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Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review

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Abstract

Increased traffic emissions and reduced natural ventilation cause build up of high pollution levels in urban street canyons/intersections. Natural ventilation in urban streets canyons/intersections is restricted because the bulk of flow does not enter inside and pollutants are trapped in the lower region. Wind vortices, low-pressure zones and channeling effects may cause build up of pollutants under adverse meteorological conditions within urban street canyons. The review provides a comprehensive literature on wind tunnel simulation studies in urban street canyons/intersections including the effects of building configurations, canyon geometries, traffic induced turbulence and variable approaching wind directions on flow fields and exhaust dispersion.

Keywords: Wind tunnel; Street canyon; Flow fields; Exhaust dispersion; Line source

Abbreviations: EWT; environmental wind tunnel; MVMS; model vehicle movement system; MMR; moving model rig; ARMA; auto regressive moving average; DC; direct current; Hp; horse power

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Nomenclature

H/W	height-to-width ratio
L/H	length-to-height ratio
u	free stream velocity
v	velocity component along the canyon
p	empirical constant
m/s	meter/second
km/h	kilometer/hour
P_{W}	energy production by winds
P_{T}	energy production by moving traffic
v_{t}	speed of vehicles
C_{DT}	drag coefficient
A_{T}	frontal area of vehicle
n_{T}	number of vehicles in prototype
n_{m}	number of vehicles models in wind tunnel
M	scale
m	model
n	prototype
u_*	friction velocity
c_{th}	constant
z	variable height/depth
H	height/depth of street canyon
B	width of street canyon
a	scaling factor.

Symbols

τ	shear stress
ρ	density of the air
θ	incidence angle
σ_{z}	vertical dispersion parameter

1. Introduction

1.1. Traffic emissions and population exposure

Traffic-induced emissions are major sources of air pollutants in urban areas. Despite significant improvements in fuel and engine technology, the urban environments are mostly dominated by traffic emissions [1,2]. For instance, in India, increased motorized transport in urban centers has led to problems of higher vehicular exhaust emissions, resulting in 64% of contribution in air pollution load [3]. The pollutants, such as respirable suspended particulate matter (RSPM), especially $PM_{2.5}$, nitrogen dioxide (NO_2), carbon monoxide (CO) and hydrocarbons (HC) are emitted directly by vehicles in urban environments. Besides, secondary pollutants (indirectly produced through photochemical reactions), pose a serious hazard to human health [4–6]. The most affected group is the urban inhabitants, especially, the population residing in close vicinity of the urban roadways/streets/intersections as well as the pedestrians [3].

1.2. Traffic-induced turbulence and exhaust dispersion

Local wind flows inside the street canyons are greatly affected by the mechanical turbulence induced by moving vehicles [7]. Systematic understanding of the exhaust dispersion mechanisms (with respect to mechanical effects as well as natural air motions) in close vicinity of the urban roadways/street canyons and intersections is of foremost importance in order to improve ways to mitigate vehicular pollution effects. The vehicle-induced turbulence coupled with natural air motions mainly cause dispersion of automobile exhausts, especially under 'calm' wind conditions (<1 m/s) [8]. Exhaust buoyancy is also an important factor but in street canyons/intersections, it becomes negligible due to rapid mixing caused by moving vehicles [9].

1.3. Wind tunnel simulation studies

Dispersion in street canyons depends on the rate at which the streets exchange air *vertically*, with the roof level atmosphere and *laterally*, with connecting streets [10]. Besides, the traffic parameters (e.g., vehicle speed, composition and volume) and surface layer micrometeorological parameters (such as wind speed, wind direction and roughness conditions) also affect the dispersion of exhaust emissions [3,8,11]. However, the influence of nearby buildings, protection walls, bushes and vegetation cause further complexities in the dispersion phenomenon [12].

Physical simulation studies in wind tunnels show a high potential to understand the wide range of complex dispersion phenomena. The main advantage using wind tunnels is the control of variables at will and economy in terms of time and money [13]. In fact, the major limitations of direct field experiments are, that all possible governing parameters are simultaneously operative; it is not easy to determine which are governing and which are secondary or insignificant parameters [14]. Thus, independent influences of building geometry (building height, width, shape of roof), street dimensions, vegetation or landscaping and surface roughness, vehicular category (size, shape and composition), and their movement may be investigated using wind tunnels by controlling each parameter individually [13–17].

2. Wind flow fields

The subsequent sections review the effects of building configurations, street canyon/intersection geometry and vehicle-induced turbulence on wind flow fields and exhaust dispersion.

2.1. Effects of building configurations

2.1.1. Flow field around isolated building

There are a number of studies on flow field around an isolated building in neutrally stable boundary layers [18–22]. These studies describe the characteristics of basic wind flow patterns around the buildings of various shapes and orientations. Fig. 1 describes the complex flow fields around cuboid-shaped building blocks [23].

2.1.2. Flow field around group of buildings

Features apparent in the flow around a single, isolated building are also present for a group of buildings, although their relative and absolute significance is generally affected by interactions within the group. The cumulative effects of group of buildings on flow field are treated by linear addition of the effects due each in turn [23,24].

2.2. Street canyon characteristics

Street canyon refers to a street with buildings lined up continuously along both sides [25]. The dimensions of a street canyon are expressed by its 'aspect ratio', i.e., the ratio of the height of the building (H) to width of the street (W). The canyon is *uniform*, if it has an aspect ratio of approximately equal to 1 with no major openings on the walls. A *shallow* canyon has an aspect ratio below 0.5; and the aspect ratio of 2, represents a *deep* canyon. The length of canyon (L) expresses the road distance between two major intersections subdividing the street canyon into *short* ($L/H = 3$), *medium* ($L/H = 5$) and *long* ($L/H = 7$). If buildings, flanking the canyon are of equal heights, the canyon is '*symmetric*' and vice-versa [26]. Asymmetric canyons with high-rise buildings in *downwind* direction are termed as *step up* canyons and reversibly *step down* canyons. The upwind side of the canyon is called *leeward* and downwind, is *windward* when the wind flow is perpendicular to the street canyon (Fig. 2).

2.3. Wind flow pattern in street canyon

This section reviews the wind flow patterns inside a street canyon that change with approaching wind directions.

2.3.1. Perpendicular approaching wind direction

Oke [27] and Husain and Lee [28] describe three types of wind flow regimes as functions of building (length-to-depth ratio) and canyon (depth-to-width ratio) geometries for perpendicular approaching wind direction with respect to the canyon axis (Fig. 3). If the spacing between two buildings is too large and the height is comparatively low, then their flow fields do not interact. At closer spacing (Fig. 3a), the wakes are disturbed and on the contrary, the smaller spacing between buildings disrupts the 'wakes' resulting in an '*isolated roughness flow regime*' [29]. If the height and spacing of the building blocks are such that they disturb the bolster and cavity

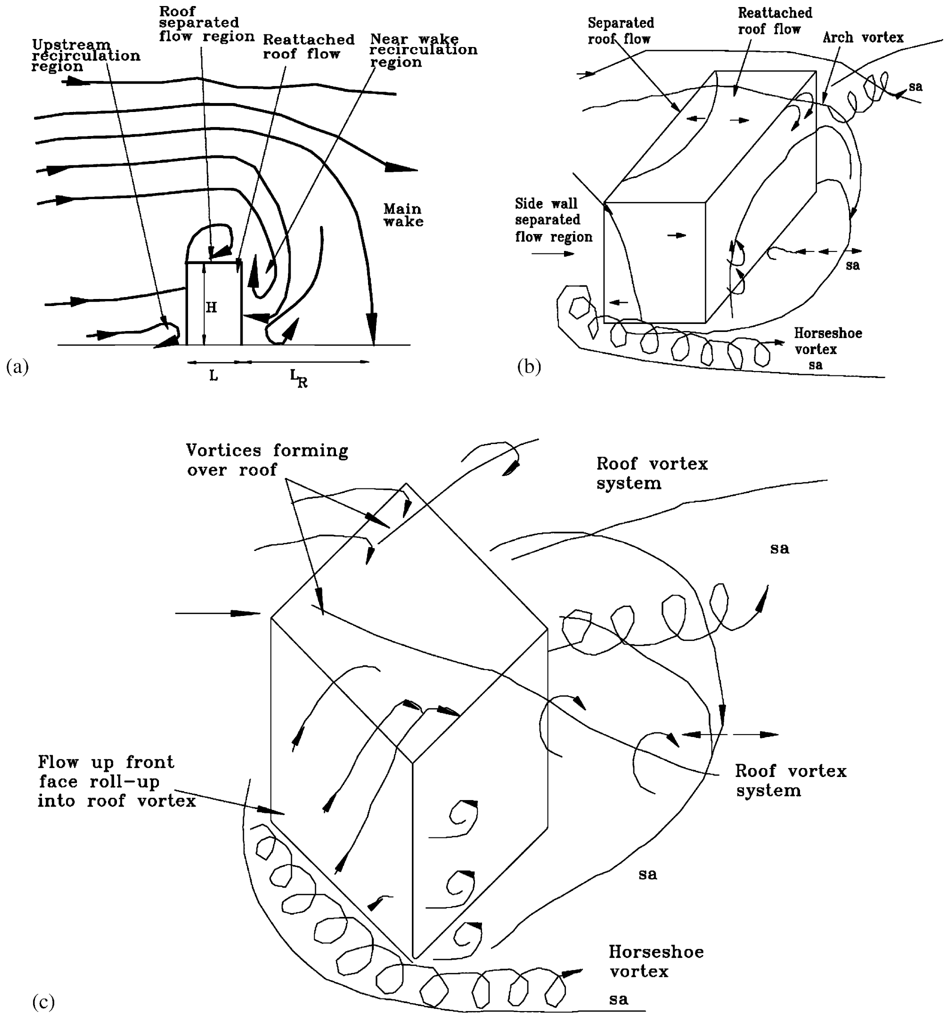

Fig. 1. Main features of flow around cuboids at 0° and 45° to the approach flow in a deep boundary layer [23]. (a) Mean streamlines on centre of a cuboid normal to the approach flow. (b) Mean flow pattern around a cuboid normal to the approach flow (lines marked 'sa' are mean separation/attachment lines). (c) Mean flow pattern around a cuboid at incidence to approach flow.

eddies (due to the deflection caused by downward flow passing over the cavity), the flow regime changes and is known as '*wake interference flow*' (Fig. 3).

At a greater H/W, the circulatory vortex is established inside the street canyon. This may be due to the transfer of momentum across the shear layer at the roof height. In this situation, the bulk of the flow does not enter inside the street canyon and forms single vortex within the canyon [30]. This type of flow regime is known as '*skimming flow regime*' (Fig. 4). The presence of canyon vortex is first demonstrated by Albrecht [31] and thereafter, Georgii et al. [32] have verified it. The wind flow

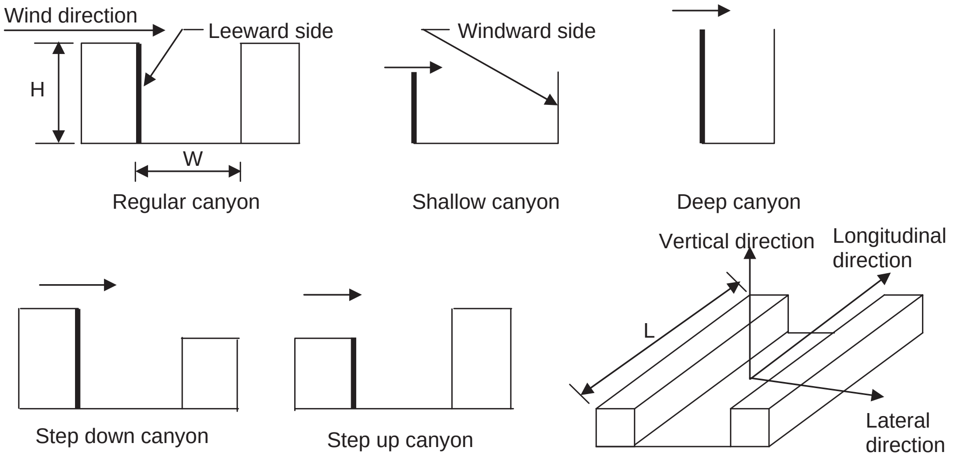

Fig. 2. Characteristics of street canyons.

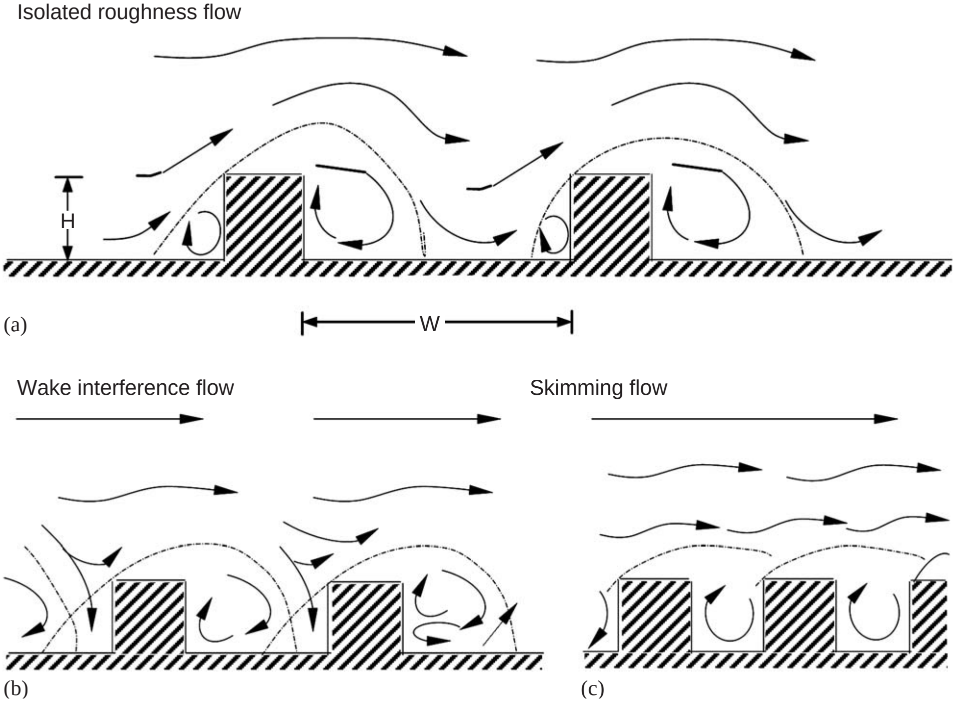

Fig. 3. Perpendicular flow regimes in urban canyons for different aspect ratios [27].

inside the street canyon (secondary wind flow) is usually driven by the mean wind flow out side the canyon (upper wind flow). If the wind speed out of the canyon is below some threshold value, the coupling between the upper and secondary flow is lost [33]. De Paul and Sheih [34] report that this threshold value ranges between 1.5 and 2.0 m/s for *symmetrical* street canyon, having depth-to-width ratio (H/W) as 1.4. Nakamura and Oke [33] describe similar values for depth-to-width ratio, close to unity. The downward transfer of momentum may cause vortex formation across the canyon at roof level shear zone.

The directions of the vortex flow near the ground and the approaching wind direction outside the street canyon are opposite to each other [33,36]. Chang et al. [37] report the formation of two vortices in *deep canyons*. Ambient wind flow drives the upper vortex, while the circulation of upper vortex drives the lower one (Fig. 5). The direction of lower vortex flow is opposite to that of the upper one [37,38].

The average vertical displacement of vortex for a *symmetric* street canyon is equal to the canyon width. In the *step up* canyon, the vortex is smaller and the mean vertical displacement is equal to 0.61 of the canyon width [36]. In addition, Yamartino and Weigand [40] and Kastner-Klein et al. [41] report that if the length-to-width ratio of the street canyon becomes 20, the canyon effects dominate over the vortex. In relatively *short canyons*, Hoydysh and Dabberdt [36] report that intermittent vortices are shed on the building corners, which are responsible for advection from the building corners to mid-block, creating a '*convergence zone*' in the mid-block region of the canyon. Meroney et al. [14] report that canyons in an open country generate unstable vortex, which continuously rises in the upward direction, while canyons in urban areas generate a stable rotating vortex that suppresses the street ventilation resulting in the trapping of pollutants.

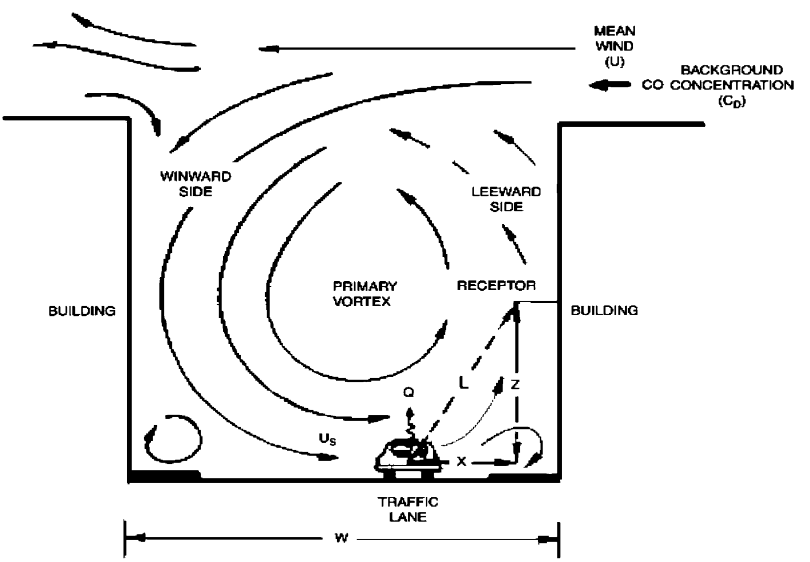

Fig. 4. Pollutant dispersion in a regular street canyon [35].

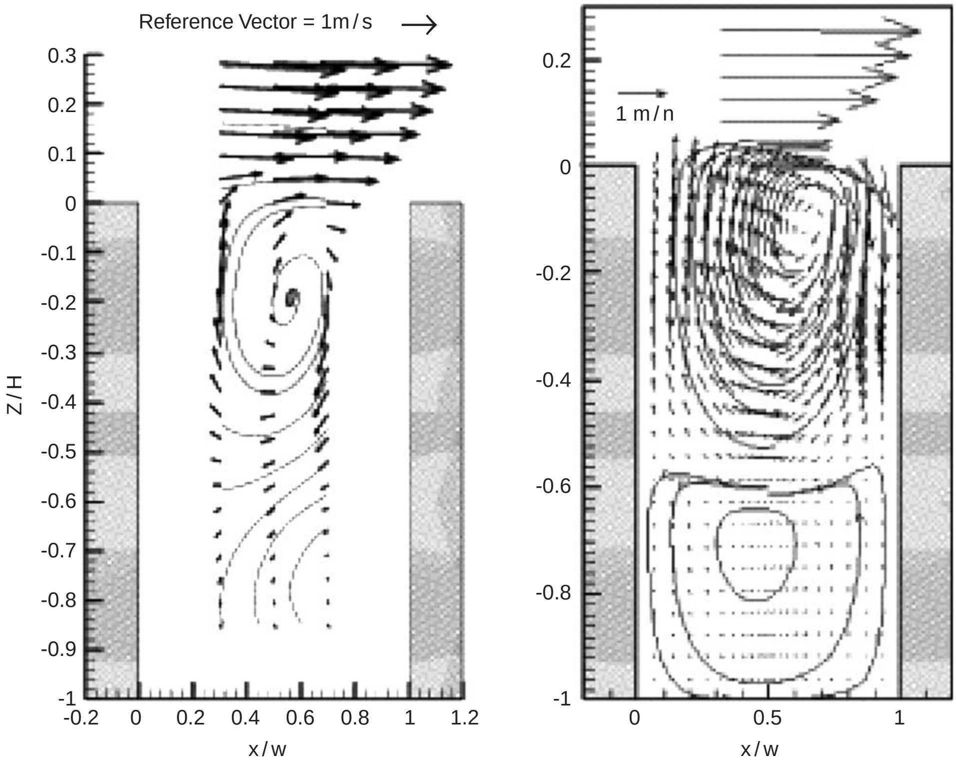

Fig. 5. Mean velocity vectors and stream traces on center-plane for $W/H = 0.5$ [39].

2.3.2. Parallel approaching wind flow direction

Wedding et al. [42] and Nakamura and Oke [33] report that parallel wind flow generates mean wind along the canyon axis with possible uplift along its walls. The friction of street canyon walls and the surface retard the approaching wind flow [43]. The longitudinal component of the velocity inside the canyon is directly proportional to the wind velocity above the roof. The proportionality of constant is a function of approaching wind flow azimuth [40]. Further, Yamartino and Wiegand [40] propose a relationship, i.e., $v = u\cos\theta$. Nakamura and Oke [33] report the linear relationship between two wind velocities (i.e., v and u), for wind speeds up to 5 m/s, which is given by $v = pu$, where p varies between 0.37 and 0.68 for the *symmetric* street canyon, having H/B equal to 1. The velocity v and u are estimated at the depth of 0.06 and 1.2H, respectively. Low p values are obtained due to the deflection of flow [33].

2.3.3. Oblique approaching wind direction

Very few studies based on wind tunnel simulation, are carried out on the development of flow fields at oblique approaching wind direction. Nakamura and Oke [33] report the formation of *spiral* vortex, (a cork screw-type) along the canyon length at oblique approaching wind direction. Similarly, Dabberdt et al. [34] and Wedding et al. [42] observe the helical flow pattern in the street canyon at oblique approaching wind direction. Table 1 summarizes the wind flow fields in the street canyons for variable wind directions.

2.4. Flow field in street intersection

Hosker and Pendergrass [24] describe the regions where the flow is channeled, diffused, deflected, displaced, accelerated, stagnated and re-circulated. The poorly ventilated regions are characterized by weak mixing of pollutants resulting in a long residence time for exhaust emissions. A significant exchange takes place between the intersecting streets. The wind is somewhat normal to the cross street and this modifies the basic street canyon vortex, changing it into a *helical vortex* (Fig. 6). Hoydysh and Dabberdt [36] observe the formation of intermittent vortices at the corners of the building. Scaperdas [46] reports that flow interchange at a simple intersection between two perpendicular streets as shown in Fig. 7. The approaching flow is along the x-axis (in Cartesian coordinate system) of the street and there is a lateral offset along the y-axis (in Cartesian coordinate system) of the street at the intersection, i.e., $\Delta y = 0.6H$, where H is the height of the four square blocks used to define the intersection; the street width is also H. The arrows and labels mark the volume of flux exchanges relative to the volume flux in the upwind along the x-axis of the street (denoted as 100%). A considerable flow of air passes into the street along the y-axis (in the section $y<0$) from the upwind part of the street along the x-axis ($x<0$) [47].

3. Exhaust dispersion behavior

Hoydysh and Griffiths [48] report that the apparent lateral and longitudinal concentration levels decrease with increase in portion of the total crosswind area below the mean roof plane, blocked by high-rise structures. Besides, the tall isolated structures are helpful in reducing the pollutant concentration. Wedding et al. [42] observe that a single isolated structure may cause favorable mixing of pollutants in the *downwind* side of the building, while a very high concentration may exist in the *leeward* side. A series of wind tunnel experiments for different street geometries is reported by Builtjes [49,50]. Hoydysh and Dabberdt [36] describe the kinematics and dispersion characteristics of flow in three canyon configurations with the street width-to-height ratio of the upwind building being 0.79 and the ratios of the street width-to-height of the downwind buildings as 2.0, 1.0 and 0.67. The distribution of the tracer gas concentration contours is nearly identical on the *leeward* side of the building, for both the *even* and *step down* canyon configurations. Higher tracer gas concentrations at mid-block are observed at *leeward* side of the building, showing the absence of convergence for the *step up* canyon configurations. Dabberdt and Hoydysh [51] observe the maximum concentration in mid-section (in case of rectangular blocks) and near the ends (for square blocks). The reduction in avenue

Table 1
Summary of flow fields in street canyon

Reference	Canyon characteristics	Flow fields		
		Perpendicular flow	Flow along the canyon	Oblique flow
[27,28]	Aspect ratio >0.05	Flow fields do not interact, resulting in the disruption of wakes. This type of flow regime is known as ‘isolated roughness flow regime’.	There is no predominant wind direction inside the canyon. At higher wind speeds, the flow is almost parallel to the axis of the canyon.	Similar to the perpendicular flow.
[44]	Aspect ratio <0.65	The bolster and cavity eddies are disturbed and the flow regime changes and is known as ‘wake interference flow’.		
[30,33–36,40,42]	Aspect ratio >0.65 and <2, $L/W>20$	The bulk of the flow does not enter inside the street canyon and forms single vortex within the canyon. This type of flow regime is known as ‘skimming flow regime.	Mean wind along the canyon axis with possible uplift along the canyon walls.	A spiral vortex is induced along the length of the canyon with a cork screw-type of action.
[37,41,45]	Aspect ratio $\geqslant 2$ and $L/W<20$	Described the formation of two vortices in deep canyons. Ambient wind flow drives the upper vortex while the circulation of upper vortex the lower one. The direction of lower vortex flow is opposite to that of the upper one.	Intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid block creating a convergence zone in the mid block region of the canyon.	Similar to the parallel flow.
[38]	Higher aspect ratios	A third weak vortex might also be formed.		

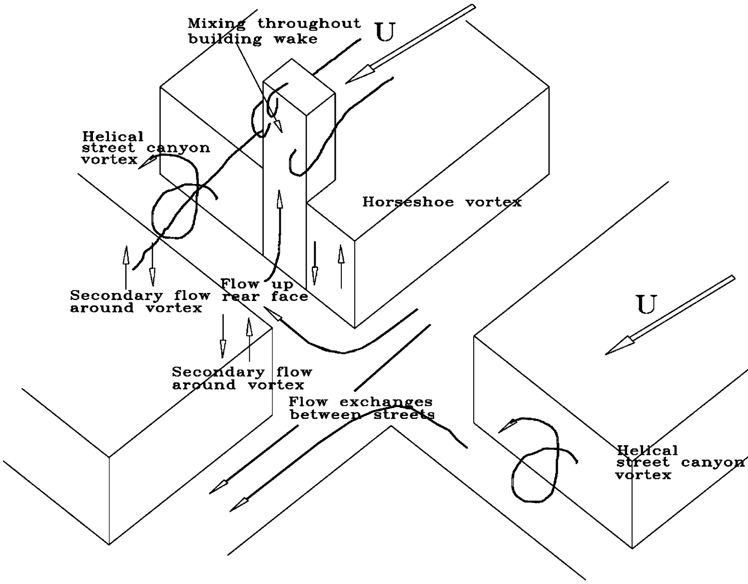

Fig. 6. Flow field at a street intersection [23].

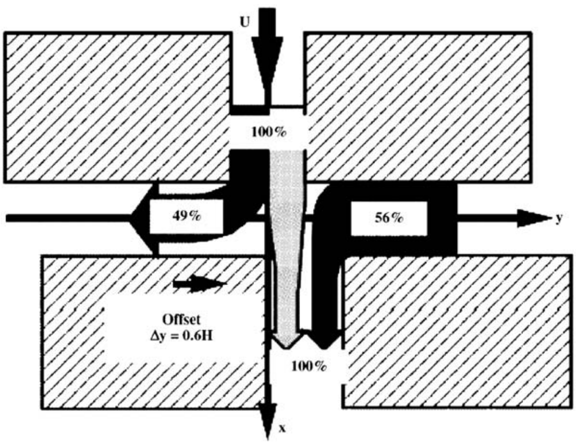

Fig. 7. Flow interchanges at an intersection defined by four blocks of height H, with a $0.6H$ off-set block size $6 \times 4H$ [47].

width results in increase in concentration for square blocks. Meroney et al. [52] report significant variations in concentration with wind directions. Rafailidis and Schatzmann [53], Rafailidis et al. [54], Rafailidis [55] and Kastner-Klein and Plate [56] observe the influence of roof shape on the distribution of pollutants within the canyon. They report that the street canyons with saddle roofs are more effective than those having flat roofs. Meroney et al. [14] report that the pollutant concentrations are almost independent of the wind speeds when the aspect ratio, equals 1. Liedtke et al. [57] describe the effects of geometrical resolution on pollutants dispersion and report distinct differences in comparison to the modeled field site study of Berckowicz et al. [58]. Leitl et al. [59] have simulated a wind tunnel model describing the pollutant dispersion in street canyons. Pavageau and Schatzmann [60] performed a wind tunnel study to investigate the turbulent characteristics and statistical properties of the concentration field, developing from the steady release of a tracer gas at the street level in a canyon amidst urban roughness with the approaching wind direction perpendicular to the street canyon axis and with a street width to building height aspect ratio, equal to 1. Gerdes and Olivery [61] report the effects of landscape, the ratio between the heights of the upstream and downstream canyon walls and the spacing between the canyon walls, on pollutants dispersion at perpendicular approaching wind direction. Recently, Kovar-Pankus et al. [62], Kastner-Klein and Rotach [63], Leitl et al. [59] and Chauvet et al. [64] reported the sensitivity of flow and turbulence characteristics to the geometry of the street and its surroundings.

Hoydysh and Dabberdt [65] reported variations in pedestrian level concentrations at intersections and also with ambient wind direction. Dabberdt et al. [66] investigated the ambient concentrations at urban intersections, using tracer gas in the boundary layer wind tunnel and three mathematical simulation models. In the tracer gas experiments, quantitative tracer gas methods have been used to study dispersion at an intersection, surrounded by a regular array of uniform low-rise rectangular blocks as well as an intersection with significant variations in the height of the adjacent blocks. For the uniform block configuration, concentrations simulated by three mathematical models (HIWAY-2, CALINE-4 and the Lagrangian dispersion model, based on the Langvin equation), have been compared with the fluid model pedestrian level concentration measurements at 15-street level intersection locations, for each of eight wind directions. The prediction of the two Gaussian models was found to be poor, while the performance of the Lagrangian model was significantly better.

4. Effect of vehicular motion on exhaust dispersion

Dispersion of gaseous pollutants in street canyons takes place under the joint influence of natural and vehicle-induced air motions. During ‘calm’ wind conditions, the turbulence produced by the moving vehicles is dominated over the natural winds in the street canyons. Kitabayashi et al. [67] and Kitabayashi [68] report the automobile exhaust gas diffusion in a typical street canyon at stable and adiabatic conditions under variable wind and vehicle speeds and found that vehicular motions for both stable and adiabatic conditions considerably affected the pollutants dispersion. Qin and Kot [69] observe a large influence of the movement of the vehicle fleet on the airflow and turbulence near the bottom of the canyon and report that the vehicle wake and the hot exhaust gases generate mechanical and thermal turbulence. They have also quantified the influence of vehicle movements on the airflow in the canyon up to 12 m above the road surface, ($z/H = 0.8$). De Paul and Sheih’s [34] observations indicate that additional turbulence generated by vehicles, has a marked influence on the turbulent velocity distribution up to a height of approximately 7 m, i.e., $z/H = 0.2$. Kastner-Klein et al. [70,71] report the effect of vehicle-induced turbulence on concentration fields within a canyon [Fig. 8(a) and (b)]. In one-way configuration, the moving vehicle leads to a pronounced transport of pollutants along the canyon axis [Fig. 8(c)]. They have also observed that the turbulence in the street has diurnal variation, which follows that of the vehicle quite well, and that in-street local concentrations may decrease when the vehicle density increases generating enhanced turbulence (Figs. 9 and 10). Holscher et al. [12] report the influence of vehicle motion on pollutant dispersion for parallel, perpendicular and oblique wind directions. In all the cases, they observe a decrease in pollutant concentration when vehicle movements are opposite to the wind flow directions. Pearce and Baker [72,73] describe the effect of vehicular motion on dispersion of pollutants in urban canyons and found a significant effect of vehicle motion on the pedestrian level concentration. Baker and Hargreaves [74] conduct the wind tunnel

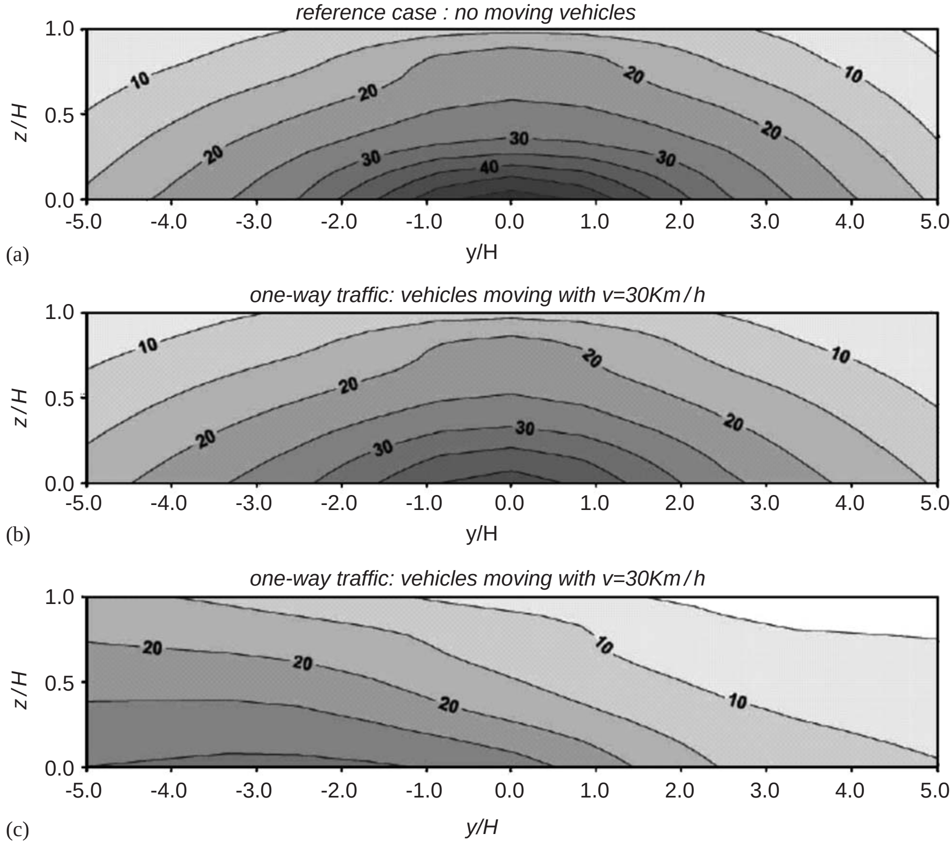

Fig. 8. Values of concentration at the lee wall of the upwind building in the wind tunnel model of a street canyon without traffic (a), with two-way traffic in opposite directions (b) and one-way traffic (c) [70].

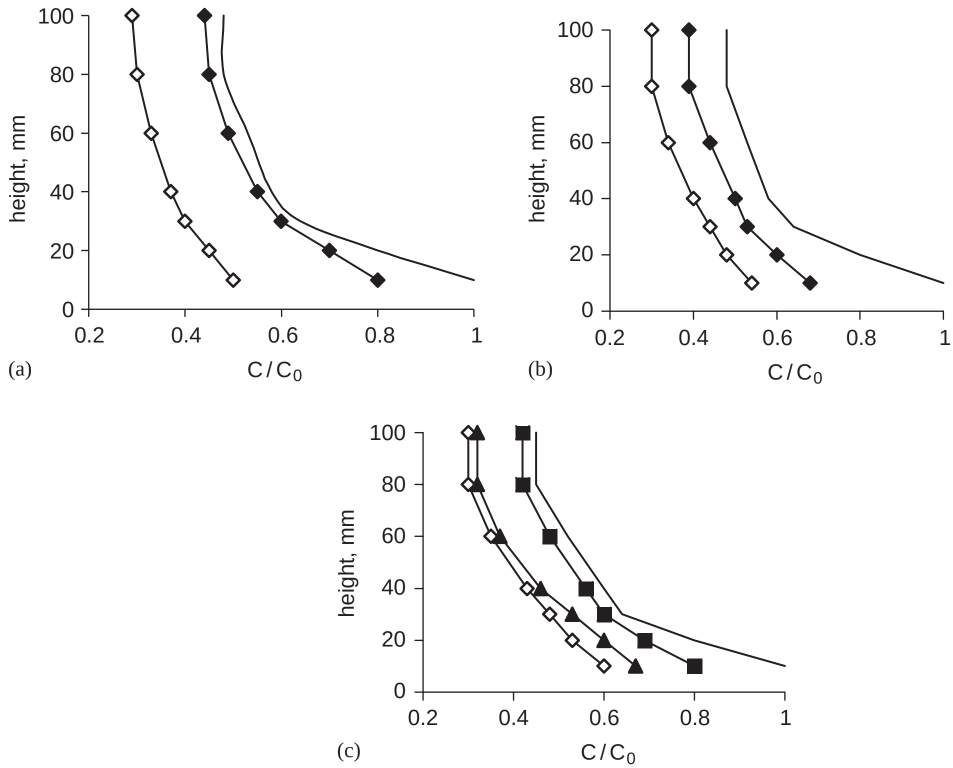

Fig. 9. Wind tunnel data on the attenuation of concentration with (a) different wind velocities: $u = 4.9\,\mathrm{m/s}$ (open symbols) and $u = 10\,\mathrm{m/s}$ (filled symbols) with fixed $v = 12\,\mathrm{m/s}$ (43 km/h), and $n_v = 7$ vehicles/100 m; (b) different traffic velocities: $v = 17\,\mathrm{m/s}$ (61 km/h, open symbols) and $v = 12\,\mathrm{m/s}$ (43 km/h, filled symbols) with fixed $u = 7\,\mathrm{m/s}$ and $n_v = 7$ vehicles/100 m; (c) different traffic densities $n_v = 13$ vehicles/100 m (open symbols), $n_v = 7$ vehicles/100 m (half-filled symbols), and $n_v = 4$ vehicles/100 m (filled symbols) with fixed $v/u = 1.7$. Solid lines show the reference concentration profile without traffic, c_0^* is the normalized concentration at the lowest position of corresponding reference profile [71].

study of pollutant dispersion in the wake of a moving vehicle in a crosswind direction for both rural roadways and urban street canyon. The results are used to assess the validity of a numerical model—PUFFER. It was found that the model performed satisfactorily when employing an ARMA generated time series as input. Bearman and Karanfilian [75], Eskridge and Thompson [76], Eskridge and Rao [7], and Thompson and Eskridge [77] report wind tunnel simulation studies on the wake behind vehicle models, in 'calm' wind conditions and shear-free ABL. The simulation studies show decay in vertical and lateral profiles of mean and fluctuating velocities and Reynold stresses behind the wake of the vehicle. Gowda [3] and Khare et al. [11] report the effects of varying traffic parameters (such as vehicle volume and speed) and vehicle model shape and size on line source dispersion in the near field of urban roadways at various roughness conditions and wind road inclinations for

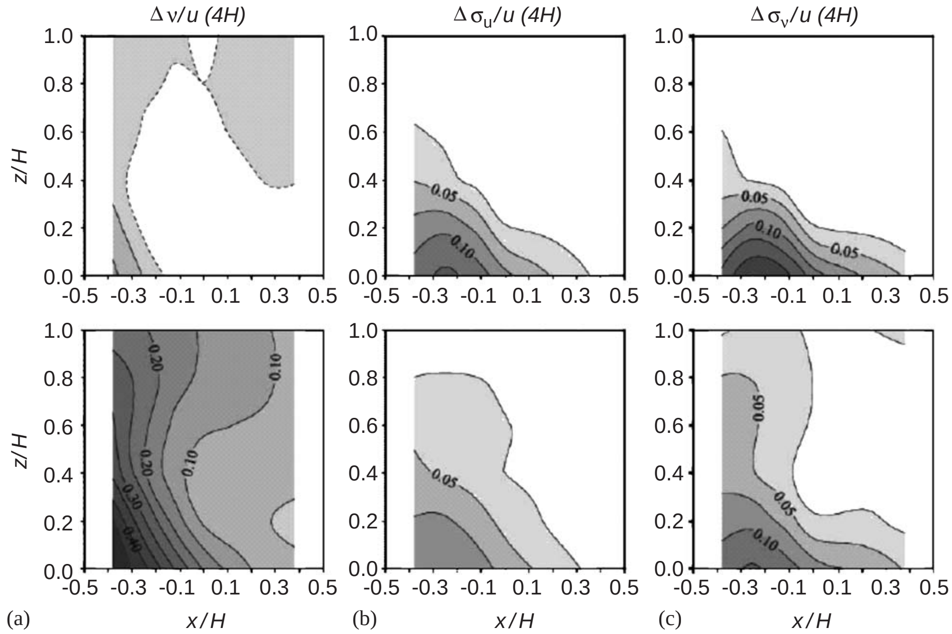

Fig. 10. Traffic-induced contributions to the normalized fields of the lateral (along-the-canyon) mean-flow velocity component (a), and r.m.s. values of longitudinal (b) and lateral velocity (c) fluctuations inside the 120 cm-long street canyon. The plots in the upper row refer to the case of two-way traffic and the lower row corresponds to the case of one-way traffic [71].

heterogeneous traffic. They found a monotonic increase in vertical spread of tracer gas concentration up to a downwind distance of $44X/H_v$ (where X is the downwind distance and H_v the average height of vehicles).

4.1. Scaling of traffic-induced turbulence

Plate [78] proposes a similarity criterion for wind tunnel simulation of the vehicle and wind-induced components of turbulent motion in an urban street canyon. According to Plate [78], the ratio of energy production P_T, caused by moving traffic to the energy production P_W, caused by the wind are the same in the wind tunnel model and in the prototype:

$$\frac{P_{Tm}}{P_{Wm}} = \frac{P_{Tn}}{P_{Wn}}, \tag{1}$$

where m represents model and n, prototype. The energy production per unit street length, P_T, in a city street canyon with the height H and width B, is

$$P_T = \frac{\rho C_{DT} A_T n_T v_t^3}{BH}. \tag{2}$$

Further, the value of P_W is evaluated as follows:

$$P_W = \tau \frac{\Delta u}{\Delta z} \approx \frac{\rho u_*^2}{H} u(H) \propto \frac{\rho c_{th} u^3}{H}, \tag{3}$$

where $u_* = \sqrt{c_{th}}\, u$ is expressed through coefficient c_{th} and u is the free stream wind velocity. Therefore, Eq. (1) becomes

$$\underbrace{\frac{C_{DTm} A_{Tm} n_{Tm}}{c_{thm} B_m}}_{a_m} \frac{v_m^3}{u_m^3} = \underbrace{\frac{C_{DTn} A_{Tn} n_{Tn}}{c_{thn} B_n}}_{a_n} \frac{v_n^3}{u_n^3}. \tag{4}$$

The friction coefficient c_{th} is assumed to be the same for both, in the model and prototype. The width of the street canyon in wind tunnel, B_m, is given by

$$B_m = B_n / M, \tag{5}$$

where M is the scale chosen. Eq. (4) is summarized as follows:

$$\frac{(v_n/u_n)^3}{(v_m/u_m)^3} = \frac{a_m}{a_n} = \frac{n_{tm}}{n_{tn} M} = a. \tag{6}$$

The variations of traffic volume in the EWT are described by the variation of factor 'a'. Finally, the modeling criterion is expressed as follows:

$$\left(\frac{v^3}{u^3}\right)_n = a \left(\frac{v^3}{u^3}\right)_m \Leftrightarrow \left(\frac{v}{u}\right)_n = a^{1/3} \left(\frac{v}{u}\right)_m. \tag{7}$$

Brilon [79] and Kastner-Klein et al. [71] have verified the above criterion for the urban street canyon under homogeneous traffic conditions. The movement of vehicles has been simulated by mounting small metal plates on two belts moving along a modeled street canyon considering the velocity, density, frontal area and drag coefficients as vehicle characteristics. The vehicle density and speed are varied and the influence of the vehicle-induced turbulence on concentration patterns at the canyon walls has been studied. It is found that the concentration decreases with an increasing ratio of vehicle to wind velocity and with an increase in vehicle density. A dimensionless combination of vehicle to wind velocity ratio and density factor is proved to be a universal parameter describing the dependence of the concentration on vehicle induced turbulence. Kovar [80] observed that the disturbance of the flow, sideward and upwards of the moving vehicle was too large and the mounted plates also created a strong mean wind flow in the moving direction of vehicles. In fact, this phenomenon is not observed under real conditions. Henne et al. [81] report that vehicle-induced turbulence is modeled physically utilizing an energy-based design rule developed by Plate [78], which does not take into account the length scale of the turbulence. Moving turbulence generators for the simulation of vehicles need to be independent of Reynolds number, even at low generator velocity.

5. Concluding remarks

Flow and dispersion patterns inside the canyon depend on its geometry, i.e., aspect ratio, and length-to-depth ratios, and above the building and roof shapes. In *deep* canyons, the vortices interact poorly with the external wind flow above the canyon and do not significantly contribute to the removal of exhaust gases. Relatively *short* canyons provide better ventilation at corners, due to formation of corner vortices but this effect fades with increasing street length. Intermittent vortices formed at corners of the building are responsible for creating a '*convergence zone*' in the mid-block region of the street canyons/intersections resulting in maximum trapping of pollutants. Canyons in an open country generate an unstable vortex, which continuously rises in the upward direction, while canyons in urban areas generate a stable rotating vortex that suppresses the street ventilation resulting in the trapping of pollutants. Within urban street intersections, wind vortices, low-pressure zones and channeling effects may cause maximum trapping of pollutants in the lower portion. In case of high-rise buildings, forming intersections provides better ventilation at corners. It is due to the formation of corner vortices.

A similarity criterion relating the wind and vehicle-induced components of turbulent motion in an urban street canyon proposed by Plate [78] is one of the major contributions. Further, it provides a separate quantification of vehicle-induced turbulence and turbulence produced by natural winds.

References

[1] J. Fenger, Urban air quality, Atmos. Environ. 33 (1999) 4877–4900.

[2] E.J. Colvile, E.J. Hutchinson, J.S. Mindel, R.F. Warren, The transport sector as a source of air pollution, Atmos. Environ. 35 (2001) 1537–1567.

[3] R.M.M. Gowda, Wind tunnel simulation study of the line source dispersion in the nearfield of roadways under heterogeneous traffic conditions, Ph.D. Thesis, Indian Institute of Technology, Delhi, India, 1999.

[4] G. Hoek, B. Brunekreef, A. Verhoef, J. Van Wijnen, P. Fischer, Daily mortality and air pollution in the Netherlands, J. Air Waste Manage. Assoc. 50 (2000) 1380–1389.

[5] F. Nyberg, P. Gustavsson, L. Jarup, T. Bellander, N. Berglind, R. Jacobsson, G. Pershagen, Urban air pollution and lung cancer in Stockholm, J. Epidemiol. 11 (2000) 487–495.

[6] W. Dab, C. Segala, F. Dor, B. Festy, P. Lameloise, Y. Le Moullec, A. Le Tertre, S. Medina, P. Quenel, B. Wallaert, D. Zmirou, Pollution atmospherique et sante: Corelation ou causalite? Le cas de la relation entre l'exposition aux particules et la mortalite cardio-pulmonaire, J. Air Waste Manage. Assoc. 51 (2001) 203–219.

[7] R.E. Eskridge, S.T. Rao, Turbulent diffusion behind vehicles: experimentally determined turbulence mixing parameters, Atmos. Environ. 20 (1986) 851–860.

[8] K. Ahmad, M. Khare, K.K. Chaudhry, Model vehicle movement system in wind tunnels for exhaust dispersion studies under various urban street configurations, J. Wind Eng. Ind. Aerodyn. 90 (2002) 1054–1067.

[9] N. Isyumov, Physical modeling of atmospheric dispersion in complex settings, wind climate in cities, Proceedings of the NATO Advance Study Institute at Waldbrown, Germany, 1993.

[10] C.M.N. Riain, B. Fisher, C.J. Martin, J. Littler, Flow field and pollution dispersion in a central London street, Environ. Monit. Assess. 52 (1998) 299–314.

[11] M. Khare, K.K. Chaudhry, R.M.M. Gowda, K. Ahmad, Heterogeneous traffic induced effects on vertical dispersion parameter—a wind tunnel study, Environ. Model. Assess. 7 (2002) 09–15.
[12] N. Holscher, R. Hoffer, H.J. Neimann, W. Brilon, E. Romberg, Wind tunnel experiments on micro scale dispersion of exhausts from motorways, Sci. Total Environ. 134 (1993) 71–79.
[13] W.H. Snyder, Guide line for fluid modelling of atmospheric diffusion, Report No. 600/8-81-009, USEPA, Research Triangle Park, NC 27711, 1981.
[14] R.N. Meroney, M. Pavageau, S. Rafailidis, M. Schatzmann, Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons, J. Wind Eng. Ind. Aerodyn. 62 (1996) 37–56.
[15] J.E. Cermak, Application of fluid mechanics to wind engineering—a free man scholar lecture, Trans. ASME J. Fluid Eng. (1975) 9–38.
[16] J.E. Cermak, Wind tunnel design for physical modelling of atmospheric boundary layers, J. Eng. Mech. Div. ASCE 108 (1981) 523–642.
[17] W.H. Snyder, Fluid modelling applied to atmospheric diffusion in complex terrain, Atmos. Environ. 24 (1990) 2071–2088.
[18] J.C.R. Hunt, C.J. Abell, J.A. Peterka, H. Woo, Kinematical studies of the flows around free or surface mounted obstacles: applying topology to flow visualization, J. Fluid Mech. 86 (1978) 179–200.
[19] A.G. Robins, J.E. Fackrell, Laboratory studies of dispersion near buildings, Proceedings of the CEC Symposium on Radio Active Releases and their Dispersion in the Atmosphere, RISO, Denmark, 1980.
[20] R.N. Meroney, Turbulent diffusion near buildings, in: E.J. Plate (Ed.), Engineering Meteorology, Elsevier, Amsterdam, 1982, pp. 425–481.
[21] R.P. Hosker, Flow and diffusion near obstacles, Atmospheric Science and Power Production, Publication DOE/TIC-27601, US Department of Energy, Washington, DC, 1984, pp. 241–326.
[22] P.M. Foster, A.G. Robins, The effects of buildings at low level atmospheric discharges, CEGB, Report No. TPRD/L/2888/R85 1985.
[23] A. Robins, R. MacDonald, Review of flow and dispersion in the vicinity of groups of buildings, Annexure B, University of Surrey, 2001.
[24] R.P. Hosker, W.R. Pendergrass, Flow and dispersion near clusters of buildings, NOAA Technical Memorandom ERL-ARL-153, Department of Commerce, USA, 1987.
[25] S.E. Nicholson, Air pollution model for street level air, Atmos. Environ. 9 (1975) 19–31.
[26] S. Vardoulakis, E.A.F. Bernard, K. Pericleous, N. Gonzalez–Flesca, Modeling air quality in street canyons: a review, Atmos. Environ. 37 (2003) 155–182.
[27] T.R. Oke, Street design and urban canopy layer climate, J. Energy Buildings 11 (1988) 103–113.
[28] M. Husain, B.E. Lee, Wind tunnel study of the mean pressure forces acting on large groups of low rise buildings, J. Wind Eng. Ind. Aerodyn. 6 (1980) 207–225.
[29] M. Santamoris, Air flow Characteristics in Urban Canyons, Department of Applied Physics, University of Athens, La Rochelle, Athens, 2000.
[30] L.J. Hunter, G.T. Johnson, I.D. Watson, An investigation of three dimensional characteristics of flow regimes within the urban canyon, Atmos. Environ. 26B (1992) 425–432.
[31] F. Albrecht, Untersuchungen der vertikalen luftzirkulation in der Grossstadt, Met. Zt. 50 (1933) 93–98.
[32] H.W. Georgii, H.W. Busch, E. Weber, Investigation of the temporal and spatial distribution of emission concentration of carbon monoxide in Frankfort/Main, Report No. 11, Institute for Meteorological and Geophysics of the University of Franfort/Main (Translation No. 0477, NAPCA), 1967.
[33] Y. Nakamura, T.R. Oke, Wind, temperature and stability conditions in an east west oriented urban canyon, Atmos. Environ. 22 (1988) 2691–2700.
[34] F.T. De Paul, C.M. Shieh, A tracer study of dispersion in an urban street canyon, Atmos. Environ. 20 (1986) 455–459.
[35] W.F. Dabberdt, F.L. Ludwig, W.B. Johnson, Validation and applications of an urban diffusion model for vehicular emissions, Atmos. Environ. 7 (1973) 603–618.

[36] W.G. Hoydysh, W.F. Dabberdt, Kinematics and dispersion characteristics of flows in asymmetric street canyons, Atmos. Environ. 22 (1988) 2677–2689.
[37] P.C. Chang, P.N. Wang, A. Lin, Turbulent diffusion in a city street, Proceedings of the Symposium on Air Pollution and Turbulent Diffusion, Las Cruces, New Mexico, 1971, pp. 137–144.
[38] S.J. Jeong, M.J. Andrews, Application of k–e turbulence model to the high Reynolds number skimming flow field of an urban street canyon, Atmos. Environ. 36 (2002) 1137–1145.
[39] A. Kovar, P. Louka, J.F. Sini, E. Savory, M. Czech, A. Abdelqari, P.G. Mestayer, N. Toy, Influence of geometry on the mean flow within urban street canyons—a comparison of wind tunnel experiments and numerical simulations, Int. J. Water Air Soil Pollut. Focus 2 (2002) 365–380.
[40] R.J. Yamartino, G. Weigand, Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon, Atmos. Environ. 20 (1986) 2137–2156.
[41] P. Kastner Klein, E. Fedorovich, J.F. Sini, P.G. Mestayer, Experimental and numerical verification of similarity concept for dispersion of car exhaust gases in urban street canyons, 1999. http://www.geo.umnw.ethz.ch/staff/homepages/pkklein/tpt/texte/pkklein/pkklein-madrid.pdf
[42] J.B. Wedding, D.J. Lombardi, J.E. Cermak, A wind tunnel study of gaseous pollutants in city street canyons, J. Air Pollut. Control Assoc. 27 (1977) 557–566.
[43] M. Nunez, T.R. Oke, Long wave radiative flux divergence and nocturnal cooling of the atmosphere within an urban canyon, Boundary Layer Meteorol. 10 (1977) 121–135.
[44] M. Santamoris, E. Dascalaki, Wind speed in the urban environment, group building environmental studies, Department of Applied Physics, University of Athens, Athens, 1999.
[45] M. Santamoris, N. Papanikolaou, I. Koronakis, Urban canyon experiments in Athens, Internal Report to the POLIS Research Project, European Commission, Directorate General for Science, Research and Technology, Athens, 1997.
[46] A.S. Scaperdas, Modelling air flow and pollutant dispersion at urban canyon intersections, Ph.D. Thesis, Imperial College, University of London, 2000.
[47] A. Robins, E. Savory, A. Scaperdas, Grigoriadis, Spatial variability and source–receptor relations at a street intersection, Int. J. Water Air Soil Pollut. Focus 2 (2002) 381–393.
[48] W.G. Hoydysh, Y. Ogawa, R.A. Griffiths, A scale model study of dispersion of pollution in street canyons, APCA Paper No. 74–157, 67th Annual Meeting of the Air Pollution Control Association, Denver, CO, 9–13 June 1974.
[49] P.J.H. Builtjes, Determination of the flow field in a street canyon by means of wind tunnel experiments, TNO Progress Report 83-09553, Apeldoom, The Netherlands, 1983.
[50] P.J.H. Builtjes, Determination of the flow and concentration field in a street canyon by means of wind tunnel experiments, TNO Report No. 84-02616, Apeldoom, The Netherlands, 1984.
[51] W.F. Dabberdt, W.G. Hoydysh, Street canyon dispersion: sensitivity to block shape and entrainment, Atmos. Environ. 25A (1991) 1143–1153.
[52] R.N. Meroney, S. Rafailidis, M. Pavageau, Summary and discussion of the findings from the wind tunnel studies of April–June 1994, Meteorologisches Institut, Universitat Hamburg, Hamburg, 1994.
[53] S. Rafailidis, M. Schatzmann, Physical modelling of car exhaust dispersion in urban street canyons, Proceedings of the 21st International Meeting on Air Pollution Modelling and its Applications, Baltimore, 1995.
[54] S. Rafailidis, M. Pavageau, M. Schatzmann, Wind Tunnel Simulation of Car Emission Dispersion in Urban Street Canyons, Annalen der Meteorologie, Deutsche Meteorologische Gesellschaft, Munich, 1995.
[55] S. Rafailidis, Influence of the building areal density and roof shape on the wind characteristics above a town, J. Boundary Layer Meteorol. 85 (1997) 255–271.
[56] P. Kastner-Klein, E.J. Plate, Wind tunnel study of concentration fields in street canyons, Atmos. Environ. 33 (1999) 3973–3979.
[57] J. Liedtke, B.M. Leitl, M. Schatzmann, Car exhaust dispersion in a street canyon—wind tunnel data for validating numerical dispersion models, Second East European Conference on Wind Engineering (EECWE), Prague, 7–11 September 1998.

[58] R. Berckowitz, F. Palmgren, O. Hertel, E. Vignati, Using measurements of air pollution in streets for evaluation of urban air quality—meteorological analysis and model calculations, The Fifth International Symposium on Highway and Urban Pollution, Copenhagen, 22–24 May 1995; Sci. Total Environ. 189/190 (1996) 259–265.
[59] B.M. Leitl, C. Chauvet, M. Schatzman, Effects of geometrical simplification and idealization on the accuracy of micro-scale dispersion modeling, Proceedings of the Third International Conference on Urban Air Quality, Loutraki, Greece, 2001.
[60] M. Pavageau, M. Schatzmann, Wind tunnel measurements of concentration fluctuations in an urban street canyon, Atmos. Environ. 33 (1999) 3961–3971.
[61] F. Gerdes, D. Olivery, Analysis of pollutant dispersion in an urban street canyon, J. Wind Eng. Ind. Aerodyn. 82 (1999) 105–124.
[62] A. Kovar, P. Louka, P.G. Mestayer, E. Savory, J.F. Sini, N. Toy, Influence on the geometry on the flow and turbulence characteristics within urban street canyons—inter comparison of the wind tunnel experiments and numerical solutions, Proceedings of the Third International Conference on Urban Air Quality, Loutraki, Greece, 2001.
[63] P. Kastner-Klein, M.W. Rotach, Parameterization of wind and turbulent shear stress profiles in the urban roughness sublayer, Proceedings of the Third International Conference on Urban Air Quality, Loutraki, Greece, 2001.
[64] C. Chauvet, B. Leitl, M. Schatzman, High-resolution flow measurements in an idealized urban street canyon, Proceedings of the Third International Conference on Urban Air Quality, Loutraki, Greece, 2001.
[65] W.G. Hoydysh, W.F. Dabberdt, Concentration fields at urban intersections: fluid modelling studies, Atmos. Environ. 28 (1994) 1849–1860.
[66] W. Dabberdt, W. Hoydysh, M. Schorling, F. Yang, O. Holynskyj, Dispersion modeling at urban intersections, Sci. Total Environ. 169 (1995) 93–102.
[67] K. Kitabayashi, K. Sugawara, S. Isomusa, A wind tunnel study of automobile exhaust gases diffusion in an urban district, in: S. Kasuga, N. Suzuki, T. Yamada, G. Kimusa, K. Inagaki, K. Onoe (Eds.), Proceedings of the Fourth International Clean Air Congress, The Japanese Union of Air Pollution Prevention Association, 1977, pp. 192–195.
[68] K. Kitabayashi, Wind tunnel experiments for automobile exhaust gas diffusion in a street canyon, Fourth International Workshop on Wind and Water Tunnel Modelling, Karlsruhe, 1988.
[69] Y. Qin, S.C. Kot, Dispersion of vehicular emission in street canyons, Guangzhou city, South China (P.R.C.), Atmos. Environ 27B (1993) 283–291.
[70] P. Kastner-Klein, R. Berkowicz, A. Rastetter, E.J. Plate, Modelling of vehicle induced turbulence in air pollution studies for streets, Proceedings of the Fifth Workshop on Harmony within Atmospheric Dispersion Modeling, Rhodes, Greece, (1998). http://www.geo.umnw.ethz.ch/staff/homepages/pkklein/tpt/texte/kklein/pkklein-rhodes.pdf
[71] P. Kastner-Klein, R. Berkowicz, E.J. Plate, Modelling of vehicle induced turbulence in air pollution studies for streets, Int. J. Environ. Pollut. 14 (2000) 496–507.
[72] W. Pearce, C.J. Baker, Characteristics of the fluctuating tracer concentrations measured at pedestrian level around a 1:125th scale wind tunnel model of a part of the city of Leicester, Report No. FR 96003, Department of Civil Engineering, University of Nottingham, 1996.
[73] W. Pearce, C.J. Baker, Wind tunnel investigation of the effect of vehicle motion on dispersion in urban canyons, J. Wind Eng. Ind. Aerodyn. 67–71 (1997) 915–926.
[74] C.J. Baker, D.M. Hargreaves, Wind tunnel evaluation of a vehicle pollution dispersion model, J. Wind Eng. Ind. Aerodyn. 89 (2001) 187–200.
[75] P.W. Bearman, S. Karanfilian, The wakes of road vehicles, in the modelling of dispersion of transport pollution, Symposium Proceedings Series No. 22, The Institute of Mathematics and its Applications, UK, 1981, pp. 78–96.
[76] R.E. Eskridge, R.S. Thompson, Experimental and theoretical study of the wake of a block shaped vehicle in a shear free boundary flow, Atmos. Environ. 16 (1982) 2821–2836.
[77] R.S. Thompson, R.E. Eskridge, Turbulent diffusion behind vehicles: experimentally determined influence of vortex pair in vehicle wake, Atmos. Environ. 21 (1987) 2991–2997.

[78] E.J. Plate, Windkanalmodellierung von Ausbreitungsvorgangen in Stadtgebieten. Kolloquiumsbericht Abgasbelastungen durch den Strabenverkehr, Verlag TUV Rheiland, Germany, 1982.
[79] W. Brilon, H.J. Neimann, E. Romberg, Wind tunnel experiments on spread of exhausts in the vicinity of motorways, Proceedings of the 14th ARRB Conference, Part 3, Transport and Planning, Australian Road Research Board, 1988.
[80] A. Kovar, Physical modeling of vehicle emissions in respect of car induced turbulence, Proceedings of the Eurotrac Symposium, 1998.
[81] S. Henne, B. Leitl, M. Schatzman, Wind tunnel studies on traffic produced turbulence and its influence on pollutants dispersion in an urban street canyon, Proceedings of the Third International Conference on Urban Air Quality, Loutraki, Greece, 2001.