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.

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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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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
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 outside 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.

\[ \text{Fig. 4. Pollutant dispersion in a regular street canyon [35].} \]
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 1.2\( H \), 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

![Fig. 5. Mean velocity vectors and stream traces on center-plane for \( W/H = 0.5 \) [39].](image-url)
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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Canyon characteristics</th>
<th>Flow fields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Perpendicular flow</td>
</tr>
<tr>
<td>[27,28]</td>
<td>Aspect ratio &gt; 0.05</td>
<td>Flow fields do not interact, resulting in the disruption of wakes. This type of flow regime is known as ‘isolated roughness flow regime’.</td>
</tr>
<tr>
<td>[44]</td>
<td>Aspect ratio &lt; 0.65</td>
<td>The bolster and cavity eddies are disturbed and the flow regime changes and is known as ‘wake interference flow’.</td>
</tr>
<tr>
<td>[30,33–36,40,42]</td>
<td>Aspect ratio &gt; 0.65 and &lt; 2, L/W &gt; 20</td>
<td>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’.</td>
</tr>
<tr>
<td>[37,41,45]</td>
<td>Aspect ratio ≥ 2 and L/W &lt; 20</td>
<td>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.</td>
</tr>
<tr>
<td>[38]</td>
<td>Higher aspect ratios</td>
<td>A third weak vortex might also be formed.</td>
</tr>
</tbody>
</table>


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

![Figure 8](image.png)

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].
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 Reynolds 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. 9. Wind tunnel data on the attenuation of concentration with (a) different wind velocities: \( u = 4.9 \text{ m/s} \) (open symbols) and \( u = 10 \text{ m/s} \) (filled symbols) with fixed \( v = 12 \text{ m/s} \) (43 km/h), and \( n_v = 7 \) vehicles/100 m; (b) different traffic velocities: \( v = 17 \text{ m/s} \) (61 km/h, open symbols) and \( v = 12 \text{ m/s} \) (43 km/h, filled symbols) with fixed \( u = 7 \text{ m/s} \) 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].
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:

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

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

$$P_T = \frac{\rho C_{DT} A_{TN} v^3_i}{BH}.$$
Further, the value of $P_W$ is evaluated as follows:

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

(3)

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

$$\frac{C_{DTm} A_{Tm} n_{Tm} v_m^3}{c_{thm} B_m} u_m^3 = \frac{C_{DTn} A_{Tn} n_{Tn} v_n^3}{c_{than} B_n} u_n^3.$$  

(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

$$B_m = B_n / M,$$  

(5)

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

$$\frac{(v_n / u_n)^3}{(v_m / u_m)^3} = \frac{a_m}{a_n} = \frac{n_m}{n_n M} = a.$$  

(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:

$$\left( \frac{v_n^3}{u_n^3} \right)_n = a \left( \frac{v_m^3}{u_m^3} \right)_m \Leftrightarrow \left( \frac{v_n}{u_n} \right)_n = a^{1/3} \left( \frac{v_m}{u_m} \right)_m.$$  

(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.

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