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MEASUREMENTS OF THE TURBULENT WIND ENVIRONMENT EXPERIENCED BY A MOVING VEHICLE

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ABSTRACT

Turbulence at fixed sites and experienced by vehicles moving through the atmospheric boundary layer has been measured in on-road tests. A model is presented to predict the moving-vehicle turbulence intensity from data obtained at fixed sites. This model worked well for roads free of traffic and roadside obstructions. Variations were found between spectra measured at fixed sites and a standard model (ESDU (1985)). Generally, longitudinal and lateral peaks were less well defined and occurred at higher frequencies than the ESDU model.

INTRODUCTION

Comparisons of drag reductions between road and wind-tunnel tests on trucks have shown reasonable agreement at low yaw angles, but at high yaw angles (≈ 15^0), road drag reductions have fallen considerably (sometimes to zero) whilst the tunnel results still predict large savings, see Buckley et. al. (1978) and Saunders et. al. (1985). Whilst research has concentrated on other modelling parameters, eg. Reynolds number and ground simulation, little attention has been paid to the effects of turbulence.

A review of existing wind data from wind engineering sources showed data are plentiful at heights of greater than 10m and for conditions of strong winds (>10m/s). However, turbulence and mean wind characteristics are a function of distance from the ground, and data close to the ground (<3m) are relatively scarce, with increasing uncertainty in the data as the ground is approached. Data have been gathered very close to the ground for studies on crops, which are relatively smooth, flat terrains, not typical of road environments. For lower windspeeds, data are not plentiful, and the intensity and spectra (or scales) of the turbulence are influenced by the effects of thermal stratification, which are not well understood.

EXPERIMENTAL TECHNIQUE

Test Routes and Fixed Sites Because of the effect of fetch roughness on the natural wind characteristics, tests were performed on routes which had relatively rough fetches and trees near the roadsides, and also on a short stretch of road which had a relatively smooth fetch, no roadside obstructions and no traffic, thereby permitting measurement of turbulence arising only from the natural wind. The surrounding terrain for most parts of the test routes would be classified in the Australian Standard 1170 (Anon (1989)) on wind forces as terrain category 2 ("open terrain with well scattered obstructions having heights generally 1.5 to 10 metres"). In contrast to this, the section of the test route with smoother upwind terrain would be classified as terrain category 1 ("exposed open terrain with few or no obstructions and in which the average height of any surrounding objects is less than 1.5 metres"). It offered an unbroken, smooth fetch with a clear 5 km of about 0.2 m high grass for the wind direction considered.

Natural wind data (obtained with the vehicle stationary) were gathered at sites near the end of each test section, which for most wind directions had clear upstream fetches of approximately one kilometre.

Instrumentation A Ford Falcon station wagon was used as the data acquisition vehicle. A Gill propeller-vane anemometer, mounted 1.9m above the roof of the car, was used as a mean velocity reference and to measure natural wind turbulence and (large) yaw angles in the fixed-site tests. For the moving tests, hot-wire measurements were taken using an unlinearised TSI Model 1054B constant temperature anemometer and X-wire probes. The hot-wire probe was located just below the Gill anemometer, and aligned such that the plane of the wires was horizontal.

Data were recorded on a 7 track Teac FM analog tape recorder, calibrated before and after each run. The data were analysed by digitising the tape recorder output using custom-made sample and hold units and a Data Translation DT2801A board in an IBM-compatible computer.

All fixed-site data were corrected for trends by testing segments of the data and removing trends given by parabolic fits to the data.

Calibration The hot-wire anemometer probes were calibrated in the normal manner, see for example Bradshaw (1971). Because of the high yaw angles expected, the probe yaw calibrations were extended to ±30 degrees. Excellent agreement with the assumed cosine law response was obtained for all probes used.

The Gill anemometer was calibrated in-situ on the car using a procedure developed by Buckley et. al. (1978). The procedure involved timing the vehicle over known distances on a selected section of the route, matching pairs of runs, and calculating the true relative velocity and yaw angle offset, whilst taking into account any (slight) crosswinds. This procedure established the influence of the proximity of the car on the Gill reading at nominally zero yaw angle, but did not adequately take into account the effect of vehicle interference at non-zero yaw angles. To determine interference effects, wind-tunnel model tests were conducted.

Test Procedure Vehicle-stationary data were obtained by finding a suitably level location close to the end of a test section, upwind of the road and removed from local obstructions, and aligning the vehicle into the mean wind direction. Data were recorded for 12 minutes, after which the car was driven over the test route at a speed of 100 km/hr (27.8 m/s), held constant to within ± 2 km/h. Vehicle-stationary measurements were then repeated. For some tests this procedure was repeated several times. Testing was undertaken only during dry periods and generally avoided traffic.

PREDICTION OF THE TURBULENCE FIELD EXPERIENCED BY A MOVING VEHICLE

Introduction Since the wind environment relative to the ground has been documented in wind engineering studies (although doubts remain as to the accuracy of data close to the ground and the effect of different thermal stratifications), it becomes possible to predict the wind environment of a vehicle traversing this field. This section describes a model for the prediction of the turbulence intensities experienced by a moving vehicle.

Prediction of Turbulence Intensities To predict the intensities experienced by the moving vehicle, it is necessary to resolve the stationary measurements of the fluctuating components of velocity in the natural wind into the directions, parallel and normal to, the *relative* velocity experienced by the vehicle (the relative wind axis system) as shown in Figure 1.

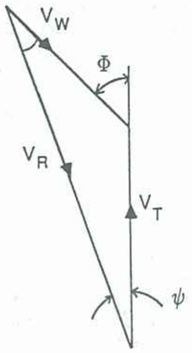

Figure 1 Mean velocity diagram for a moving vehicle.

In this figure, V_T is the vehicle velocity relative to the ground, V_W is the windspeed relative to the ground, V_R is the relative wind velocity and ψ is the yaw angle.

To determine a velocity component at an arbitrary angle θ to the mean natural wind direction, u_θ, consider an instantaneous velocity vector (Figure 2):

$$u_\theta = u\cos\theta + v\sin\theta \quad , \qquad (1)$$

where u and v are fluctuating velocity components parallel and perpendicular to the mean natural wind direction.

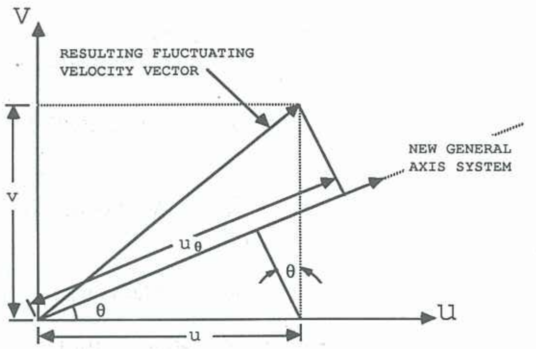

Figure 2 Resolving from Wind Axis System to a General Axis System.

Then,

$$u_\theta^2 = u^2\cos^2\theta + v^2\sin^2\theta + 2uv\cos\theta\sin\theta \qquad (2)$$

and a temporal average with u and v uncorrelated, gives

$$\overline{u_\theta^2} = \overline{u^2}\cos^2\theta + \overline{v^2}\sin^2\theta \qquad (3)$$

Thus

$$\frac{\overline{u_\theta^2}}{V_W^2} = \frac{\overline{u^2}}{V_W^2}\cos^2\theta + \frac{\overline{v^2}}{V_W^2}\sin^2\theta \qquad (4)$$

or

$$I_\theta^2 = I_u^2\cos^2\theta + I_v^2\sin^2\theta \qquad (5)$$

where I_θ is the intensity at any angle θ.

A typical result may be obtained by using the natural wind intensity data of Flay (1978) taken at a height of 3.3 m: $I_u = 0.190$ and $I_v = 0.144$.

The longitudinal intensity, J_u, of the relative airstream V_R is given by :

$$J_u = \frac{V_W \, I_\theta}{V_R} \qquad (6)$$

where

$$V_R^2 = V_T^2 + V_W^2 + 2V_W V_T\cos\Phi \qquad (7)$$

The lateral intensity, J_v, of the relative airstream may be found by replacing θ by $\theta + 90^0$.

The intensities J_u and J_v have been calculated for a range of windspeeds, and are shown plotted in Figures 3 and 4 as a function of the yaw angle, for a vehicle speed of 100 km/h.

As the turbulence intensities are calculated in the relative wind axis, the bounding lines represent the minimum turbulence intensities that should, in theory, be generated relative to a wind-tunnel centreline to correctly model the turbulence intensities in the natural wind.

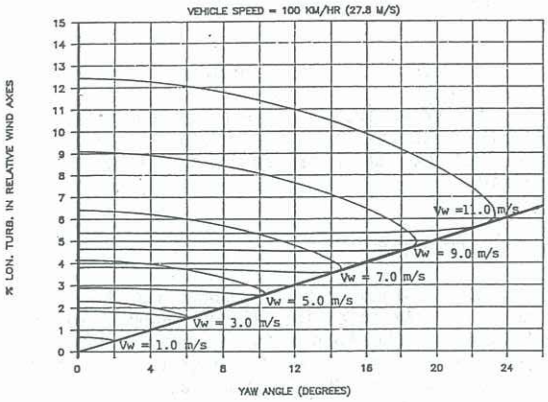

Figure 3 Predicted Longitudinal Turbulence Intensity versus Yaw Angle.

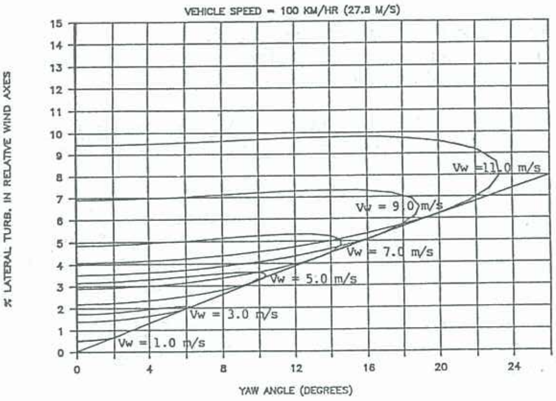

Figure 4 Predicted Lateral Turbulence Intensity versus Yaw Angle.

RESULTS

Fixed Site Data

<u>Turbulence Intensity</u> Figure 5 shows the variation in intensities for all sites as a function of windspeed. It seems that whilst the data are scattered due to the nature of the wind and the variations of local roughness, there is a distinct correlation between velocities and intensity.

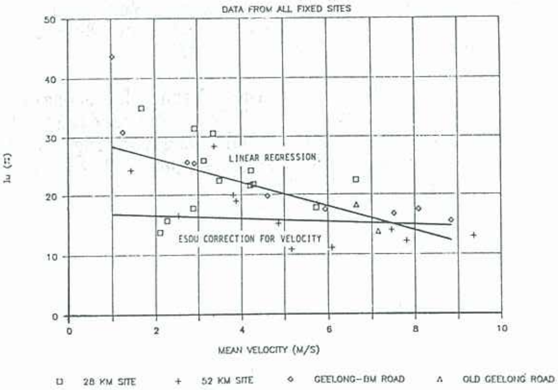

Figure 5 Longitudinal Turbulence Intensity as a Function of Windspeed.

Until fairly recently, it was considered by wind engineers that intensity and scale were independent of windspeed. However, ESDU (1985) gives a correction on intensity for the effect of mean velocity in the range of 10 to 20 m/s, for neutrally-stable conditions. An extrapolation of the correction factor is indicated on Figure 5 as well as a linear regression fit to the data. The data presented here are taken under a variety of different (and unknown) thermal stabilities, but the ESDU correction is for neutrally-stable conditions, which may explain the difference between the two lines.

<u>Turbulence Spectra</u> Space does not permit a detailed discussion of the spectra measured at the fixed sites. For some sites longitudinal spectra showed reasonable agreement with ESDU (1985), but other spectra exhibited no well-defined peak. For the lateral spectra, peaks occurred at higher frequencies than either the longitudinal values or the ESDU model. To adequately determine spectra close to the ground it seems necessary to obtain many samples for each location under similar wind conditions and thermal stabilities, and average them in the frequency domain, thus averaging out the large variations in energy at the low frequency end of the spectra.

Moving Vehicle Data

<u>Turbulence Intensities</u> Measured and predicted intensities compared reasonably well for the test route with the smooth upwind terrain and no local roadside obstructions, as shown in Figure 6.

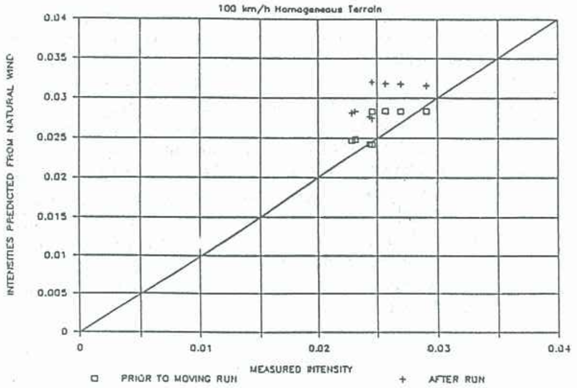

Figure 6 Comparison of Predicted and Measured Longitudinal Intensities: Homogeneous Terrain.

However, for the other test routes, large variations between predicted and measured intensities are evident from Figure 7, where, again, only longitudinal intensities are plotted.

<u>Turbulence Spectra</u> For both longitudinal and lateral spectra, energy was centred at frequencies of approximately 1.0 Hz with most energy concentrated between 0.1 Hz (the high-pass filter frequency) and 10.0 Hz. Investigation of spectra from the various routes shows that the peak energy frequency does not appear to be significantly affected by local roadside obstructions.

Where possible, the measured spectra were compared to predicted spectra of Cooper (1984), and although slight differences existed between measured and predicted conditions, it was found that the moving vehicle spectra exhibited a higher peak frequency than Cooper's predicted value.

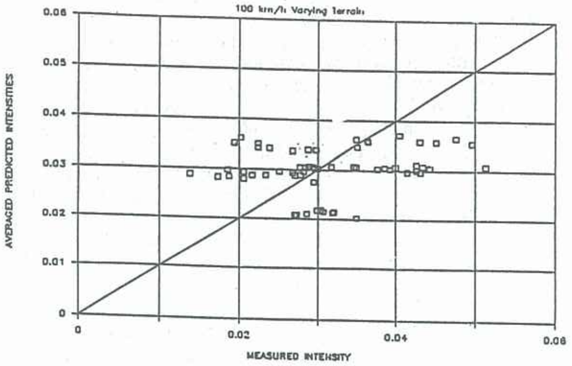

Figure 7 Comparison of Predicted and Measured Longitudinal Intensities: Varying Terrain.

DISCUSSION

The approach of using natural wind data to predict moving data should be valid if the vehicle is traversing a homogeneous turbulence field with no other local factors modifying the flow. However this generally is not the case due to the nature of local obstructions that surround most roads: the flow being considered is not removed from the surface roughness that is contributing to the local structure of the turbulent atmospheric boundary layer.

A crosswind, even if considered steady, causes local wind effects and wake flows on a road with local roadside roughness. These are experienced by a moving vehicle as a change in wind velocity and direction and can vary considerably from road to road. Smith (1972) found that the majority of "gusts", as measured by an anemometer on a moving car, were attributable to these local wind effects; Watkins (1985) also noted large variations in yaw angle and relative velocity which appeared to be related to roadside topography. Traffic will have a similar effect, although, in addition, wakes of other vehicles will also interact with the flow field of the vehicle under consideration.

CONCLUSIONS

1. The fixed-site data showed:
(i) Longitudinal and lateral intensities varied with windspeed with the highest intensities being measured for mean windspeeds of about 1 m/s. Under stronger winds, turbulence intensities reduced, and for sites with smoother upstream fetches typical values are I_u = 13% and I_v = 11%. These values for higher winds compare well with data in the literature.

(ii) Spectra varied considerably from run to run. Some longitudinal spectra obtained under higher winds compared reasonably with the most commonly-used model, ESDU (1985). Lateral spectra showed an energy peak that was generally at a higher frequency than the longitudinal value or the ESDU model.

2. The moving vehicle data showed the following:
(i) Intensities varied with varying windspeeds and amount of roadside aerodynamic obstructions; typical values were I_u = 2.5% to 5%, I_v = 2% to 10%, for various crosswind directions.

(ii) Frequencies at which energy peaks occurred in both longitudinal and lateral spectra were centred at about 1.0 Hz with most energy in the range 0.1 Hz to 10 Hz.

3. Comparison of the predicted and measured turbulence intensities showed that:
A mathematical model predicted approximately 10% higher intensities than measured values, for a road that had no local roadside obstructions or traffic.

ACKNOWLEDGEMENTS

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