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Experimental Verification of Plate's Criteria for Urban Roadways Intersection

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ABSTRACT

In recent past, significant efforts have been made to improve the scientific understanding of exhaust dispersion phenomenon in urban street canyons/intersection. The amount of turbulence generated by natural winds within the street canyon might be smaller than that of traffic induced turbulence. Therefore, the influence of traffic-induced turbulence on exhaust dispersion has to be quantified. In the present study, Plate's energy based criterion for physical modelling of traffic-induced turbulence has been verified for urban intersection under heterogeneous traffic conditions, using environmental wind tunnel. The experimental results revealed that the effect of traffic-induced turbulence in concentration reduction increases with increase in traffic volume. The trends of reduction in tracer gas concentration with variable traffic volume and velocity ratio for all sampling locations have been found to be similar. This strongly supports the idea proposed by Plate (1982) for wind tunnel simulation studies.

Keywords: *Exhaust dispersion, traffic induced turbulence, heterogeneous traffic, and urban intersection*

1.0 INTRODUCTION

Despite significant improvements in fuel and engine technology, the urban environments are mostly dominated by traffic emissions. For instance, in India, increased motorised transport has led to problems of higher vehicular exhaust emissions, resulting in 64% of contribution in air pollution load in many urban centres (Gowda, 1999). In recent past, significant efforts have been made to improve the scientific understanding of exhaust dispersion phenomenon in urban street canyons/intersection. The amount of turbulence generated by natural winds within the street canyon might be smaller than that of traffic induced turbulence. The traffic-induced turbulence may become an important variable affecting the dispersion of exhaust emissions, especially under calm wind conditions (<1 m/s) in the street canyons and congested intersections (Ahmad et. al. 2002). Therefore, the influence of traffic-induced turbulence on exhaust dispersion has to be quantified. Plate (1982) has proposed an experimental concept for simulating the effects of traffic-induced turbulence on exhaust dispersion in a wind tunnel. Kastner Klein et. al. (2000) have verified the above criterion for street canyons using conventional moving belt type vehicle movement system under homogeneous traffic conditions. The present study aimed to verify Plate (1982) criterion for congested urban street intersection using new designed flexible model vehicle movement system under heterogeneous traffic conditions.

1.1 PLATE (1982) CRITERION: AN OVERVIEW

According to Plate (1982) the ratio of energy production P_T caused by moving traffic to the energy production P_W caused by the wind should be same in the wind tunnel model and in the prototype:

$$\frac{P_{Tm}}{P_{Wm}} = \frac{P_{Tn}}{P_{Wn}} \quad \ldots \qquad (1)$$

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

$$P_T = \frac{\rho . C_{DT} . A_T . n_T . v^3}{B . H} \qquad (2)$$

where ρ is the density of air, C_{DT} is the drag coefficient, A_T the frontal area, n_T is the number of vehicles per unit length and v is the average velocity of vehicles. Further, the value of P_W can be evaluated as follows:

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

where the shear velocity $u_* = \sqrt{c_{th}} . u$ has been expressed through coefficient c_{th} and u is the free stream wind velocity. Consequently, equation 1 becomes:

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

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

$$B_m = B_n / M$$

where M is scale chosen. Further, the equation 4 can be summarize as follows:

$$\frac{\left(v_n / u_n\right)^3}{\left(v_m / u_m\right)^3} = \frac{a_m}{a_n} = \frac{n_{tm}}{n_{tn}.M} = a \qquad (5)$$

The variations of traffic volume in the EWT have been described by the variation of factor a. Finally, the modeling criterion can be expressed as follows:

$$\left(\frac{v^3}{u^3}\right)_n = a.\left(\frac{v^3}{u^3}\right)_m \Leftrightarrow \left(\frac{v}{u}\right)_n = a^{1/3}.\left(\frac{v}{u}\right)_m \quad \ldots \quad \ldots \quad \ldots \qquad (6)$$

In the present study, this form of the Plate (1982) criterion has been experimentally verified for the urban intersection under heterogeneous traffic conditions.

2.0 EXPERIMENTAL SETUP

All the experiments have been carried out in an open circuit, low speed and suction type 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 height of the bottom surface of the test section is 45 cm above the ground level. To prevent surge and other disturbances induced by outside air at the entrance to EWT a wall has been constructed so as to ensure smooth plenum chamber for the entry of air into the entrance section of the wind tunnel. Further, since there was no built up area in the vicinity of EWT, there was always an undisturbed flow condition at the entrance of the EWT. The detailed constructional features and operational characteristics of the EWT have been described in Ahmad et al (2002).

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 (1969), 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 (1971), Wooding et al (1973) and Gartshore and De Cross (1977). The characteristics of the simulated flow have been described as follows:

2.1.1 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 (i.e. before the turntable). The mean velocity profile in the simulated ABL, can be represented by well known power – law form which is given as follows:

$$\frac{u}{U_\infty} = \left(\frac{z}{\delta}\right)^\alpha \quad \ldots \quad \ldots \qquad (7)$$

The normalized profile of observed longitudinal mean velocity u / U_∞ versus normalized depth z / δ has followed the well known power law. The power law index (α) and boundary layer depth (δ) were found to be 0.333 and 800 mm (i.e., the point where u / U∞ = 0.995) respectively. This value of power law exponent (α) was typically in the range quoted by Snyder (1981), Davenport (1963) and Counihan (1975) for urban terrain categories. Davenport (1963) 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 (1996) 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.

Comparing the boundary layer depth simulated in the wind tunnel with the urban atmospheric boundary layer depth recommended by Davenport (1963)'s δ of 457 m. The simulated atmospheric boundary layer represented to a scale of 1:570, the urban ABL.

2.1.2 Log law profile

The lowest 10 – 15 % of the ABL, termed as 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:

$$\frac{u}{u_*} = \frac{1}{\kappa}.\ln\left[\frac{(z-d_0)}{z_0}\right] \ldots \qquad (8)$$

in the equation (8), the three parameters u_*, z_0 and d_0 has been evaluated using the least square analysis, based on quality of fit of observed velocity profiles recommended by Schaudt (1998). 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. (1980) and Bottema (1997) have been adopted. The recommended logarithmic height range for evaluating the surface roughness parameters are $Z_{min} > 2h$ (where, h is roughness element height) and $Z_{max} < 0.25\ \delta$, in general $Z_{max} / Z_{min} > 2$. The roughness parameters evaluated for the simulated ABL have been given in table 1. The values of σ_d and σ_{z0} in table 1 showed 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	$u_* / U\infty$
0.127	29.27	6.59			1.65	0.29	0.085

2.1.3 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 and ESDU as shown in table 2. It can be observed that the value of z_0 was well represented the situation of the apartment residential or central business district land use type. Further, the comparison of the values of d_0 with recommended value of ESDU for city centres have also showed good agreement.

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

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

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 the two building blocks has been kept. The Snyder's (1981) and Cermak (1975) 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) high represent six storey buildings in the close vicinity of urban intersection. Further, to ensure the similitude between the full scale and model, the building Reynolds number has been calculated using following relationship:

$$\mathrm{Re}_H = \frac{u_H H}{\nu} \qquad (9)$$

where H is the building height, u_H is the wind speed at that height and ν is the kinematic viscosity of the air. In the present study, the building Reynolds number has been found to be 18150 which quite above the critical building Reynolds number value of 11000.

2.3 DESIGN OF MODEL VEHICLE MOVEMENT SYSTEM

A flexible MVMS with real traffic situation for urban streets at various configurations has been designed, developed and fabricated in the turntable of EWT. It could be operated for variable traffic volume, speed and multi-lane traffics for two-way urban roads/intersection without disturbing the ABL flow. The detail constructional features can be seen in Ahmad et al. (2002). The simulation of line source for urban intersection has been achieved more or less similar to that recommended by Meroney et al (1996) 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 has been placed 5 mm above the tube holes so that any initial vertical gas momentum was deflected laterally to release the tracer gas along its edge. Further, this metal strip has represented the divider of the road into two-way simulation and also helps in the exhaust emissions either side of the road.

2.4 CONVERSION OF TRAFFIC VOLUME AND SPEED

The Kastner-Klein et. al. (2000) have reported the following equation for the conversion of prototype traffic volume to model traffic volume/meter in wind tunnels.

$$\frac{N_m}{N_t . M} = a \quad \ldots \quad \ldots \quad (10)$$

Where, N_m is the number of traffic per meter in wind tunnel, N_t is the number of traffic per meter in field, M is the scale and a is constant. Using the above relation, the number of traffic models/meter in the EWT has been calculated for M = 100 and a = 0.5, 1.0, 1.5 and 2.0.

Further, Froude's law has been used to simulate the model vehicle speed (equation 11) in the EWT. According to Froude's law:

$$v_m = v_p \sqrt{1/M} \quad \ldots \quad (11)$$

where, v_m is speed of models in EWT, v_p is the speed of Vehicle at field and M is the scale chosen.

2.4 PARAMETERS FOR PLATE' CRITERIA

- Traffic volume: 3300 vehicle/hr
- Traffic speed (v_p): 15, 20, 25, 30, 35, 40 and 45 km/hr
- Approaching wind flow rate (u): 1.5 m/s
- Scaling factor (a): 0.5, 1.0, 1.5 and 2.0

Table 3: Numbers of model vehicles* for varying scaling factor 'a' in EWT

v_m/u	a: 0.5	a: 1.0	a: 1.5	a: 2.0
0.332	20	39	59	78
0.443	15	29	44	59
0.553	12	23	35	47
0.664	10	20	29	39
0.775	08	17	25	33
0.885	07	15	22	30
0.997	06	13	19	26

3.0 SAMPLING AND ANALYSIS OF TRACER GAS

The sampling points have been located at the centers of the walls of building blocks as well as corners to investigate the dispersion behavior as shown in Fig. 1(a) and Fig. 1(b). The tracer gas sampling has been carried out at receptor height (i.e. at 2 m above the ground level). For the reference case, samples have been collected under 'no vehicle conditions' at all locations and then, sampling of tracer gas has been carried out for various traffic volumes and relative speeds as mentioned in table 3 at all locations. The schematic of tracer gas dispersion experimental set up used in the present study has been shown in Fig. 2. The tracer gas used was a mixture of 5 % acetylene in a 95 % grade I nitrogen. The sampling of tracer gas at each desired locations has been carried out online. The sampling probes have been fixed at pre – selected locations and have been made online. The online samples have been injected into column through manual sampling valve and analyzed using flame ionization detector.

3.1 TRANSFORMATION OF CONCENTRATION DATA

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

$$C = \frac{C_0 . U_{ref} . L . H}{Q} \quad \ldots \qquad (12)$$

where C is non dimensionalized concentration, C_0 is measured concentration, Uref free stream velocity, L is the length of line source, H is the characteristic height and Q is the strength of the line source. This normalization ensures that the tracer gas concentration at any location for a particular case of experiments is independent of source emission/discharge. Thus source of uncertainty involved in the variable discharge or any other experimental conditions has been eliminated.

4.0 RESULTS AND DISCUSSION

The experimental results describing the behavior of reduction of tracer gas concentration at the receptor height (in the canyon center) for leeward direction have been shown in Fig. 3(a). The results showed that the normalized tracer gas concentration decreased with increase in velocity ratio. Further, the tracer gas concentrations have also been decreased with increase in traffic volumes for a particular velocity ratio. The results revealed that the tracer gas concentration is a function of the velocity ratio for four different traffic volumes, represented by factor 'a'. Furthermore, the correction $\sqrt[3]{a}$ has been applied for all velocity ratios, v_m/u. The graph between concentration ratios vs. combined ratio $\sqrt[3]{a} . {}^{v}\!/_{u}$, showed that all the curves have been merged in a single curve Fig. 3(b). This scaling allows summarizing the results for different traffic volumes and provides appropriate scaling for wind tunnel generated data. Furthermore, it supports the applicability of Plate (1982) criteria for wind tunnel simulation studies in the close vicinity of urban intersection under heterogeneous traffic condition. Similar behavior has been observed by Kastner – Klein et. al. (2000) for urban street canyon under homogeneous traffic conditions in their wind tunnel simulation studies.

The tracer gas concentration values at receptor height in the windward direction have been found to be nearly half than that of leeward direction.

This may be due to vortex flow generated inside the canyon and consequently, recirculation of pollutants in the street canyon. The normalized tracer gas concentration ratio decreases with increasing velocity ratios, which was similar to that of leeward side as shown in Fig. 4(a). Almost similar behavior as discussed in the case of leeward side has been found in the windward direction as shown in Fig. 4(b).

The experimental values at inner corners for leeward and windward directions have been found to be less than that of the concentration values found at canyon centers for leeward and windward directions respectively. This may be due to corner vortices formed at the inside corners which, provides ventilation for intersections and play vital role in the reduction of the pollutants at inner corners. For both leeward as well as windward inner corners, the concentration of tracer gas decreases with increasing traffic volume and velocity ratios as shown in Fig. 5(a) and Fig. 5(b). Similar phenomenon has been observed as previously discussed cases.

Further, the tracer gas concentration values at ‘no traffic condition’ for d/s mid point have been found to be approximately twice than that of u/s mid point. This may be due to accumulation of the tracer gas, which was coming from the u/s direction. Here also, the concentration of tracer gas decreases with increasing traffic volume and velocity ratios as shown in Fig. 6(a), 6(b), 7(a), 7(b), 8(a) and Fig. 8(b).

Thus, it has been observed that the value of concentration for ‘no traffic condition’ varies at all sampling points but the trends of reduction in the tracer gas concentration with variable traffic volume and velocity ratio have been found to be similar. This strongly supports the idea proposed by Plate (1982) for wind tunnel simulation studies.

Further, the results showed that the concentration of the tracer gas decreases linearly with increase in $\sqrt[3]{a}\,.\,{}^{v}\!/_{u}$ as follows:

$$c(a,u,v)=c_0\left(1-\gamma\,.\,a^{1/3}\,\frac{v}{u}\right)\ldots(13)$$

Where, c_0 is the normalized concentration at receptor height with ‘no traffic’ condition. The values of the gradient γ have been found to be 0.65 to 0.69 for different location of the intersection. These values are quite above from the values obtained by Kastner – Klein et. al. (2000), in their wind tunnel simulation studies. This may be due to the fact that in the present study, the terrain roughness was more than that of Kastner – Klein et. al. (2000). Due to high roughness condition, mixing of pollutants might be more and further variability of traffic size and shape might also become helpful in the dilution of the pollutants.

5.0 CONCLUSIONS

The study concluded that value of concentration for ‘no traffic condition’ varies at all sampling points but the trends of reduction in the tracer gas concentration with variable traffic volume and velocity ratio have been found to be similar. This verifies the Plate’s energy based criteria for physical modeling of traffic-induced turbulence at urban intersection. A simple scaling factor derived from the condition of similarity between the turbulent energy production in the wind tunnel and in the field is proved to be representative for the observed effects of traffic induced turbulence.

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