the adjacent streets. Further, the isocontours show relatively higher values of concentration, i.e., K = $4.13*10^6$, at receptor heights (z/Z = 0.96). However, the concentration decreases as the distance from the line source increases, in horizontal as well as vertical directions. It becomes minimum, (K = $1.33*10^6$) at the VI-floor (z/Z = 0.96) of the building D. It is due to the 'uplift' of the wind-induced turbulence along the street wall, which causes dispersion of tracer gas [7, 32, 33, 34, 35, 36 and 37]. Fig. 9(b) shows the vertical concentration profiles at various locations of the street C to D. It has been observed that the maximum concentration persists at the receptor height (z/Z = 0.08). It decreases exponentially obtains the minimum concentration at the VI-floor (z/Z = 0.96) of the building block.

Line source dispersion across street D to A

The isocontours show relatively higher values of concentration, (K = $4.13*10^6$) at the receptor heights (z/Z = 0.08). However, the concentration decreases as the distance from the line source increases in horizontal as well as vertical directions and becomes minimum, (K = $1.13*10^6$) at the VI-floor (z/Z = 0.96) of the building D (Fig. 10a). It is again due to the 'uplift' of the wind-induced turbulence along the street wall, which causes dispersion of tracer gas [7, 32, 33, 34, 35, 36 and 37]. Fig. 10(b) shows the vertical concentration profiles at various locations of the street D to A. It has been observed that the maximum concentration persists at the receptor height (z/Z = 0.08). It decreases exponentially and becomes minimum at the VI-floor (z/Z = 0.96) of the building block.

Line source dispersion across the corner A to C and B to D

Fig. 11(a) and (c) show the spatial distribution of normalized concentration across inner corners of the building blocks A to C and B to D, respectively. The concentrations at upwind corners (corners DAB and ABC) have been observed less than that at downwind corners (corners BCD and CDA). The maximum concentration (K = $3.32*10^6$) has been observed at the receptor height (z/Z = 0.08) of downwind corner CDA. Further, the concentration of tracer gas at all corners has been observed less than that at other locations of the intersection. It is due to the formation of corner vortices, which dilute and decreases the concentration of tracer gas and prevents its accumulation [5]. Fig. 11(b) and 11(d) show the vertical normalized concentration profiles, across corners A to C and B to D. The concentration decreases exponentially with height and becomes minimum at VI-floor (z/Z = 0.96).

4.3 Line source dispersion at 60^0 approaching wind direction

Line source dispersion across street A to B

Fig. 12(a) shows the spatial distribution of normalized concentration from the building block A to B in both, the horizontal and vertical directions at 60^0 approaching wind. The isocontours show the accumulation of tracer gas towards the wall of building block B. It may be due to the low pressure, generated in that region that carries the tracer gas towards B. Further, the sharp convergence of isocontours along the height of the street shows the induction of 'spiral' vortices with a cork-screw type of action. Similar observations have been reported by Dabberdt et al. [32], Wedding et al. [33], De Paul and Shieh [34], Yamartino and Wiegand [35], Nakamura and Oke [36], Hoydysh and Dabberdt [7] and Hunter et. al. [37]. Fig. 12(b) shows the vertical profiles of normalized concentration at six locations between A and B. The maximum concentration, (K = $3.14*10^6$) has been observed at the receptor height, (z/Z = 0.08) and at w/W = 0.6. The concentration decreases exponentially and attains the minimum value (K = $0.67*10^6$), at the VI-floor (z/Z = 0.96) of the building block A.

Line source dispersion across street B to C

Fig 13(a) shows the spatial distribution of normalized concentration from the building block B to C in both, the horizontal and vertical directions. The isocontours show that the normalized concentration at 'leeward' direction is more than that at 'windward' direction. Fig. 13(b) shows the vertical concentration profiles at different locations between B to C. The maximum concentration, (K = $2.67*10^6$) is observed at the receptor height (z/Z = 0.08) and at w/W = 0.4 ($2/5^{th}$ of the street width) and the minimum (K = $0.67*10^6$), at the VI-floor (z/Z = 0.96) of building block C.

Line source dispersion across street C to D

Fig. 14(a) shows the spatial distribution of normalized concentration from the building block C to D in both, the horizontal and vertical directions. The concentration at each location of the street C to D is more than that at corresponding locations of upwind directions. It may be due to the accumulation of the tracer gas in the downwind direction and the contribution from the adjacent streets. Further, Fig.

14(b) shows the vertical concentration profiles at various locations of the street C to D. The relatively higher values of concentration, (K = 4.78*10^6) has been observed at the receptor heights (z/Z = 0.08). However, the concentration decreases as the distance from the line source increases, in the horizontal as well as vertical directions. It becomes minimum, (K = 1.83*10^6) at the VI-floor (z/Z = 0.96) of the building D. It may be due to the 'uplift' of the wind-induced turbulence along the street wall, which causes dispersion of tracer gas [7, 32, 33, 34, 35, 36 and 37].

Line source dispersion across street D to A

Fig 15(a) shows the spatial distribution of normalized concentration from the building block D to A in both, the horizontal and vertical directions. Fig. 15(b) shows the vertical concentration profiles at various locations of the street D to A. It has been observed that the maximum concentration persists at the receptor height (z/Z = 0.08). It decreases exponentially reaches the minimum value at the VI-floor (z/Z = 0.96) of the building block. The relatively higher values of concentration, (K = 4.33*10^6) at receptor heights and the minimum, (K = 0.63*10^6) at the VI-floor (z/Z = 0.96) of the building D, have been observed. It may be due to the uplift of wind-induced turbulence along the street wall, which cause dispersion of the tracer gas [7, 32, 33, 34, 35, 36 and 37].

Line source dispersion across the corner A to C and B to D

Fig. 16(a) and (c) show the spatial distribution of normalized concentration across inner corners of the building blocks A to C and B to D, respectively. The concentration at upwind corners (corners DAB and ABC), have been observed less than that at downwind corners (corners BCD and CDA). The maximum concentration, (K = 3.34*10^6) has been observed at the receptor height (z/Z = 0.08) of downwind corner CDA. Further, the concentration of the tracer gas at all the corners has been observed less than that at other locations of the intersection. It may be due to the formation of corner vortices, which dilute and decreases the concentration and thus prevents its accumulation [5]. Fig 16(b) and (d) show the vertical normalized concentration profiles, across corners A to C and B to D. The concentration decreases exponentially and becomes minimum at VI-floor (z/Z = 0.96).

5. Conclusions

Higher concentrations of tracer gas are observed in the leeward and downwind sides of building blocks A and B at 0^0 approaching wind direction. It may be due to presence of 'leeward' effect and accumulation of tracer gas in the downwind direction at 0^0 approaching wind angle, which result in increase of tracer gas concentration. When the approaching wind directions are 30^0 and 60^0 the tracer gas concentrations decrease at 'leeward' and downwind sides of building blocks at A and B as wind flow enters inside the intersection and reduces the tracer gas concentration, indicating improved ventilation conditions. The windward and upwind sides of building blocks are having low concentrations of tracer gas at all approaching wind directions. It may due to the enhanced ventilation conditions in these regions resulting into increased dilution of the tracer gas. The formation of the corner vortices at the innermost corners facing the intersection results in lower concentration of the tracer gas when compared to mid regions of building blocks at all approaching wind directions.

References

[1] S. Vardoulakis, E.A.F. Bernard, K. Pericleous and N. Gonzalez–Flesca, Modeling air quality in street canyons: a review, Atmospheric Environment, 37 (2003) 155 – 182.

[2] J. Zammurs and R.J. Perraci, Modeling of carbon monoxide hot spots, Air Pollution Control Association, 32 (1982) 947 – 953.

[3] J.P. Nelli, A.D. Messina and J.A. Bullin, Analysis and modeling of air quality at street intersections, Journal of Air Pollution and Control Association, 33 (1983) 760–764.

[4] J. Zammurs, Intersection carbon monoxide modeling, Journal of Air and Waste Management Association, 40 (1990) 769 – 771.

[5] W.G. Hoydysh and W.F. Dabberdt, Concentration fields at urban intersections: Fluid modelling studies, Atmospheric Environment, 28 (1994) 1849 – 1860.

[6] W. F. Dabberdt, W. G. Hoydysh, M. Schorling, F. Yang and O. Holynskyj, Dispersion modeling at urban intersections, The Science of the Total Environment, 169 (1995) 93–102.

[7] W.G. Hoydysh and W.F. Dabberdt (1988) Kinematics and dispersion characteristics of flows in asymmetric street canyons, Atmospheric Environment, 22 (1988) 2677 – 2689.

[8] K. Ahmad, M. Khare and K.K. Chaudhry, Wind tunnel simulation study of line source dispersion at urban intersection – Part II: traffic induced effects, communicated to Journal of Wind Engineering and Industrial Aerodynamics (2005).

[9] M. Khare, K.K. Chaudhry, R.M.M. Gowda and K. Ahmad, Heterogeneous traffic induced effects on vertical dispersion parameter- A wind tunnel study, Environmental Modelling and Assessment, 7 (2002) 09 – 15.

[10] K. Ahmad, M. Khare and K.K. Chaudhry, Model vehicle movement system in wind tunnels for exhaust dispersion studies under various urban street configurations, Journal of Wind Engineering and Industrial Aerodynamics, 90 (2002) 1054–1067.

[11] J. Counihan, An improved method of simulating atmospheric boundary layer in a wind tunnel, Atmospheric Environment, 3 (1969) 197 – 214.

[12] J. Counihan, Wind tunnel determination of roughness length as a function of the fetch and the roughness density of three-dimensional elements, Atmospheric Environment, 5 (1971) 637 – 640.

[13] R.A. Wooding, E.F. Bardly and J.K. Marshall, Drag due to regular arrays of roughness elements of varying geometry, Boundary Layer Meteorology, 5 (1973) 285 – 308.

[14] I.S. Gartshore and K.A. De Cross, Roughness element geometry for wind tunnel simulation of the atmospheric wind, Transaction of ASME, Journal of Fluid Engineering, 99 (1977) 480 – 485.

[15] W.H. Snyder, Guide Line for Fluid Modelling of Atmospheric Diffusion, Report No. 600/8 – 81 – 009 (1981), USEPA, Research Triangle Park, NC 27711.

[16] A.G. Davenport, The relationship of wind structure to wind loading Proc. Conf. on wind effects on buildings and structures, National Physical Laboratory, HMSO, London, (1963) 54 – 102.

[17] J. Counihan, Adiabatic atmospheric boundary layer: a review and analysis of data from period 1880 – 1972, Atmospheric Environment, 9 (1975) 871 – 903.

[18] ASCE Standard 7 – 95, Minimum design loads for buildings and other structures, 1996.

[19] K.J. Schaudt, A new method for estimating roughness parameters and evaluating the quality of observations, Journal Applied Meteorology, 37 (1998) 470 – 476.

[20] M.R. Raupach, A.S. Thom and I. Edwards, A wind tunnel study of turbulent flow closed to regularly arrayed rough surfaces, Boundary Layer Meteorology, 18 (1980) 373 – 397.

[21] M. Bottema, Urban roughness modeling in relation to pollutant dispersion, Atmospheric Environment, 31 (1997) 3059 – 3075.

[22] US EPA Report (1992) Guideline for modeling carbon monoxide from roadway intersections, EPA – 454/R – 92 – 005, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

[23] ESDU: 85020 (1993) Characteristics of atmospheric turbulence near the ground, Engineering Science data unit, International, London, U.K.

[24] A.G. Robins, The development and structure of simulated neutrally stable atmospheric boundary layers, Journal of Wind Engineering and Industrial Aerodynamics, 4 (1979) 71 – 100.

[25] J. Counihan, Simulation of an adiabatic urban boundary layer in a wind tunnel, Atmospheric Environment, 7 (1973) 691 – 705.

[26] B.E. Lee, Simulation of atmospheric boundary layers in the Sheffield University, 1.2 m x 1.2 m boundary layer wind tunnel, Department of Building Science, Report BS 38, University of Sheffield (1977).

[27] T.A. Reinhold, H.W. Tieleman and F.J. Maher, Simulation of the urban neutral boundary layer for the model study of wind loads on tall buildings, Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Report VPI-E-77-12 (1978).

[28] A.E. Akins and J.E. Cermak, Wind pressures on buildings, Fluid Dynamics and Diffusion Laboratory, Report CER76-77REA-JEC15 (1976), Colorado State University, Fort Collins.

[29] C. Farrel and A.K.S. Iyengar, Experiments on wind tunnel simulation of atmospheric boundary layers, Journal of Wind Engineering and Industrial Aerodynamics, 79 (1999) 11 – 35.

[30] J.E. Cermak, Application of fluid mechanics to wind engineering – a free man scholar lecture, Transactions of ASME, Journal of Fluid Engineering, (1975) 9 – 38.

[31] R.N. Meroney, M. Pavageau, S. Rafailidis and M. Schatzmann, Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. Journal of Wind Engineering and Industrial Aerodynamics, 62 (1996) 37– 56.

[32] W.F. Dabberdt, F.L. Ludwig and W.B. Johnson, Validation and applications of an urban diffusion model for vehicular emissions, Atmospheric Environment, 7 (1973) 603 – 618.

[33] J.B. Wedding, D.J. Lombardi and J.E. Cermak, A wind tunnel study of gaseous pollutants in city street canyons, Journal of the Air Pollution Control Association, 27 (1977) 557–566.

[34] F.T. De Paul and C.M. Shieh, A tracer study of dispersion in an urban street canyon, Atmospheric Environment, 20 (1986) 455 – 459.

[35] R.J. Yamartino and G. Weigand, Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon, Atmospheric Environment, 20 (1986) 2137 – 2156.

[36] Y. Nakamura and T.R. Oke, Wind, temperature and stability conditions in an east west oriented urban canyon, Atmospheric Environment, 22 (1988) 2691 – 2700.

[37] L.J. Hunter, G.T. Johnson and I.D. Watson, An investigation of three dimensional characteristics of flow regimes within the urban canyon, Atmospheric Environment, 26B (1992) 425 – 432.