

On-road Turbulence: Part 2

Scott Wordley

Monash University, Melbourne, Australia

Jeff Saunders

Vehicle Aero-acoustic Laboratories (VAL), Melbourne, Australia

Copyright © 2009 SAE International

ABSTRACT

This work presents a second series of turbulence measurements made in a range of different on-road terrains and traffic conditions. Wind measurements were captured using a rake of four separate multi-hole pressure probes mounted to the front of a test vehicle traveling at a road speed of 100 km/h. Analysis of the data shows how the turbulence intensities and length scales are modified by terrain type, road side obstacles and the upstream wakes of other moving vehicles. A vertical 'profile' of turbulence near the ground is generated and spatial correlations between probes are examined. These on-road results are then compared to the turbulence levels generated by the Monash University wind tunnel. A new method and a series of targets are then proposed for improving the modeling of turbulence in automotive wind tunnels.

INTRODUCTION

Traditionally, the aerodynamic testing of automobiles has been conducted in extremely low turbulence wind tunnels (< 1% turbulence intensity). This is contrary to the small amount of wind data that currently exists for heights and conditions relevant to road cars, which suggests that higher levels of turbulence are routinely experienced on-road.

Correctly modeling turbulence in automotive wind tunnels is difficult for a number of reasons.

1. The on-road turbulent environment is not well understood, which means that it has not been

possible to set realistic and accurate targets for turbulence levels.

2. It is difficult to produce both the correct ratios of turbulent components, and turbulence spectra in full scale automotive wind tunnels using simple passive turbulence generation systems (such as grids). Active turbulence generation systems can be used to improve the low frequency spectrum content, but are expensive and may not be an option in some tunnels due to design and space limitations.
3. The addition of turbulence will likely increase the variability in back-to-back tests and also the variability in results between different wind tunnels. It has taken several decades just to bring open-jet and closed-jet wind tunnel results into line, and few researchers are keen to complicate matters anew by introducing another potential variable.
4. This combination of difficulties in simulating turbulence makes it hard to produce research which quantifies its effects. Without such research it is not possible to make a case for the need to simulate it, which is somewhat of a 'Catch-22' situation. In spite of this, new research into the effect of turbulence on cars is slowly emerging.

This work attempts to address the first of these difficulties by presenting an extensive body of wind measurements captured on-road in various terrains and wind conditions. These results document the level of

turbulence intensity, length scale and spatial correlation that is commonly experienced on-road.

This paper also addresses the second issue by proposing a new methodology for the simulation of turbulence in automotive tunnels. Measurements made in the Monash University Full Scale Wind Tunnel are used as a case study which demonstrates how the introduction of relatively low intensity, small length scale turbulence can be used to represent the light wind and traffic conditions commonly found on-road. Further research will then be required to determine if reproducing this proposed target spectra is sufficient to capture the major turbulence effects.

THE EXISTING BODY OF KNOWLEDGE

There are several published reviews of the turbulent wind environment as it relates to road vehicles. The current authors have previously presented a suggested framework for the experimental measurement of turbulence on-road [1]. This paper also describes, in detail, the different ways in which turbulence can be measured statistically (turbulence intensity, power spectra, time and length scales etc).

More recent companion review papers by Cooper and Watkins [2, 3] provide a very thorough analysis of existing wind engineering data and the ways in which it can be applied to road vehicles. The second of these companion papers focuses upon how turbulence might affect the vehicle development process by changing the drag, lift, crosswind, cooling and acoustic performance of a given vehicle. More recently, Newnham et. al. [4] have shown how turbulence affects the flow around a leading edge radii; Lawson et. al. [5] have examined the effects of on-road turbulence on the A-pillar region, and Bischof [6] has measured a vehicle's response to longitudinal wind gusts.

The proceeding paper, by the current authors, titled "On-road Turbulence" [7, 8] contains reviews of the turbulent wind environment, predictive turbulence models, and early findings on the effects of turbulence on automobiles. In addition, it presents a series of wind measurements captured on-road, using 2 multi-hole pressure probes, at a measurement height of 500 mm above the ground. The major findings of this initial research were:

- Terrain type and traffic conditions modify both the turbulence intensity and length scale. Different terrains can be represented as 'regions' on a chart of length scale versus component turbulence intensity. (Fig. 1)
- The ratio of the three different turbulence intensities (known as the anisotropic ratio) was relatively constant across all the data (Fig. 2). This ratio was:

$$I_u : I_v : I_w$$

$$1.00 : 1.01 : 0.61 \quad \dots(\text{Eqn 1})$$

These results compare well with recent on-road turbulence measurements made by Lindener et al [9] as a part of an aero acoustic road-to-tunnel correlation study. They examined only the longitudinal wind component and recorded turbulence intensities of up to 10% and maximum length scales of 10m.

This paper seeks to refine and expand upon these prior findings by using a total of 4 probes, which can be arrayed both vertically and horizontally. Analysis of this data will be extended beyond turbulence intensity and scale to also examine spatial correlations.

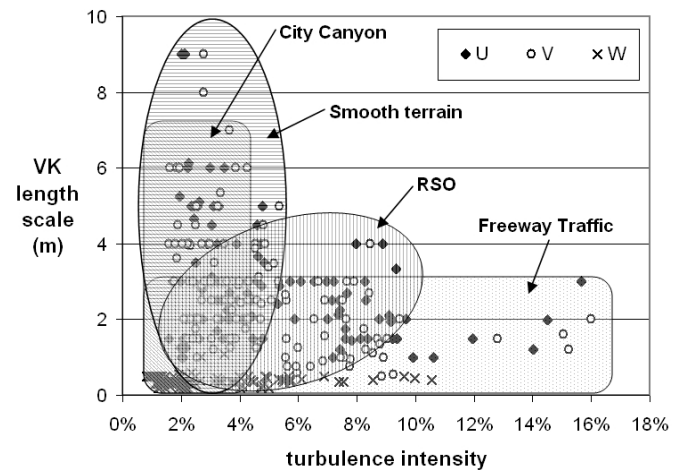


Fig. 1: Von Karman spectrum derived turbulent length scales versus turbulence intensity, 0.5m measurement height, 100 km/h road speed, all on-road data. [from 7,8]

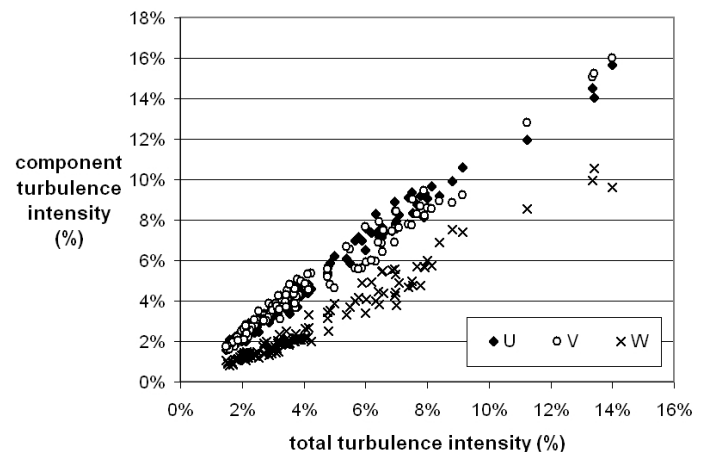


Fig. 2: Component turbulence intensities versus total turbulence intensities, 0.5m measurement height, 100 km/h road speed, all on-road data. [from 7,8]

EXPERIMENTAL METHOD

WIND SPEED DEVICE SELECTION - Four-hole dynamic pressure probes, also known as "cobra"

probes, were used to measure the wind environment. These probes are able to record the mean and fluctuating wind velocity vector as a function of both yaw and pitch angles within a $\pm 45^\circ$ cone of acceptance, at frequencies of up to 5000 Hz. The general operating principles of this instrument are described in [9].

PROBE LOCATION AND MOUNTING - The four probes were mounted to the front end of a large sedan vehicle.

In tests which used a horizontal array of probes, all probes were mounted at the height above the ground of 500 mm, and 1000 mm ahead of the car's front bumper. One probe was placed on the vehicle's centerline. Two probes were located 500 mm either side of the centerline, and the fourth probe was located 250 mm to the left of the car's centerline (Fig. 3). This spacing was chosen to allow analysis of the level of correlation between probes over a range of horizontal distances (250 mm, 500 mm and 1000 mm).

For the tests which used a vertical array of probes, the four probes were mounted on the vehicle's centerline, at heights above the ground of 250 mm, 500 mm, 750 mm and 1000 mm respectively (Fig. 4). This vertical spacing was chosen to provide a profile of turbulence in the range of interest for automobiles and also to allow the study of vertical correlations between these heights. All probes were located 1000 mm ahead of the test vehicle's front bumper.

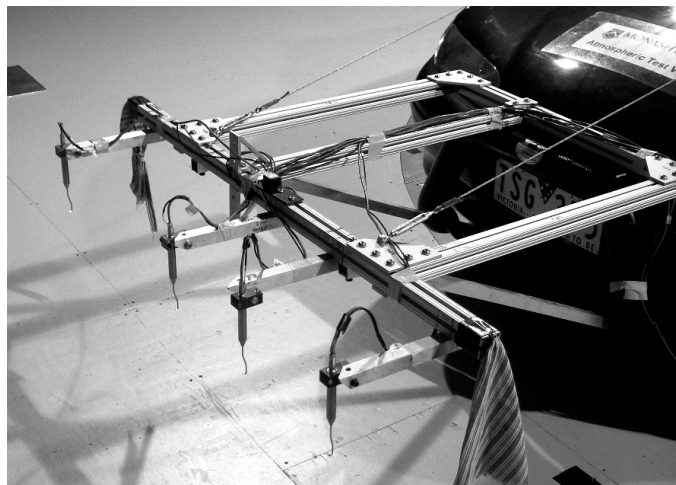


Fig. 3: Horizontal array of four cobra probes

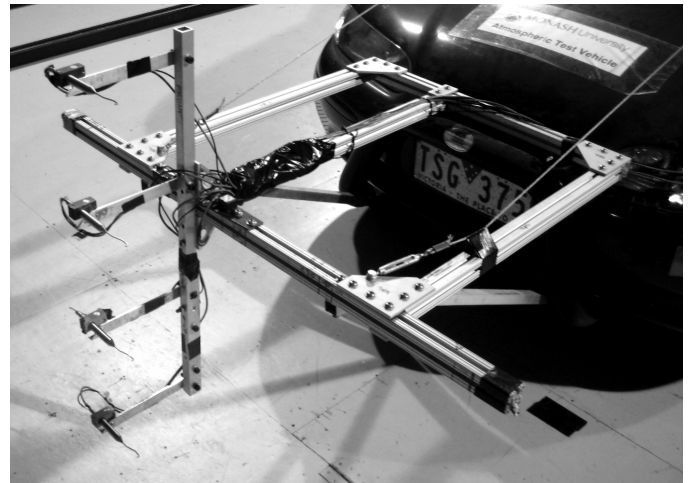


Fig. 4: Vertical array of four cobra probes

VEHICLE INTERFERENCE EFFECTS - Previous on-road tests have shown that corrections for vehicle interference effects were not required for this vehicle at probe-to-vehicle spacings of greater than 1000 mm. Analysis of the average raw wind speed of several back-to-back runs in opposite directions along the same stretch of road in the same wind conditions came within the error margins of the road speed of the car, which indicated that the car interference effect at this probe spacing was insignificant.

Wind tunnel tests at Monash University (See appendix) were also used to estimate the effect of yaw angle on the measurements made by the probes in these locations, for the range of combined vehicle-wind speeds expected on-road. For vehicle yaw angles of less than 8 degrees, it was found that a maximum u correction of less than 1% was required, and so no corrections were made to account for yaw. Subsequent checks of the on-road test showed that all data fell within this yaw angle range.

CORRECTION FOR PROBE MOTION - To measure and correct for any motion seen at the probes, a tri-axis accelerometer (Crossbow CXL10LP3) was attached to the forward most point of the common probe mount structure. This accelerometer was sampled simultaneously with the cobra probes. Previous tests [7,8] have shown that it was necessary to correct for the pitching motion of the vehicle, which contributed to the vertical wind component measured by the probes. This was done by integrating the measured accelerations to give velocity time histories which were then subtracted from the recorded wind data.

ANCILLARY MEASUREMENT DEVICES - A number of ancillary measurement devices were used in addition to the cobra probes during on-road testing.

A GPS-speed measurement system (Garmin eTrex Vista 370) was used to ensure correct and constant vehicle speed during data taking runs. This device was used to accurately set the cruise control to a speed of

100.0 km/h. In most cases the cruise control was able to hold speed within ± 0.2 km/h which was considered acceptable. A digital barometer was used to measure the ambient barometric pressure which was a required input for the pressure probe software. Ambient temperature was measured using a calibrated digital temperature gauge. Stationary wind measurements at each test location were made at a height of 500 mm, using a low-speed, hand held anemometer (Schiltknecht C-51451) which was wind tunnel calibrated.

A desk top computer running off a 240 volt AC inverter and battery pack was used in-car to run the TFI© software which logged both the cobra probe and accelerometer data. The tri-axis accelerometer was powered using a dedicated power supply to eliminate electrical noise from the inverter and the car's alternator.

TEST PROCEDURE - Once at the testing location, the probes were mounted to the car and the ambient weather conditions measured (temperature, barometric pressure, stationary anemometer wind speed and direction). The probe heads were then shrouded and the wind speed zeroed via the TFI© software.

The vehicle was accelerated to the test speed of 100.0 km/h and the cruise control engaged. Approximately 5 seconds was allowed for the vehicle speed to stabilize. Recording then commenced, and depending on the particular road and wind direction, between 20 and 40 seconds of data was collected at a sampling frequency of 1250 Hz. This sampling rate corresponded to 1 sample every 0.03 m at the highest expected combined vehicle-wind speed of 140 km/h (38.9 m/s). This rate was deemed the minimum necessary to resolve down close to the spatial limit imposed by the size of the probe head (0.004 m). For consistency this sampling frequency was used for all tests.

Tests were conducted in both road going directions for each site, and each direction was tested a minimum of 5 times to provide enough data to identify extraneous results and allow for variations which might not be noticed until the data analysis stage. Ambient weather conditions were rechecked at each site half way through the series of tests and also at their conclusion.

TEST LOCATIONS AND CONDITIONS - A large number of test sites were scouted and trialed for the first series of on-road turbulence measurements [7,8]. These sites were selected with the aim of spanning the range of terrain and traffic conditions that automobiles most commonly traverse. These sites were grouped into four separate categories: smooth terrains; roadside obstacle terrains; city canyon terrains; and freeway traffic terrains.

For consistency and comparability between the two data sets, the same sites were revisited (where possible) for this testing. Unfortunately due to change of speed limit (from 100 km/h to 80 km/h) it was not possible to retest

the city canyon terrain featured in the initial testing. A detailed description of all the tests sites can be found in the initial paper, and some examples are reproduced in Fig. 5a-5c.



Fig. 5a, 5b, 5c: (Top to bottom) Example test terrains; a: smooth terrain, b: road side obstacle terrain, c: freeway traffic terrain / conditions. [from 7,8]

The smooth terrain and roadside obstacle terrain sites were tested with no other traffic on the road. The roadside obstacle terrain site was only tested when the wind was blowing through these obstacles at an angle of at least 45 degrees to the road. The freeway traffic tests were conducted with a range of different vehicles upstream at different separation distances. The data captured included:

- A single upstream car at two separation distances, approximately 20m and 40m.
- A single SUV, at distances of approximately 20m and 40m.
- A tanker truck, at distances of approximately 20m and 40m.
- In the midst of a convoy of vehicles, with a lead vehicle 20m directly ahead and vehicles approximately 10m ahead on both sides.

DATA PROCESSING

The raw accelerometer and cobra probe data was read into Matlab© for processing (see Fig. 6 below). The vertical component of the accelerometer data was integrated to give velocity and subsequently

vertical (w) component of wind speed measured by all four probes. All data was then de-trended using a two piece linear interpolation to correct for any small movement of the mean over the course of the run.

The level of stationarity of the data was then checked using two methods. Firstly, the time histories of each component were visually inspected to check for obvious transient events and unacceptably large movements of the mean over the course of the run. Datasets which passed this check were divided into four equal lengths and the turbulence intensities were calculated for each of the four subsets. If the coefficient of variation (standard deviation divided by mean) of these results was less than 10% the data was considered adequately stationary. Data sets which failed this test or the initial visual inspection were discarded.

The mean wind speeds for each component were then calculated, saved, and removed from the time series.

In the preceding paper, two different methods were trialed for the calculation of turbulent length scale. These methods are described and discussed below.

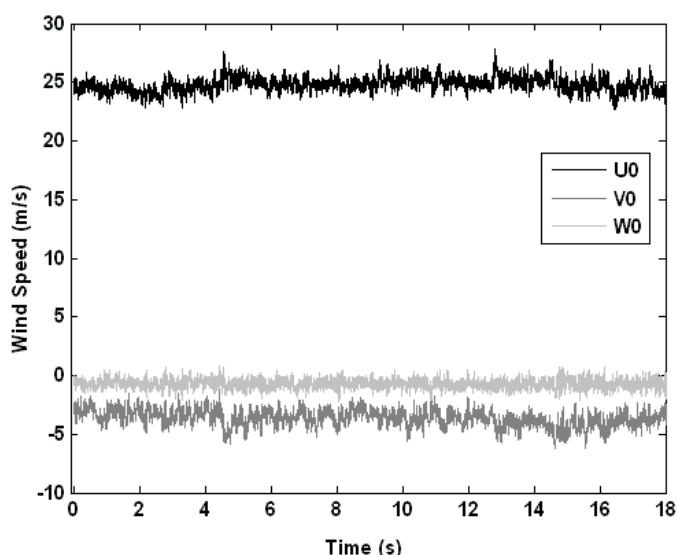


Fig. 6: Example raw wind speed data versus time for a single cobra probe.

AUTOCORRELATION METHOD - Autocorrelation functions were determined for each component and turbulent length scales calculated based on the integral of the area under the autocorrelation graphs up to the point where they first cross the time axis (see Fig. 7 below).

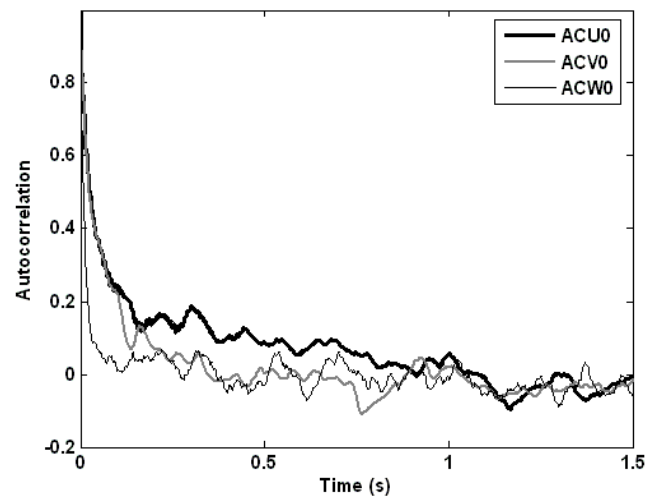


Fig. 7: Example autocorrelation functions versus time.

VON KARMAN SPECTRAL FITTING METHOD - Non-dimensional power spectra were calculated using a frequency resolution of 4096. The resulting graphs of spectral density (vertical axis) were normalised by multiplying by frequency and dividing by variance. The frequency axis (horizontal) was normalized by dividing by the mean u velocity. The Von Karman (VK) spectrum [11] was then fitted to each power spectrum to give an estimation of the Von Karman turbulent length scale (VK LS), as shown in Fig. 8.

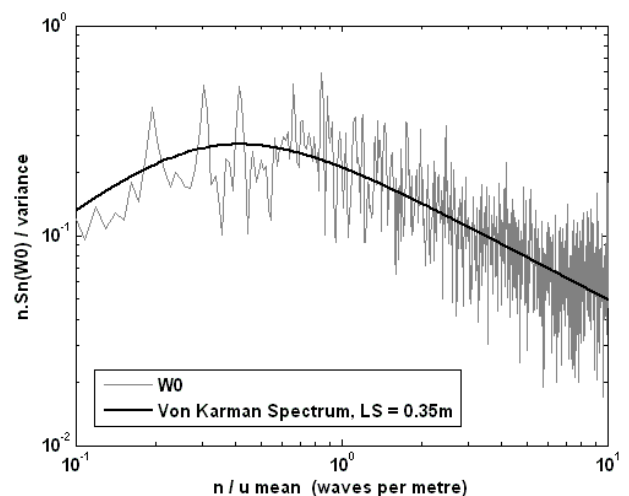


Fig. 8: Example non-dimensional power spectrum and Von Karman spectra fit.

In the preceding work, it was found that the autocorrelation method predicted length scales which were an average of twice the magnitude of the Von Karman spectral fitting method. This difference was attributed to the fact that the Von Karman spectra were manually fitted, primarily to the inertial sub-range (high frequencies) where the majority of data points exist, whereas the autocorrelation method returns the frequency (and hence length scale) at which the peak energy occurs. For the series of tests reported in this paper an automated Von Karman spectral fitting method

has been used exclusively. Details of this automated method are provided in [4, 12]. Comparisons with spectral fits made manually in previous work showed less than a 4% variation on average, which was considered acceptable.

The use of four probes for this series of tests allowed calculation of correlation coefficients between different probes. It is important to understand the rate at which the self-correlation of each orthogonal component decays with increasing separation distance so that attempts can be made to model it in wind tunnel simulations.

Correlation coefficients were calculated using the *corrcoef.m* function in MatLab® between similar wind speed components (i.e. *uu*, *vv* or *ww*) sampled from the reference probe and each of the other three probes. For the case of the horizontal array, the far left probe, located 500 mm left of the car's centerline, was taken as the reference (Fig. 9). For the vertical probe array, the lowest probe, located at a height on 250 mm above the ground, was taken as the reference (Fig. 10). Due to the high vehicle speed (100 km/h) and therefore, the low wind yaw angles measured by the probes, the correction for the time lag between the different probes was of the order of a single sample length, and therefore neglected.

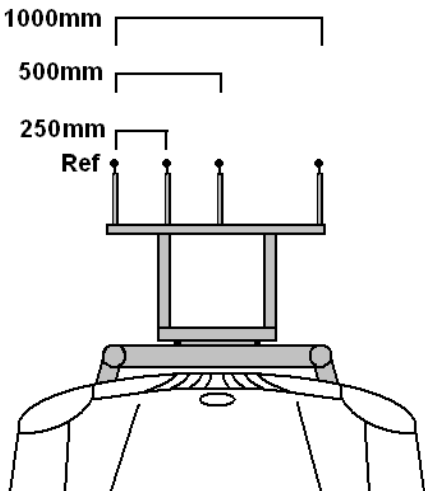


Fig. 9: Top view, correlation distances for horizontal probe array. The left most probe is used as the reference signal.

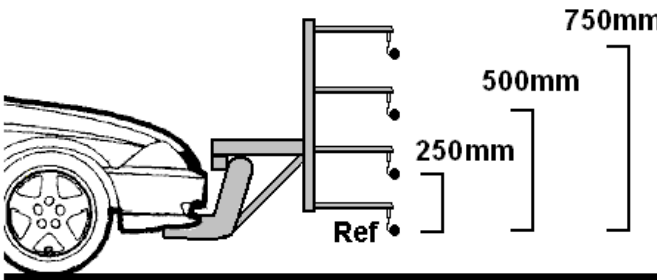


Fig. 10: Side view, correlation distances for vertical probe array. Lowest probe at 250 mm height is used as the reference signal.

RESULTS

TURBULENCE INTENSITY AND LENGTH SCALE

Vertical Rake Results - A vertical rake of four cobra probes, located on the vehicle's centerline at heights of 250mm, 500mm, 750mm and 1000mm was used to measure the vertical profile of turbulence. These tests were conducted in a range wind conditions on roads classified as either smooth or RSO terrains. Highway traffic tests were not included in this series of vertical rake tests because measurements made in the wakes of other vehicles show large variations in vertical profile due to differences in wake type (up-lifting or down-lifting), its size, the separation distance between the two vehicles, and the prevailing wind conditions.

Figures 11 – 14 plot component turbulence intensities versus total turbulence intensity for each of the vertical rake measurement heights. Due to the high degree of correlation ($R^2 > 0.91$) linear regression lines are drawn and these relationships are reported for each component below the graph's legend.

If these three linear regression coefficients are all normalized by the longitudinal (*u*) component, the resulting three part ratio is the average anisotropic ratio of the component turbulence intensity.

The relative variance of each dataset is measured by calculating the standard deviation of the data points *about* their regression lines. The resulting standard deviations are expressed as a *percentage* of the linear regression coefficient so that they scale in magnitude based upon the level of total turbulence intensity. These standard deviations can also be applied to the average anisotropic ratios.

The anisotropic ratios of the three components are plotted versus measurement height in Fig. 16. Horizontal error bars are plotted at one standard deviation.

The similarity of these results shows that the anisotropic ratio of the three orthogonal turbulence intensities is close to constant at heights of between 250 and 1000 mm above the ground. Taken as an average over this height range, the anisotropic ratio of turbulence near the ground was found to be:

$$\begin{array}{l} I_u : I_v : I_w \\ 1.00 : 0.96 : 0.59 \end{array} \quad \dots(\text{Eqn. 2})$$

This result compared well with the initial findings from the previous paper, for a single measurement height (500 mm) of:

$$\begin{array}{l} I_u : I_v : I_w \\ 1.00 : 1.01 : 0.61 \end{array}$$

The magnitudes of the standard deviation for each component are also observed to be very similar, or effectively constant at these heights.

If both the average ratios and variance in these ratios are assumed constant for these heights, the probability distribution of the anisotropic ratio of turbulence intensity can be determined (Fig. 15).

This shows a very similar distribution for u and v, and a lower proportion and wider spread in w. It should also be remembered that these three ratios are interdependent, for example, high proportions of both u and v are only possible if offset by a low proportion of w and vice versa.

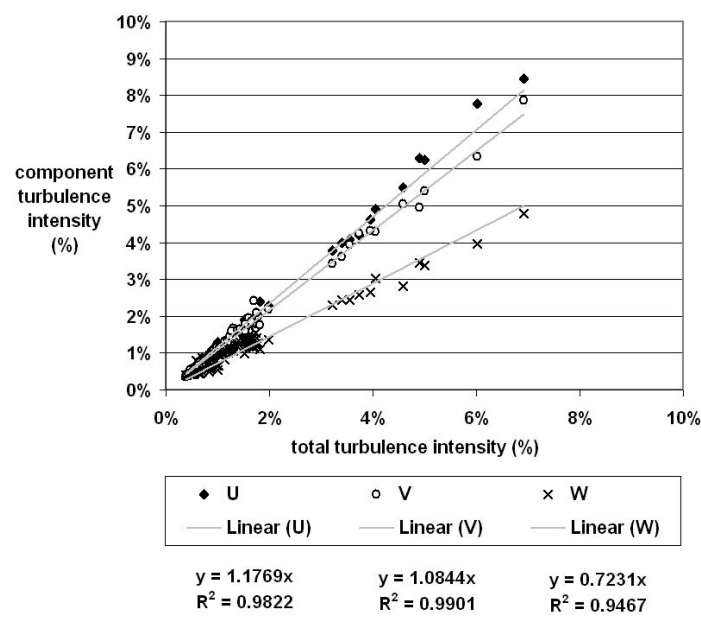


Fig. 11: Component turbulence intensity versus total turbulence intensity, 250 mm measurement height, smooth and RSO terrains.

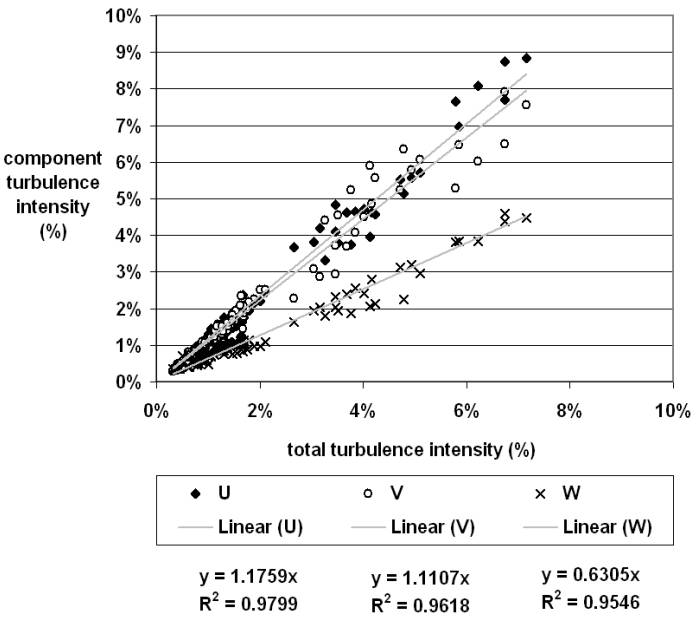


Fig. 12: Component turbulence intensity versus total turbulence intensity, 500 mm measurement height, smooth and RSO terrains.

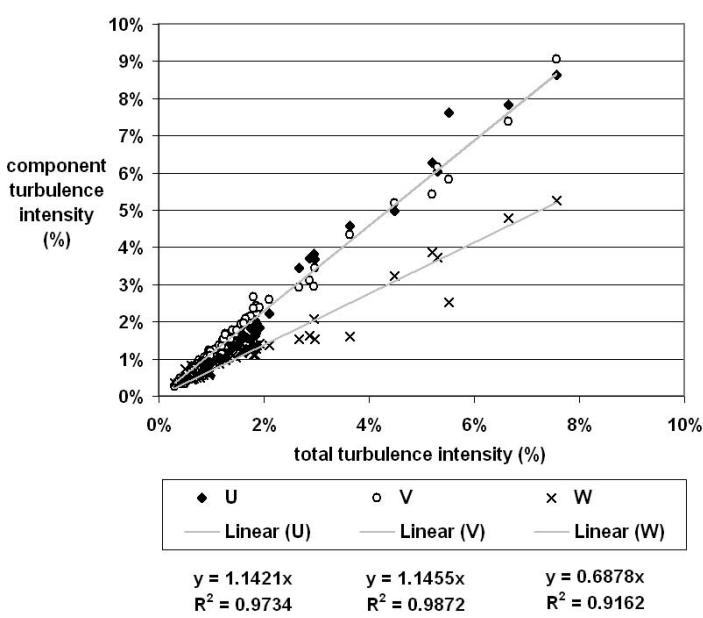


Fig. 13: Component turbulence intensity versus total turbulence intensity, 750 mm measurement height, smooth and RSO terrains.

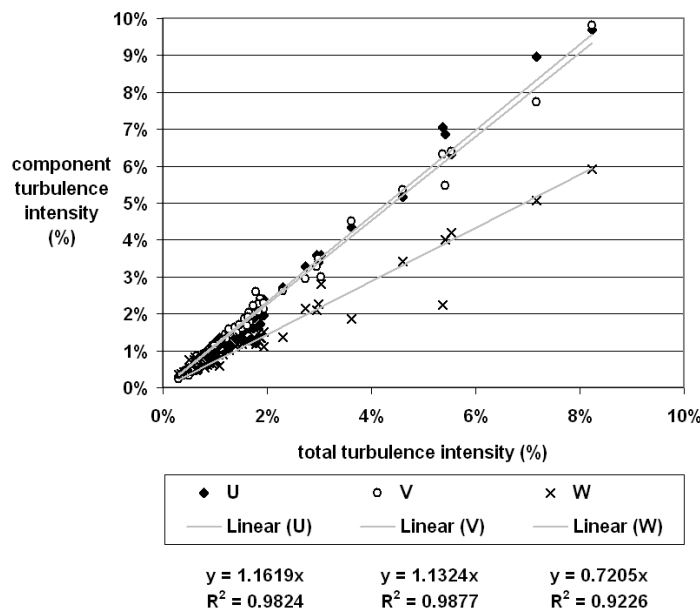


Fig. 14: Component turbulence intensity versus total turbulence intensity, 1000 mm measurement height, smooth and RSO terrains.

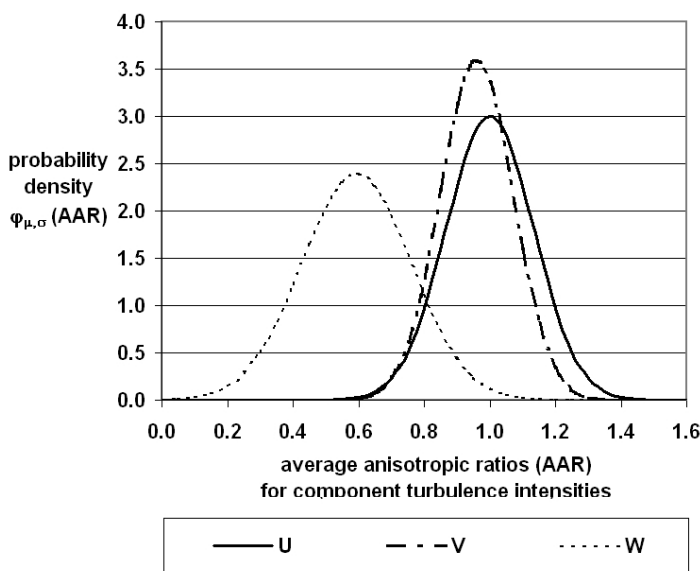


Fig. 15: Probability density of anisotropic ratios for component turbulence intensities, average over 250mm - 1000mm height range smooth and RSO terrains.

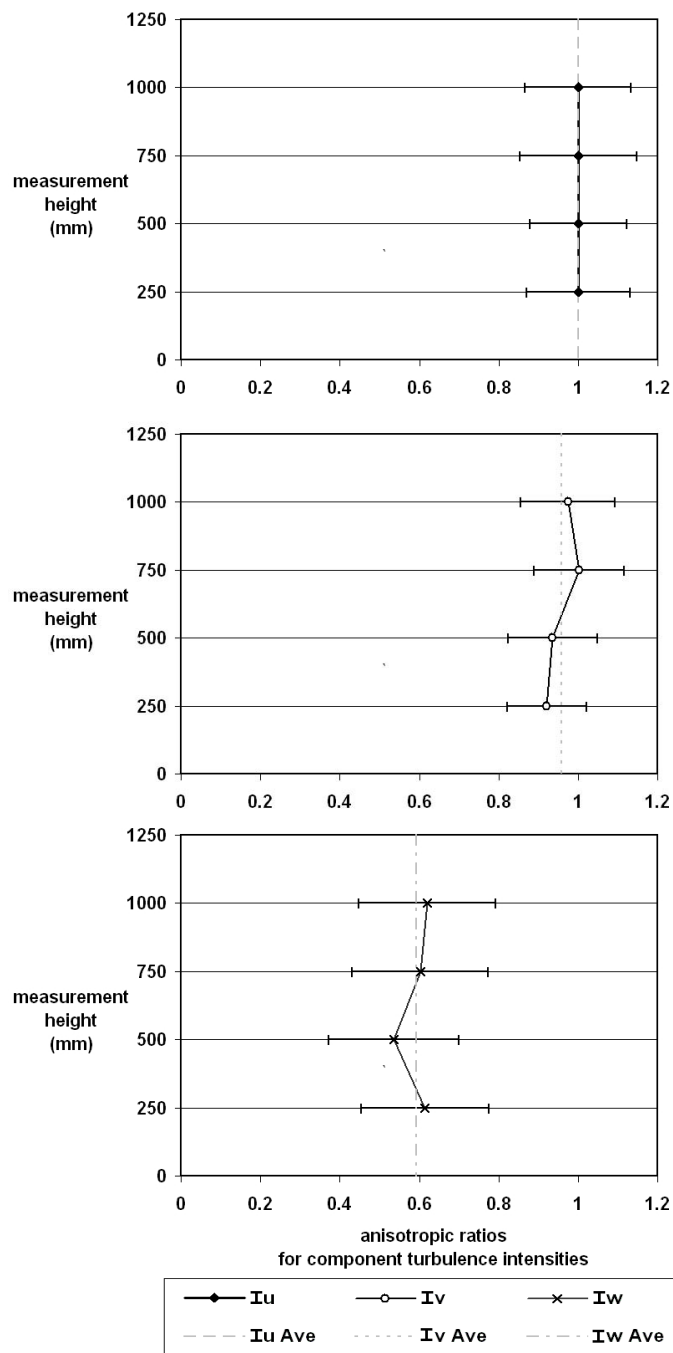


Fig. 16: Anisotropic ratio of component turbulence intensities versus measurement height, smooth and RSO terrains. Error bars at ± 1 standard deviation. Vertical averages are plotted as dashed lines, $I_u = 1.00$, $I_v = 0.96$, $I_w = 0.59$.

Horizontal Rake Results - A horizontal rake of four cobra probes, all located 500 mm above the ground (shown in Fig. 3) was used to collect turbulence measurements in different roadside terrains and wind conditions. These results are used to examine the inter-related nature of turbulence intensity, turbulence length scale, terrain type and ambient wind speed.

The effect of terrain type on turbulence intensity - In the following graphs (Figs 17, 19 and 21) turbulence intensity components are plotted versus total turbulence

intensity for the three different terrain types (smooth, road side obstacles and highway traffic). Due to the high degree of correlation ($R^2 > 0.96$) linear regression lines are drawn and these relationships are reported for each component below the graph's legend.

As explained previously, the linear regression coefficients are all normalized by the longitudinal (U) component, to yield the three part, average, anisotropic ratio of turbulence intensity.

The relative variance of each dataset was again measured by calculating the standard deviation of the data points *about* their regression lines. Using both the mean and standard deviation of the anisotropic ratios, probability distributions are plotted for each terrain type in Figs 18, 20 and 22.

Results from the three different terrains show significant differences in both the ratio of the three turbulent components and their respective levels of variance. This is illustrated in Fig. 23 which compares these anisotropic turbulence ratios for each terrain.

These results show that:

- For smooth terrains, the average longitudinal and lateral intensities are of a similar magnitude, while the average vertical intensities were significantly lower (almost half). This is to be expected very close to the ground where vertical fluctuations will be damped out and deflected (by the ground) into the lateral and longitudinal directions.
- Road-side obstacle terrains have the highest average proportion of lateral turbulence due to the influence of wakes from trees located upstream. The fact that these terrain sites were only tested in side wind conditions (minimum wind angle of 45 deg to the road) could also have contributed to the marked increase in average lateral turbulence levels observed.
- Highway traffic terrains show the highest average proportion of vertical turbulence (lw) due to the influence of wakes generated by upstream vehicles.
- Smooth and road-side obstacle terrains returned similar standard deviations of anisotropic ratio for all components, of between 16% and 24%. The standard deviations of the highway terrain anisotropic ratios were significantly lower, at between 10% and 13%, showing that turbulence generated by the wakes of upstream vehicles is surprisingly consistent, especially considering the wide range of vehicle sizes and separation distances captured in this data.

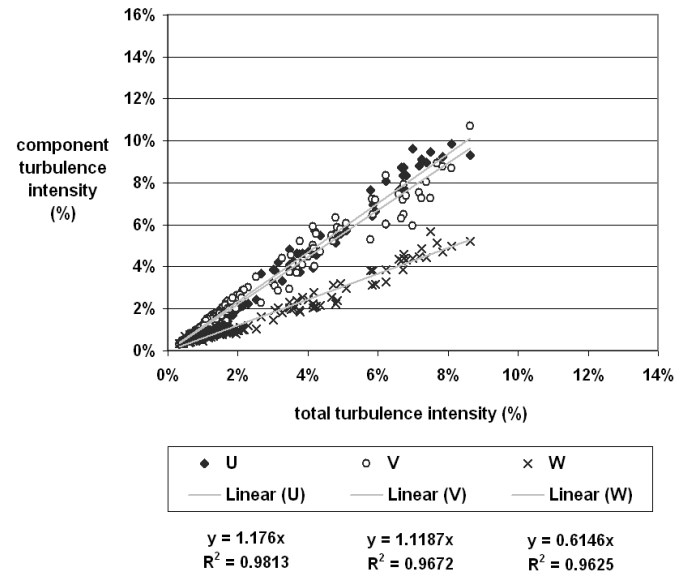


Fig. 17: Component turbulence intensity versus total turbulence intensity, 500 mm measurement height, smooth terrain.

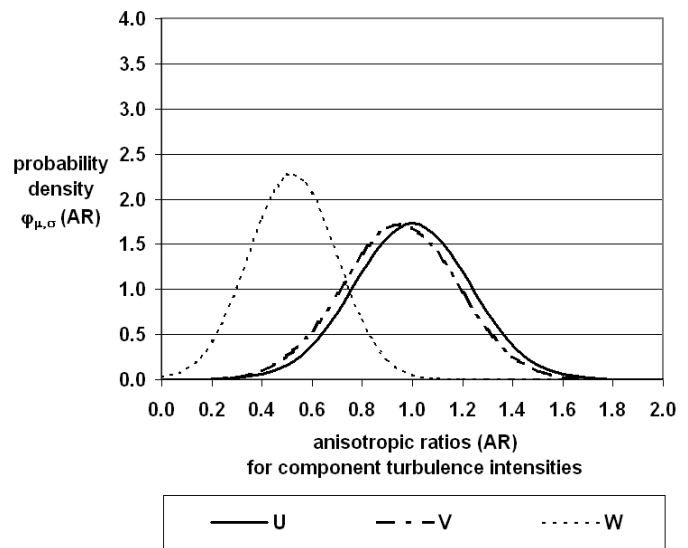


Fig. 18: Probability density of anisotropic ratios of component turbulence intensity, 500 mm measurement height, smooth terrain.