

On-road Turbulence

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ABSTRACT

The turbulent environment experienced by ground vehicles is currently not well understood. Due to this, and other historical reasons, the aerodynamic testing of automobiles is usually conducted in extremely low-turbulence wind tunnels ($<1\%$), which is in clear contradiction with the small amount of wind data available to date for these heights. This work presents a series of turbulence measurements made in a range of different on-road terrains and traffic conditions. This data was captured using 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 both the turbulence intensities and turbulent length scales are modified by terrain type, road side obstacles and the upstream wakes of other moving vehicles

INTRODUCTION

The study of automotive aerodynamics is driven by customer demands for improved fuel economy, higher top speeds, increased stability and quiet cabin environments. At present, the vast majority of aerodynamic testing on road vehicles is conducted in wind tunnels with extremely low levels of turbulence, a condition that is very rarely found on-road. There are several reasons for this.

Firstly, the study of automotive aerodynamics largely grew out of the aeronautics industry following the Second World War. Aeronautical tunnels were adapted for low speed use, with the low turbulence design criterion being carried over. Automotive wind tunnels built at a later date followed this precedent, using screens and large contraction ratios to ensure a high 'flow quality' and homogeneity through low turbulence levels. The Society of Automotive Engineers Standard (SAE, 1994) recommends turbulence intensities of substantially less than 1% for automotive testing. Pragmatically, for many years this turbulence level has not been challenged as wind tunnels specified to aeronautical specifications gave the best opportunity for motor cars tested in different

wind tunnels to give similar aerodynamic results, even if these results were generated in a flow environment that was not as close to the on-road conditions as was possible.

The second reason why turbulence is not presently modeled in automotive wind tunnels is because there is no thorough description of it for the heights and conditions relevant to cars. While wind-engineering aerodynamicists have quantified a large portion of the atmospheric profile, the last few meters close to the ground pose problems for traditional measurement techniques. Therefore these aerodynamic regions are still not well understood.

This paper aims to present a body of new wind data recorded with probes that can be used for measuring velocity whilst mounted to a moving vehicle, in a range of different terrains, wind and traffic conditions. It is hoped that this data will improve our understanding of the wind environment in which cars and other ground vehicles operate, allowing more appropriate test methods and ultimately, products, to be developed.

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 (Saunders and Wordley, 2006). 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 (2007) 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 the companion papers focuses more upon how turbulence might affect the vehicle development process, by changing the drag, lift, cross wind, cooling and acoustic

performance of a given vehicle (Watkins and Cooper, 2007). A summary of the most relevant data from these three review papers and other sources is provided below.

THE TURBULENT WIND ENVIRONMENT

There exists a great body of knowledge of the turbulent wind environment relevant to buildings, and this research is well summarized by the ESDU data sheets (ESDU, 1976, 1986, 1985). The third data sheet incorporates the data of Flay (1978) who measured winds down to a height of 3m, but this is still substantially higher than the stagnation point location of automobiles, which is closer to 0.5m. It is extremely unlikely that wind data taken at 3m or above can be extrapolated down to this level, particularly considering the complex terrain that road vehicles commonly traverse. In the absence of extremely low level wind data, automotive aerodynamicists have developed turbulence models which attempt to make predictions about the turbulent environment that road vehicles operate in. These models generally use wind data from heights above 3m and try to account for the effects of the vehicle's velocity and even the wakes generated by road side obstacles and upstream moving vehicles.

PREDICTIVE TURBULENCE MODELS

Watkins et al (1995) predicted turbulence intensities for a vehicle traveling at 100 km/h by using trigonometry to resolve the intensities of the natural wind at 3 m (as measured by Flay, 1978) into the relative wind axis system for the moving vehicle. A relative wind axis system was chosen as this frame of reference is immediately applicable to the wind tunnel modelling of turbulence. Watkins also observed that the wakes of roadside objects will give rise to a relative velocity and yaw angle that changes as the vehicle traverses these wakes. Due to the lack of data for the steady wake behind an isolated tree, an idealized wake was assumed, where for typical vehicle to local roadside object spacing, a steady deficit of 50% of free stream exists for 10% of the given road length, allowing intensities to be estimated for a range of wind to road angles.

Cogotti (2003) extended the usefulness of this model by including more detailed and parametric descriptions of the roadside obstacles, including object width, spacing and side distance from the car. A discussion of "statistically significant" conditions was then used to develop a range of likely operating conditions which were applied to the model. :

Velocity of the vehicle:	20 – 50 m/s
Velocity of the wind:	5 m/s
Turbulence Intensity:	20 % (at a fixed point)
Wind to vehicle angles:	30 – 150°

Randomly generated roadside obstacles were defined by the following parameters, and are illustrated in Fig. 1.

Widths in the range (a):	0.5 – 5.0 m
Spacings in the range (b):	1.5 – 10.0 m
Side distances from the car of (c) :	2.0 – 10.0 m

Distortion of the wind due to the roadside obstacles was calculated on the following basis:

Resultant Wind = 0 for $c/a < 1$

Resultant Wind = tending linearly from 0 to Normal Wind for $c/a = 1$ to 10

Resultant Wind = Normal Wind for $c/a > 10$

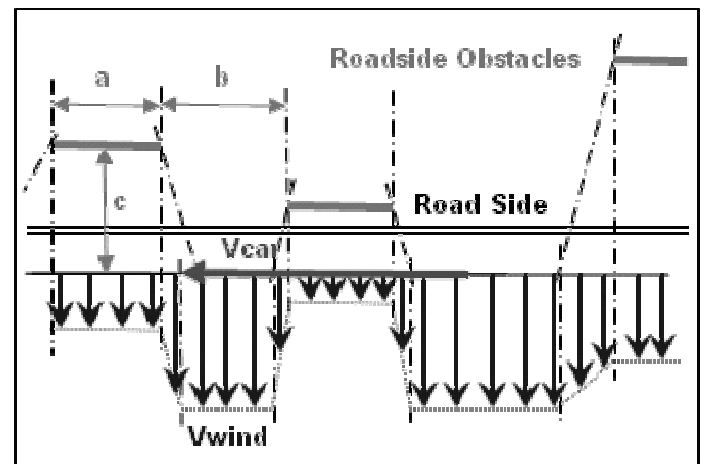


Fig. 1: Modelling scheme for the simulation of roadside obstacles (Cogotti, 2003)

By randomly varying the obstacle width, spacing and side distance the model predicted:

Total Turbulence Intensities in the range:

$$I = 2\% - 7\%$$

Longitudinal Turbulence Intensities in the range:

$$I_u = 2\% - 6\%$$

Lateral Turbulence Intensities in the range:

$$I_v = 0.7\% - 4\%$$

Ratios of I_v / I_u in the range of:

$$I_v / I_u = 0.7 - 4.0$$

These models attempted to demonstrate, at least theoretically, how the localised effects of roadside objects can generate levels of lateral turbulence which are greater than those seen longitudinally. Some

experimental evidence of this effect was captured on road by Watkins and Saunders (1995).

Other aspects of the turbulent environment have been modeled and predictions made. Reflecting their primary interests in vehicle stability and safety, a number of researchers have contributed to the development of methods for the prediction of turbulent spectra. These predicted spectra give an indication of the frequency content for the various turbulence components. The lateral velocity fluctuations in particular are used to investigate (with an aim to prevent) transverse excitation of vehicles due to atmospheric turbulence.

The first step in this process was made by Balzer (1977), who curve-fitted experimental data for the longitudinal spectrum obtained in strong winds by Davenport (1960). Using the more comprehensive statistical description of turbulence offered by ESDU 74031 (1976), R.K. Cooper (1984) extended the model to include the effects of lateral velocity fluctuations, and predicted correlations, coherence functions, phase lag and power spectral densities in the wind axis for a moving vehicle. K.R. Cooper (1989) further improved this model by using mathematical expressions to resolve the turbulence components into the *relative* wind direction.

This resolution generated predictions that highlighted the fact that we should expect to find low frequency peaks in the on-road turbulence spectra. These low frequency peaks are a result of large length scales inherent in the turbulent flow and are difficult to reproduce in a full scale automotive wind tunnel using passive mechanisms. In this case, 'active' turbulence generation was deemed a requirement (Cooper, K.R., 1989).

For the most part, the predictive models described here have been generated due to a lack of relevant data on-road. They are based on wind information collected at heights greater than that at which the turbulence models are applied, and therefore contain assumptions and simplifications that may not prove to be valid.

MEASURES OF TURBULENCE FOR GROUND VEHICLES

A small number of researchers have made measurements of the turbulent environment at heights, and in conditions, approaching those relevant to automobiles.

The turbulence measurements made by Flay (1978), mentioned previously, are frequently cited by automotive aerodynamicists as being among the most appropriate results currently available for application in this field. Flay used anemometers to investigate strong winds over "suburban terrain" at a range of heights between 20m and 3.3m, and found that the variation with height, of the velocity data, was well described by the log law profile. Values of typical turbulence intensity (for stationary measurements) at the height of 3.3m were given as:

$$I_u = 19.0 \% \quad I_v = 14.4 \% \quad I_w = 7.0 \%$$

While the turbulent length scales measured at the same height were:

$$L_u = 60 \text{ m} \quad L_v = 22 \text{ m} \quad L_w = 10 \text{ m}$$

To validate the predictive model described previously, Watkins et al (1995) used this data as a base and also made turbulence measurements at a similar height of 3.35m using a 2-Axis hot-wire probe mounted to the roof of a moving automobile.

Moving tests were all conducted at a road speed of 100 km/h, and generally avoided traffic. Two different test routes were used: the first, a 2 km stretch of road with a relatively smooth fetch, no roadside obstructions and no traffic; the second of 20 km length having relatively rough fetch and trees bordering the roadside.

For data measured on the smooth fetch route, the average measured turbulence intensities of approximately 2.6% (longitudinal) and 2.9% (lateral) compared reasonably well with the predictions from their model.

The data collected along the rougher fetch route exhibited considerably more spread, and large variations between predicted and measured intensities were evident. Measured values of lateral intensity were up to twice the model's predicted values with an average increase of 30%, which was mainly attributed to the effect of stationary wakes from roadside trees.

Saunders and Mansour (2000) used a single multi-hole pressure probe to measure on-road atmospheric turbulence and the buffeting effects of different upstream cars. A total of three different vehicles (Large Sedan, Medium Sedan, 4WD), and two different test tracks (Ford – Geelong, Australia and Ford – Dearborn, USA) were utilised in the test program.

Their single car results showed that even in very light winds, turbulence intensities of between 1% and 2% can be expected. Their vehicle buffeting tests found that intensities of up to 25% can be expected for very close separations (<5m), and that even for gaps of 15m, turbulence intensities of 5% – 10% are typical. More detailed data in the report showed that the level of turbulence generated by the upstream vehicle was fairly consistent with separation distance, and did not seem to be dependant on the ambient wind conditions.

For the on-road tests with no upstream buffeting, the integral length scale spanned a range from 2 to 17m, with an average of 6.5m. The large spread of results was attributed to the range of wind speeds tested and the probable transition from thermal dominated effects at low wind speeds to mechanical dominated effects at higher wind speeds. The buffeting tests showed less variation and a significant reduction in length scale of between 0.4 and 1.2 m, with an average of 0.8m.

MODELLING TURBULENCE IN AUTOMOTIVE WIND TUNNELS

A wide variety of techniques can be used to improve the simulation of on-road conditions for wind tunnel testing. In general, automotive tunnels are not designed to produce a natural wind boundary layer, nor the levels of turbulence experienced on road. Some historical reasons for this current state of affairs are outlined by Saunders and Mansour (2000). In special cases where large variations have been observed between wind tunnel and on-road results, researchers have been compelled to modify the flow conditions simulated by their wind tunnels to investigate the disparities. Such modifications can be grouped under three broad categories:

- Simulation of the natural wind boundary layer (and its associated 'skew')
- Simulation of turbulence through 'passive' means
- Simulation of turbulence through 'active' means

Simulation of the natural wind boundary layer

Cogotti (1995) adopted techniques common in wind engineering to generate a boundary layer velocity profile, representative of the natural wind in the Pininfarina wind tunnel. The motivation for this work was to develop a realistic profile for studies of side wind effects, as the usual process of simply yawing a vehicle in the wind tunnel is not an accurate representation of the on-road experience. This velocity profile generator was made using four rows of vertical tubes, whose spacing, height and diameter were modified to produce the required profile. Levels of turbulence were increased through the use of this system but were not measured, and no attempt was made to 'skew' the flow. With a variable speed profile the choice of reference position becomes arbitrary, so for calculation of aerodynamic coefficients the wind velocity at a height of 1.0 meter was used.

One unpublished example of the generation of a skewed velocity profile has been undertaken at Monash in commercial testing, where a device resembling a sail was used to skew low speed flow in the Monash Wind Tunnel for the study of the aerodynamic performance of yachts.

Simulation of turbulence through 'passive' means

Watkins (1990) describes the passive generation of increased turbulence levels in the RMIT tunnel, through the use of various 'grids'. These grids were constructed on a trial and error basis, with the most effective design increasing the turbulence levels by only a small amount, from 1.7% to 3.7% for longitudinal and from 1.8% to 5.7% for the lateral.

In a different study undertaken in Germany, Watkins et al (2001) generated turbulence through the use of a large

plate (6.0 m by 4.2 m) positioned in the settling chamber of the FKFS tunnel, which is upstream of the contraction. A cobra probe mounted to the roof of a car in the test section was used to record longitudinal turbulence intensities (at this single point) of 3.1%. The characteristic frequencies of the turbulence were quoted as, "high compared with the frequencies experienced when driving through atmospheric crosswinds," a statement which acknowledges that the length scales produced in the tunnel were much smaller than those found on road. The length scales achievable with passive, grid-type turbulence generators are limited by the size of the grid itself. Active methods are deemed necessary to approach the larger length scales seen on road. A small car was also placed upstream of the test vehicle on the centre line of the nozzle to generate additional turbulence. Because only interior acoustics and not forces were being measured, it was possible to locate the test vehicle downstream of the balance, near the collector. No exact measurements of the separation distances were given. For this configuration the measured longitudinal intensity above the roof of the test vehicle was 10%. When the upstream car was moved to the edge of the nozzle and 0.5 m off the centre line the intensity decreased to 2.5%, illustrating the non-homogeneity of the flow and the sensitivity of the measurement location.

Simulation of turbulence through 'active' means

The major difficulty in accurately modelling atmospheric turbulence in automotive wind tunnels is achieving the correct length scales. The limited data available at heights relevant to cars suggests that integral length scales of between 2 – 17m are typical of those seen on-road in the presence of light winds (Saunders and Mansour, 2000). Given the size and geometry of current wind tunnels, it is arguable that such length scales can only be achieved through the use of 'active' means.

Mullarkey (1990) provides an example of active turbulence generation, where a pair of oscillating aerofoils were used, up stream of a scale test model, to produce sinusoidal lateral gusts of known frequencies and wavelengths of the order of the model length.

Mullarkey used X-wires to investigate the gust quality, and it was found that the lateral velocity spectrum had a dominant component at the aerofoil oscillation frequency, and contained around 98% of the total power of the spectrum. Higher harmonics were also present but were 3 orders of magnitude less than the fundamental. The power spectral density of the fluctuating longitudinal component had the greatest response at twice the aerofoil frequency, the component at aerofoil frequency being somewhat less, with other higher harmonics present at reduced magnitudes.

In a more recent example, Cogotti (2003) made use of a "flapping wing" technique to generate more representative magnitudes and scales of turbulence for the testing of full scale cars. Unlike Mullarkey's constant

cross section aerofoils, the 5 pairs of flapping vortex generators possess tapered profiles, designed to develop a realistic velocity profile in addition to increasing the turbulence (see Fig. 2).



Fig. 2: The Pininfarina Turbulence Generation System (Cogotti, 2003)

In summary, the examples provided show that there are a variety of different techniques that can, and are currently being used to generate turbulence in automotive wind tunnels. However, due to the lack of data concerning the actual turbulent conditions experienced by cars, a number of assumptions have been made concerning the on-road aerodynamic environment for vehicles.

EFFECTS OF TURBULENCE ON AUTOMOBILES

Research is slowly emerging which shows that turbulence is an important factor in the aerodynamic performance of cars in the real world. Some of its effects on drag reducing devices, fluctuating side glass pressures, front lift forces and the aero-acoustic noise have been studied, and will be presented briefly here.

Watkins (1990) studied the effect of turbulence on drag reducing devices for trucks, by comparing a series of on-road tests with those performed with scale models in the wind tunnel under various levels of grid generated turbulence. He found that tunnel measurements obtained in smooth flow would consistently over predict on-road drag coefficient reductions arising from add on aerodynamic devices at high yaw angles. Deflection-type devices, which relied on a stable wake to shield the load, were found to produce the biggest discrepancies between the tunnel and the road results. When the levels of wind tunnel turbulence were raised using grids, drag reductions from the aerodynamic devices were closer to those measured on-road.

Gilhome and Saunders [2002] provided evidence that turbulence directly affects average and peak pressures on the front door of a sedan automobile. High speed pressure tapping equipment was used to record the fluctuating pressures on a car door and side glass both

in the wind tunnel and on-road under various wind conditions. The higher turbulence on-road conditions indicated that turbulence was increasing the aerodynamic forces acting on the door above the hinge line. The instantaneous peak forces experienced by the door were thought to be a function of the turbulent length scale, with larger scales contributing to higher peak forces. Appropriate turbulent intensities and also length scales were deemed necessary for replication of this phenomenon in wind tunnels.

Carlino (2004) presented results which showed how large scale, turbulent vortices similar to those produced by an upstream car, could result in a 120 point (0.120 CL) variation in front end lift. The Pininfarina turbulence generation system was used in this study to subject a test car to a range of both up-lifting and down-lifting vortices of various strengths. In another test, the lift and drag of a station wagon was measured in smooth flow and with turbulence. Their results show that the addition of turbulence and a more representative velocity profile increases both the lift and the drag.

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. These probes have a number of key advantages over other, more traditional apparatus including; high frequency response (compared to anemometers), general robustness (compared to hot wires), and they do not require seeding of the flow (like laser Doppler methods). The general operating principles of this instrument are described in more detail by Hooper and Musgrove (1997, 1998).

PROBE LOCATION AND MOUNTING

For this series of testing, cobra probes were mounted to the front end of a large sedan vehicle. Two probes were spaced laterally to provide a measure of spatial correlation which is needed for wind tunnel modeling of turbulence and forms part of an ongoing investigation. A lateral probe spacing 0.500 m (about the car's centre line) was selected, as an initial starting point, with the scales of interest ranging from around two car lengths (10m) down to a fraction of a car length (0.01m). Quick locking aluminum extrusion was used to build structure forward from the car's chassis mounted nudge bar to mount the probes. This extrusion allowed quick assembly and disassembly for transit to and from test sites and permitted fine tuning of the probe locations and angles. The structure was triangulated using lower support members and also tension stays connected to a roof rack to minimize any bending or vibration. The two probes heads were located at a height of 500mm above the ground, which is the approximate height of the

stagnation point on a vehicle of this size. The reference pressure tubes for both probes were routed to a common ventilated box in the back seat of the car, which was not subjected to localized drafts.

Tests were made in the Monash University Wind Tunnel (see Appendix, Fig. A). This full scale wind tunnel was used to determine an adequate distance ahead of the car to locate the probes. At very small car separation distances (less than 0.5m), the u component (longitudinal) of wind speed measured by the probes was found to be adversely affected by the pressure field of the car, giving u velocity readings which were much lower than the actual free stream velocity, as shown in Fig. 3. In cases where the probes are not located close to the stagnation height, pitch angle will also be generated, and again the severity of these errors will increase as the car is approached.

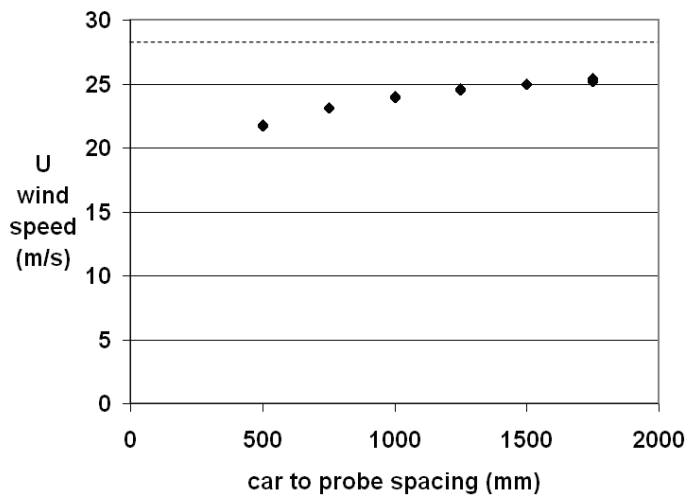


Fig. 3: Graph of u versus car to probe spacing, dashed line $U_{\infty} = 27.8$ m/s, Monash wind tunnel.

While this observation would suggest that the probes should be located as far from the car as possible, this is not practical for two main reasons. The first and most obvious is the issue of safety; apparatus which projects more than a meter or so in front of a vehicle pose a risk to pedestrians when testing on public roads and are likely to attract attention from traffic authorities. Secondly, the vehicle cannot be assumed to sit flat and ride smoothly at test speed (100 km/h in this case). Any pitching or yawing motions will be seen by the probes as false wind velocities in the v and w components. These errors become more pronounced with increasing distance between the probes and the centre of the car's rotation, which is approximately mid-wheelbase.

Analysis of the wind tunnel data showed that, at and beyond 1 meter separation distances, the standard deviations in wind speed recorded for all three wind components (u , v , w) had stabilized, and the small changes in the measured turbulence intensities were due to differences in mean u value. For this reason a distance of 1.0 meter was chosen as the car-to-probe spacing.

Wind tunnel data was measured over the range of expected total vehicle-wind speeds and used to determine a small speed-dependant correction for the total velocity vector which is essentially u . Initially this correction was applied as an increment which was added to the mean u velocity, so as not to affect the measured u standard deviation. Later on-road testing showed that this correction was not needed as 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. This logic is illustrated in Fig. B which can be found in the Appendix.

Wind tunnel tests also were made 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 on-road tests showed that all data fell within this yaw angle range.

Fig. 5 shows the probes mounted to the test vehicle. Some care was required to ensure that the probes were aligned correctly each time they were mounted to the car. Tests showed that it was possible to align the probes by eye, within $\pm 1^\circ$ which was considered adequate.

CORRECTION FOR PROBE MOTION

To measure, and if needed, 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. Using data from preliminary tests, the three acceleration time histories were integrated to give velocities. It should be remembered that these velocities are acting in addition to the test vehicle speed of 27.8 m/s.

Fig. 6 gives an example of the on-road probe motion velocity data, while Fig. 7 plots power spectrums for the u , v and w wind velocity components and the U , V and W motion velocities recorded by the accelerometer. These spectra have been left in their dimensional form.