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Field experimental study of traffic-induced turbulence on highways

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Abstract

This paper is focused on traffic-induced turbulence (TIT) analysis from a field campaign performed in 2011, using ultrasonic anemometers deployed in the M-12 Highways, Madrid (Spain). The study attempts to improve knowledge about the influence of traffic-related parameters on turbulence. Linear relationships between vehicle speed and turbulent kinetic energy (*TKE*) values are found with coefficients of determination (R^2) of 0.75 and 0.55 for the lorry and van respectively. The vehicle-induced fluctuations in the wind components (u', v' and w') showed the highest values for the longitudinal component (v) because of the wake-passing effect. In the analysis of wake produced by moving vehicles it is indicated how the turbulence dissipates in relation to a distance d and height h. The *TKE* values were found to be higher at the measuring points closer to the surface during the wake analysis.

Keywords: Vehicle-induced turbulence; parameterization; highway turbulence; turbulence intensity

1. Introduction

Pollutant emissions from vehicles are a significant issue in relation to the environment and human health. Occasionally these contaminants are dispersed by the wind from roads to population centers. Therefore, better knowledge of the turbulence processes that are involved in the environment of roads is valuable in the definition of new pollutant diffusion models. One of the sources in the generation of turbulence is vehicle traffic (Rao et al., 1979). Some researchers have shown that the pollutant dispersion models that consider in detail the traffic-induced turbulence (TIT) effects provide a better fit with field measurements, than other models as CALINE4 and CFD models without this consideration (Wang and Zhang, 2009 and Sahlodin et al., 2007). In conditions of low wind velocity and wind direction perpendicular to the road, the traffic contribution to diffusion of pollutants still remains above 50% at 30m away downwind of the road (Sedefian et al., 1981).

As a result, some researchers have studied TIT from different perspectives. A theoretical analysis of the vehicle wake was carried out by Eskridge and Hunt (1979). This research proposes some equations for velocity of the vehicle wake from fundamental motion equations. Hider et al. (1997) extended the wake formulation in conditions of lateral and vertical wind using the main equations of Eskridge and Hunt (1979). Field experiments were also carried out in which the vehicle wake is analyzed according to different methodologies (Chock, 1980; Rao et al., 2002). Rao et al. (2002) installed anemometers on the back of moving vehicles to measure the turbulence just behind of the vehicle while Chock (1980) located anemometers on both sides of the road to measure turbulence parameters in the lee/windward side of the highway. They found that wind direction perpendicular to the road increases TIT effects.

TIT was also analyzed in wind tunnel installations (Eskridge and Thomson, 1982) although turbulence generation systems required improvement since occasional differences between measurements in field campaigns and in wind tunnels have been found (Cooper and Campbell, 1981). Cooper and Campbell (1981) used wind-tunnel and full-scale measurements of the aerodynamic drag on trucks to show the influence of wind turbulence. In addition a quasi-steady theory is developed to consider the effects of turbulence. Watkins et al. (1995) explained how to improve the similarity between turbulence levels in wind tunnels and in the field through structural elements.

Urban street canyons in cities are locations with high concentrations of contaminants because the air flows are smooth in these sheltered zones (Jicha et al., 2000; Vachon et al., 2000; Kastner-Klein et al., 2001; Longley et al., 2004). Kastner-Klein et al. (2001) showed how traffic affects the turbulent airflow in canyons by means of wind tunnel tests. Recently, some researchers (Jicha et al., 2000; Katolicky and Jicha 2005; Dong and Chan 2006; Xia et al., 2006; Sahlodin et al., 2007) have studied the turbulent process relative to the traffic using CFD (Computational Fluid Dynamics) codes because of the good fit with field measurements. Katolicky and Jicha (2005) showed that if TIT is included in atmospheric turbulence models (e.g. using a *k-ε* model), the air flow in canyons increases by 10%, so pollutant concentrations decrease.

In addition to TIT, the roads themselves influence and modify the flow and turbulence, the additionally generated turbulence being of significance for pollutant dispersion (Kalthoff et al., 2005).

Thermally induced turbulence can also be produced due to the presence of highways, as sensitive and latent heat fluxes are different compared to those coming from natural environments (Oke, 1987; Kalthoff et al., 1991). However, the influence on the production of turbulent kinetic energy (*TKE*) seems to be smaller compared to dynamic effects (Weiβ, 2002; Kalthoff et al., 2005).

In this paper, TIT is analyzed in a field experiment. The experiment shows the relationship of turbulent parameters with vehicle type and speed and how TIT varies with the perpendicular distance to vehicles on their leeward side. The first part of the paper describes the experimental setup and the turbulence measurement, and the second part presents and discusses the results of the experiment. The main goal is to improve knowledge about TIT in space near vehicles and how different parameters affect it.

2. Methodology and experimental setup

Wind velocity variances (σ) registered from fixed points on the highway are produced by ambient and vehicle turbulence (Kalthoff et al., 2005). The ambient turbulence, produced within the so-called Atmospheric Boundary Layer (ABL), is caused mechanically by wind shear and buoyancy induced by thermals (Stull, 1988). It is common practice in turbulent flows to express variables (temperature, velocity, etc.) as sums of mean and fluctuating parts (Arya, 2001):

$$u = u' + \bar{u} \tag{1}$$

Two kinds of velocity fluctuations are recorded by a fixed anemometer on road when moving vehicles pass by it: the wake when the wind hits the vehicle as an obstacle and the wake-passing effect which is specifically generated by moving vehicles, even in the absence of wind (Eskridge and Rao, 1983). Parameters such as the turbulent momentum fluxes (e.g. $\overline{u'v'}$) involving covariance between velocity component fluctuations, and the *TKE* defined as:

$$TKE = 0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \tag{2}$$

may be interesting to analyze TIT. Variances of wind components ($\sigma^2{}_u$, $\sigma^2{}_v$ and $\sigma^2{}_w$) are directly related to the three wind component perturbations:

$$\begin{aligned} \sigma_u^2 &= \overline{u'^2} \\ \sigma_v^2 &= \overline{v'^2} \\ \sigma_w^2 &= \overline{w'^2} \end{aligned} \tag{3}$$

Where *u*, *v* and *w* are the perpendicular, longitudinal and vertical directions relative to the highway. The TIT measuring campaign presented in this work was supported by the first Spanish project on future highway design, OASIS (www.cenitoasis.com).

2.1. Experimental setup: M-12

Highway M-12 near Madrid airport was the location to carry out the experiment from 2 to 4th August 2011. This highway has two lanes running from North (0º) to South (180º) and is limited by guardrails (Fig. 1). A toll booth with twelve lanes is located on the east side of the experimental setup and flat land is found to the west. The surroundings are quite flat with small embankments. The location was chosen because it has low traffic density and a long straight section, which facilitates the different experimental procedures. The Spanish Meteorological Agency (AEMET) has a measuring station situated approximately at 2.4km from the experimental site. In this station (Barajas Airport), the climatological (1971-2000) wind direction in August is from NE with a 3m s^{-1} mean wind velocity.

The M-12 experiment was divided into three different tests. In all tests, four Gill ultrasonic anemometers (Wind Master model) with a maximum sample frequency of 20Hz and a resolution of 0.01m s^{-1} were used. Three of them were installed on the guardrails maintaining a distance among them of 4m and their heights *h* and distances *d* (Fig. 1) were set depending on the test being done. The fourth anemometer was located at a height of 6.7m in order to measure ambient wind (Fig. 1), this height is beyond the influence of traffic according to Eskridge and Thompson (1982).

Test-1 studies how the wake-passing effect behaves at different heights. Anemometers *1*, *2* and *3* were installed at heights *h* (Fig. 1) of $0.25H_{vehicle}$, $0.75H_{vehicle}$ and $1.25H_{vehicle}$ ($H_{vehicle}$ is the vehicle height), respectively (Table 1). The vehicle heights for car and lorry are respectively 1.4m and 3.2m. The minimum horizontal distance between the vehicle trajectory and anemometer *d* (Fig. 1) was approximately 1m. For this test, a car and a lorry (Fig. 2a and Fig. 2c) were used; both vehicles performed 3 runs at 90km/h.

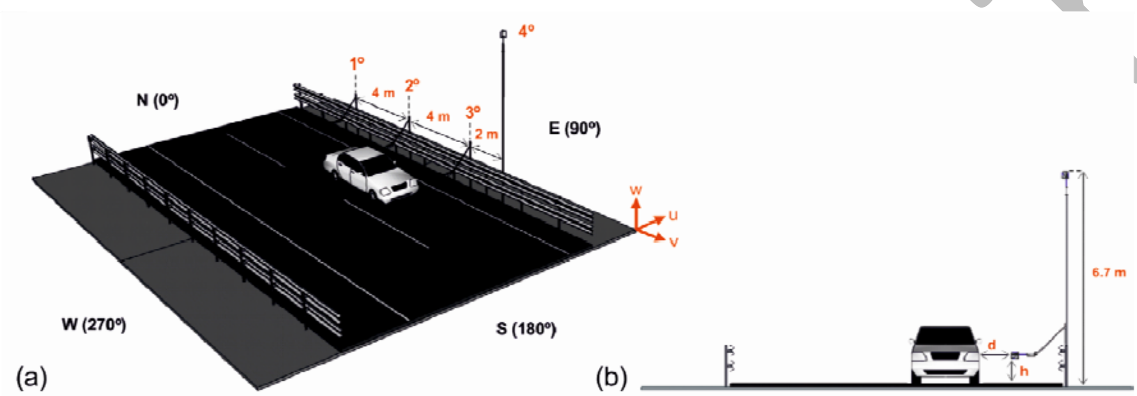

Fig. 1. Sketch of the experiment with the position of four ultrasonic anemometers on the highway M-12. (a) Perspective view and (b) frontal view.

Fig. 2. Vehicle classes used in the experiment: (a) Car, (b) Van and (c) Lorry.

Test-2 was designed to show how vehicle speed and vehicle type relate with turbulence parameters. Anemometers *1*, *2* and *3* were installed at a level of 0.7m and the distance was the same as for Test-1 for all anemometers (Table 1). A van with a $H_{vehicle}$ of 2.6m (Fig. 2b) a car and a lorry, were included in the experiment, to establish the influence of an intermediate size. All vehicles performed 3 runs each, at speeds of 90km/h, 80km/h, 70km/h and 60km/h.

Test-3 aimed to analyze how TIT ranges with the distance, *d* (Fig. 1). Anemometers *1*, *2* and *3* were placed at a height of 0.7m while the separation distances were 1m, 2.2m and 3.4m respectively (Table 1). The lorry was chosen to perform 3 runs at 90km/h, because it had caused the strongest turbulence in the previous tests.

Table 1
Position of anemometers on highway M-12 during each test.

Test	$d_1^a(m)$	$d_2^a(m)$	$d_3^a(m)$	$h_1^b(m)$	$h_2^b(m)$	$h_3^b(m)$
1	1	1	1	$0.25H_{vehicle}$	$0.75H_{vehicle}$	$1.25H_{vehicle}$
2	1	1	1	0.7	0.7	0.7
3	3.4	2.2	1	0.7	0.7	0.7

[a]Minimum horizontal distance between the anemometers and the trajectory of vehicles (Fig. 1).
[b]Height over ground (Fig. 1).

The anemometers were sampled at 20Hz during a period of 120sec. The maximum fluctuating components ($u'_{max}, v'_{max}, w'_{max}$), *TKE* and turbulent momentum fluxes were obtained in the time range from when the vehicle passed anemometer *1* (Fig. 1) until the vehicle covered 230m. Some parameters were normalized with the average of the perpendicular component, *U* from anemometer *4* (Fig. 1). A correlation analysis between study parameters was carried out for all tests with SPSS (statistical software). The Pearson correlation was obtained to reflect the degree to which the variables are related. This parameter ranges from +1 to -1. A correlation value equal to +1 means that there is a perfect positive linear relationship between variables. Sometimes vehicles not involved in the test coincided with the test vehicles and these runs were rejected. Other runs were not analyzed because of signal errors.

3. Results and discussion

Unlike other studies, such as Kalthoff et al. (2005) and Chock (1980), the present research is oriented to analyzing TIT near traffic.
As was indicated (***Experimental setup: M-12***), three tests were run within the experiment. Now the results of these different tests will be analyzed.

3.1. Test-1: Height dependence

This test attempts to illustrate how the wake-passing effect changes at different heights. Therefore, the relationship between turbulence parameters and height will be studied.
TKE values significantly correlated well with the height parameter, *h* (Fig. 1) in the car and lorry cases, where the Pearson correlation coefficients were -0.84 and -0.94 respectively (Fig. 3). The turbulence is stronger near the road surface, which may be due to ground roughness and the guardrail's effect. The larger size of the lorry induces a higher momentum interchange between it and the surrounding air and the *TKE* values obtained during lorry runs were about 10 times higher than in car runs. The slope for the

lorry fit is larger than that corresponding to the car, indicating the stronger vertical gradient in the *TKE* for the lorry case. Two simple linear models describe the relationship between the *TKE* parameter and height, *h* for both kinds of vehicles. The coefficient of determination R^2 for the lorry model is 0.89 and in the case of the car is 0.70 (Fig. 3). The linear fits obtained for the lorry and the car are

$$TKE / U^2 = 5.66 - 4.30 h / H_{lorry} \quad (4)$$

and

$$TKE / U^2 = 0.77 - 0.58 h / H_{car} \quad (5)$$

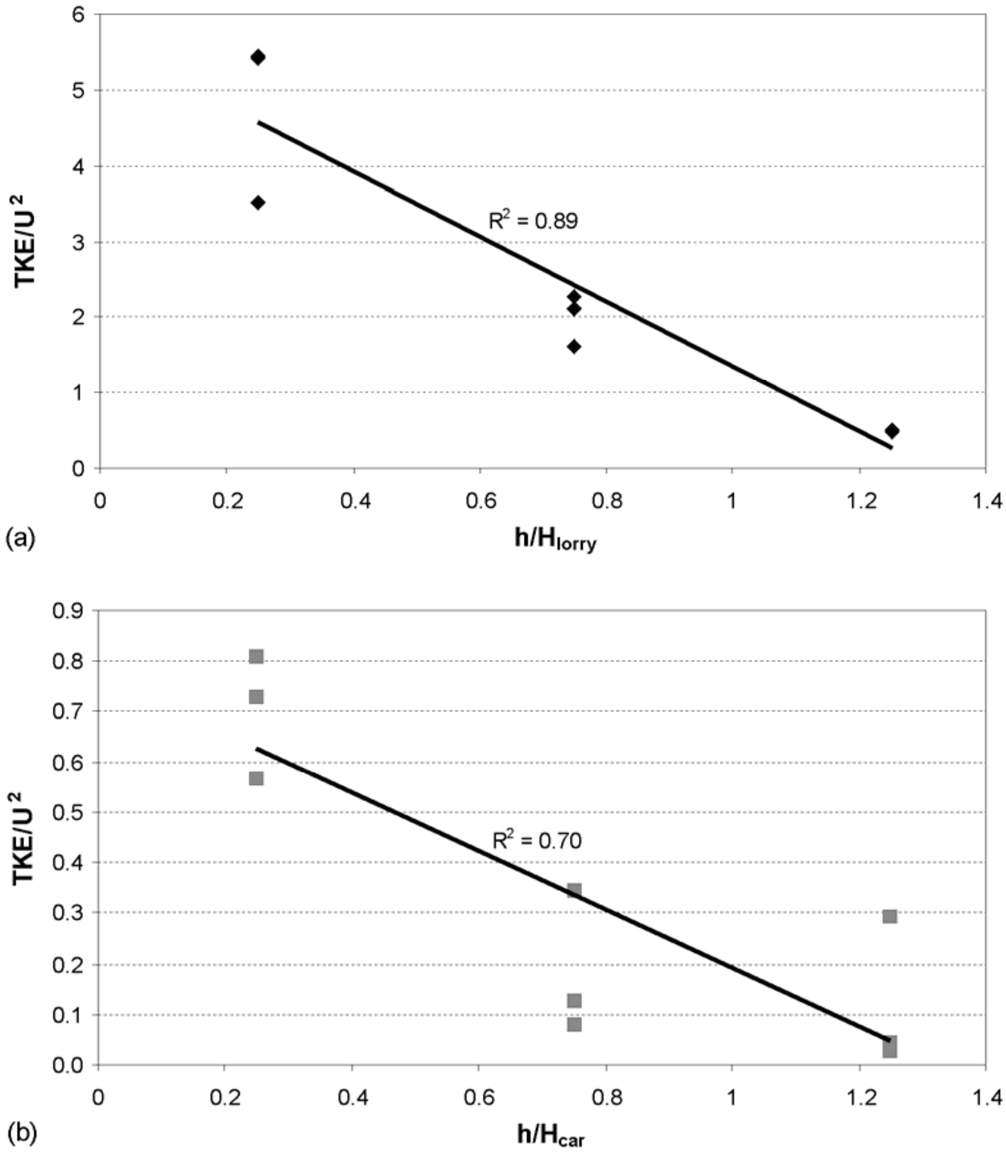

Fig. 3. Normalized *TKE* values depending on the height ratios (Table 1) of both the lorry (a) and the car (b).

Fig. 4 shows how the longitudinal component (*v*) undergoes the maximum fluctuation compared to the other components (*u*, *w*). This is caused by the wake-passing effect.

Thus turbulence originated from vehicles exhibits a strong anisotropy. In the lorry case both the longitudinal and perpendicular components significantly correlate with the height ratio, while in the car case only with the longitudinal component (Fig. 4). In addition the vertical fluctuating component is independent of the height for both vehicles. Moreover, Eskridge and Rao (1983) also found that the fluctuating component with highest values was longitudinal. Therefore, the highest proportion of *TKE* is caused by the turbulent flow induced in the vehicle path. The coefficient of determination, R^2 is not shown in some graphics (Fig. 4) because the correlation between those variables is not significant.

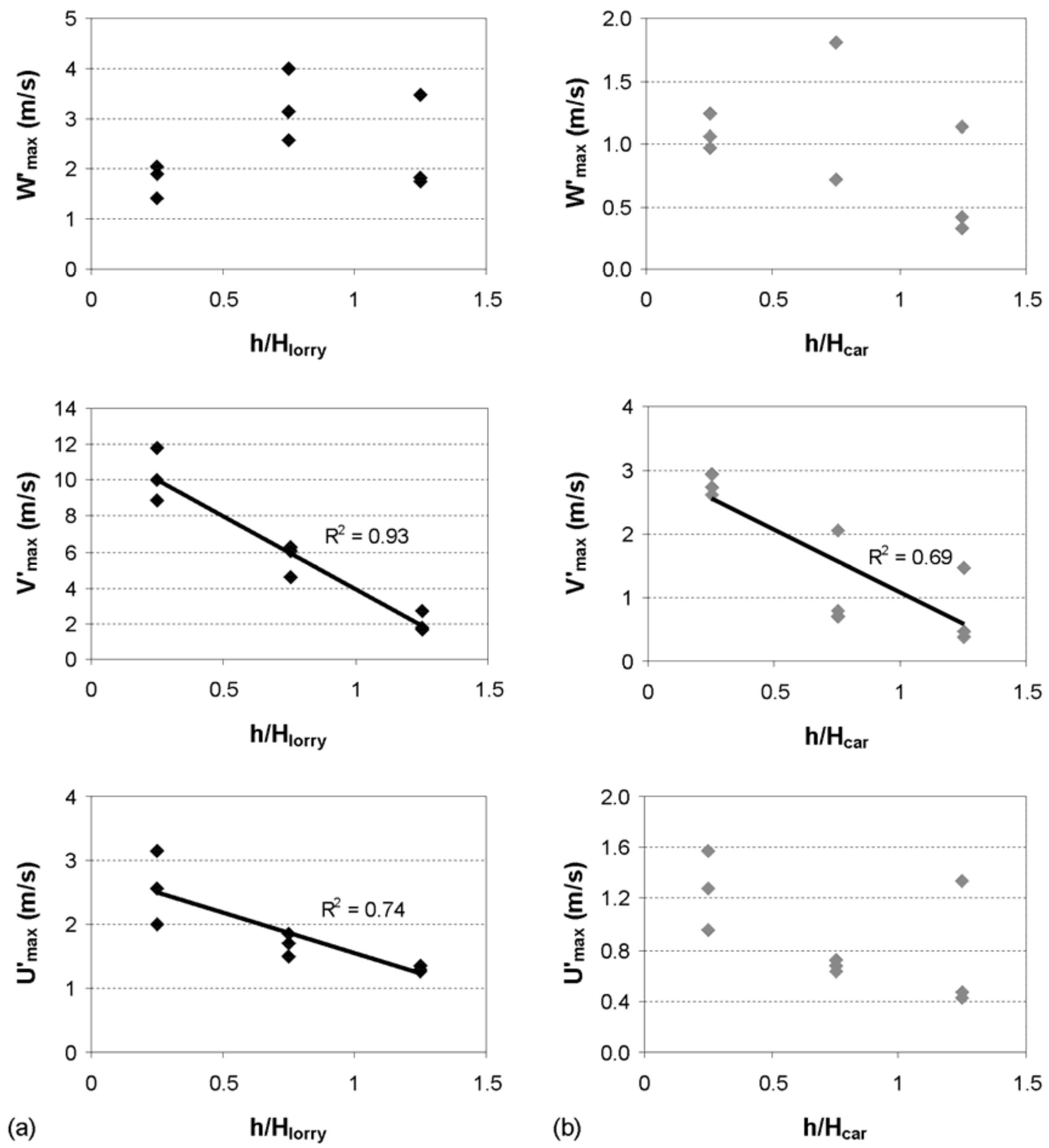

Fig. 4. Relationship between maximum fluctuation of components and height ratio for both the lorry (a) and the car cases (b).

3.2. Test-2: Speed and volume dependence

The total drag on a vehicle essentially consists of the friction and pressure drags (Geropp and Odenthal, 2000) and it increases with vehicle speed. Therefore, the momentum transfer from vehicle to air through friction and pressure drags must also increase with speed and vehicle size. This test includes an intermediate vehicle size in relation to ***Test-1: Height dependence***, a van. Values of wake-passing effect are obtained from 3 anemometers located at a height of 0.7m. Both the lorry and the van show a significant Pearson correlation between *TKE* and vehicle speed, whose values are 0.86 (lorry) and 0.74 (van). The linear models obtained from the fits to the data (Fig. 5) for the lorry and van, are

$$TKE = -11.60 + 0.27V \tag{6}$$

and

$$TKE = -3.19 + 0.06V \tag{7}$$

where V is vehicle speed and the coefficients of determination R^2 are 0.75 and 0.55 respectively. The *TKE* values obtained for the lorry are much larger than those reached with the van and car, the increase produced as the vehicle increases its speed also being greater, so the turbulence produced by the lorry becomes much more influential than the other two vehicles as the speed increases. Even, for the car case *TKE* values do not exhibit distinct functional relationship with vehicle speed. The differences of TKE values between lorry and the other vehicles will diminish if the lorry has a better aerodynamics with lower drag coefficient. Since the streamlines could keep better close to lorry's surface.

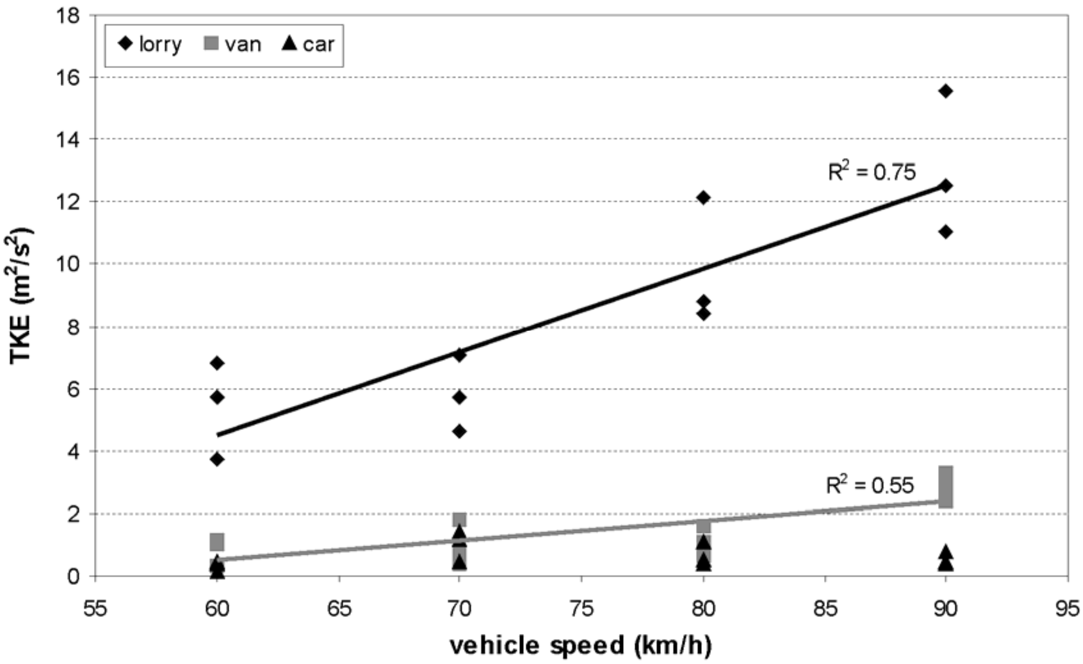

Fig. 5. *TKE* depending on the vehicle speed for different kinds of vehicles.

Turbulent momentum fluxes involve covariance between velocity fluctuations in different directions (Arya, 2001). The matrix is shaped by the nine momentum fluxes in relation to combinations among components. In order to analyze the covariance between the three components of the flow, only off-diagonal components: $\overline{w'u'}$, $\overline{w'v'}$ and $\overline{v'u'}$, have been calculated. These components contribute to the transport of mean momentum while diagonal components are related to *TKE*, as was described in eq. (2) (Tennekes and Lumley, 1972).

The longitudinal fluxes of vertical and perpendicular momentum ($\overline{w'v'}, \overline{u'v'}$) have the highest values and better correlation both for the lorry and van (Fig. 6). Again, this is because of the higher fluctuations in the longitudinal component (*v'*).

As, in a non-perturbed ABL (Atmospheric Boundary Layer), vertical transfer of momentum (*v'w'*, *u'w'*) is usually much larger than horizontal fluxes (*u'v'*), especially in homogeneous terrain (Stull, 1988; Arya, 2001; Wyngaard, 2010), the results obtained are clearly influenced by TIT. All momentum fluxes smoothly increase with vehicle speed, but all coefficients of determination R^2 are quite low. Results from the car case are not shown because no correlation is found (R^2 <0.009). The vertical fluxes of longitudinal momentum, $\overline{v'w'}$ exhibit the highest differences between the lorry and van.

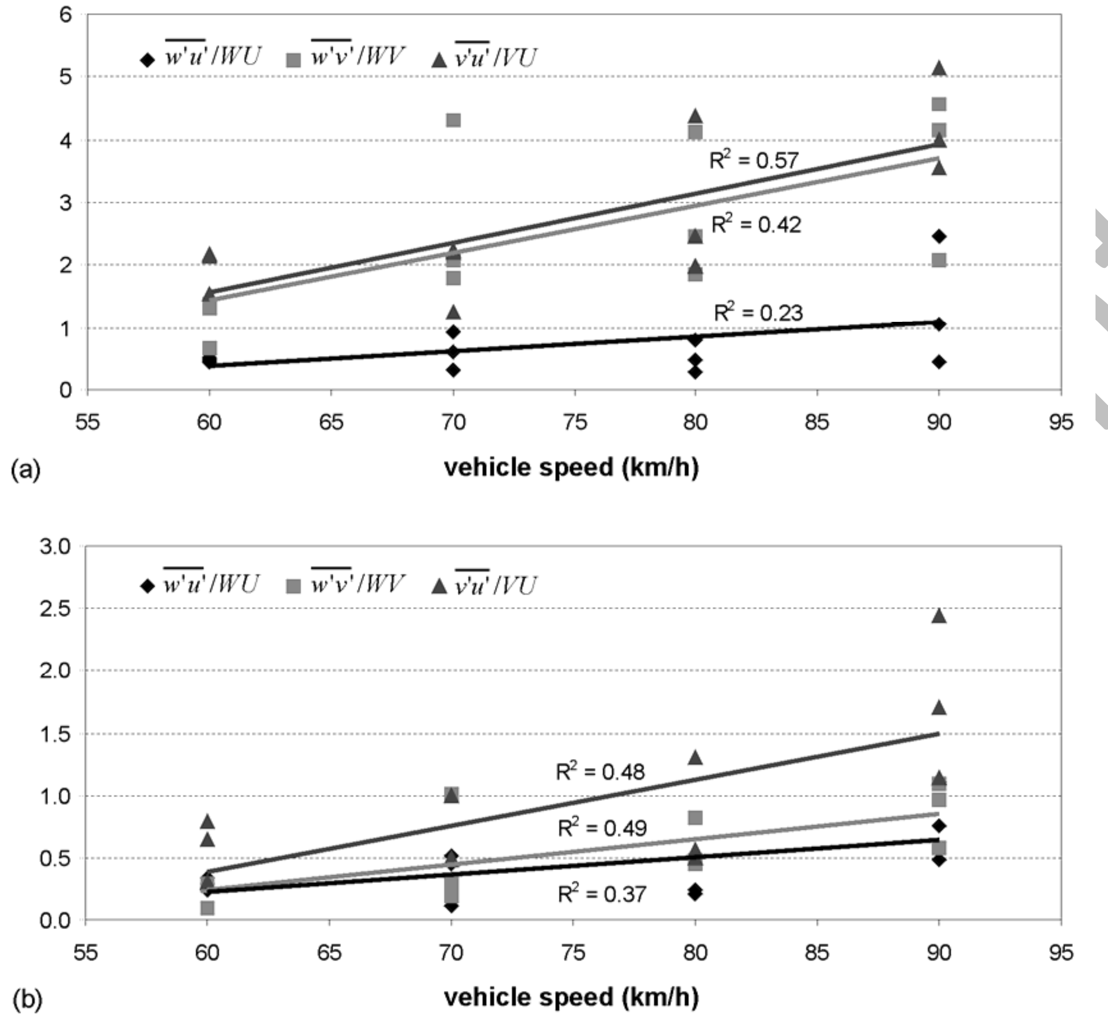

Fig. 6. Variation of normalized turbulent momentum fluxes with vehicle speed for the lorry (a) and van case (b).

The normalized turbulent fluxes that show highest Pearson correlations with vehicle speed are $\overline{w'v'}/WV$ for the van and $\overline{v'u'}/VU$ for the lorry (Table 2).

Table 2
Pearson correlation between normalized turbulent momentum fluxes and vehicle speed.

	Pearson Correlation		
	$\overline{w'u'}/WU$	$\overline{w'v'}/WV$	$\overline{v'u'}/VU$
Vehicle speed (Lorry)	0.48	0.65[a]	0.76[a]
Vehicle speed (Van)	0.61[a]	0.70[a]	0.69[a]

[a]The correlation is significant with 95% probability.

3.3. Test-3: Distance dependence

The lorry was chosen for this test because it helps to better distinguish the vehicle turbulence from ambient turbulence; moreover, it produces much more turbulence. This test attempts to demonstrate how the wake from a moving vehicle dissipates over distance, *d* (Fig. 7). *TKE* values that were obtained at closer points to the vehicle trajectory are higher than at farther points, as would be expected (Fig. 7). The dissipation rate of *TKE* values with distance is -3.4m^{-1} s^{-2}. On the other hand, the average of the perpendicular component, *U* from anemometer *4* was used to obtain the turbulence intensities components. The longitudinal turbulence intensity (σ_v/U) contributes a higher proportion to *TKE* values (Fig. 8). In addition this component shows the highest coefficient of determination R^2, 0.78. Although all turbulence intensities are correlated significantly with distance from the vehicle trajectory, the longitudinal component decreases faster than the other components (Fig. 8). The values of perpendicular and vertical turbulence intensity (σ_u/U and σ_w/U) are quite similar.

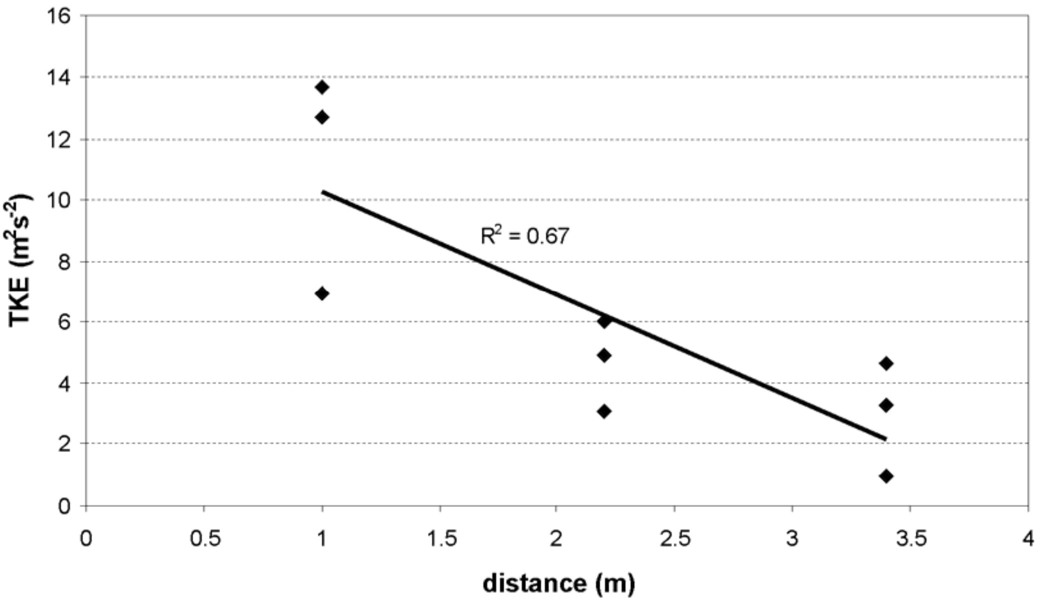

Fig. 7. Relationship between normalised *TKE* values and the distance, *d* (Fig. 1) for the lorry case.

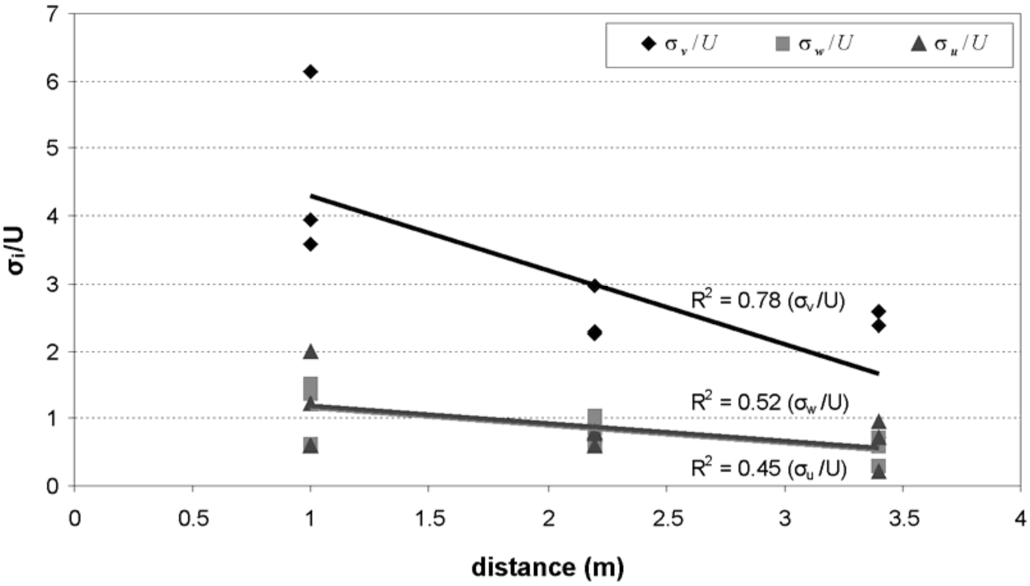

Fig. 8. Turbulence intensity components depending on the distance, *d* (Fig. 1) for the lorry case.

4. Summary and Conclusions

Results from a field campaign to study traffic-induced turbulence (TIT) are presented in this work. The field campaign was carried out in August 2011, with the aim of studying the relationship between TIT and different parameters. First, the influence of parameters related to vehicles, such as speed and size were analyzed. Second, the spatial variation of the TIT along the perpendicular and vertical direction to vehicle trajectory is determined. The wake-passing effect produced by the vehicles causes the longitudinal direction to contribute the highest proportion to the *TKE* values for the three tests performed. Both the turbulent momentum fluxes and the *TKE* values correlated well with the vehicle speed for the lorry and the van, but not for the car, where the turbulence produced is much lower. As would be expected, the *TKE* values and the coefficient of determination R^2, found for the different fits, are higher for the lorry than for the van and the car. The turbulent momentum fluxes, which depend on fluctuations in the longitudinal component, are higher compared to the other directions. The Pearson correlation coefficients between the values of *TKE* and the height parameter for the car and the lorry are -0.84 and -0.94 respectively, indicating that the turbulence level increased as the distance to the road decreases. The intensity of turbulence from the vehicles decreases significantly with the distance perpendicular to the vehicle trajectory. Moreover, the dissipation energy rate in the longitudinal component is higher than the other components.

This analysis shows clearly that TIT can be an important source of turbulence, in addition to the natural turbulence produced in the surface layer, and it should be considered in air quality models simulating pollutant concentrations. The study also confirmed that TIT could be modelled taking into account some parameters relative to the vehicles.

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and vehicle speed.