11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

ON THE GENERATION OF TUNNEL TURBULENCE FOR ROAD VEHICLES

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1. INTRODUCTION

To determine a vehicle's on-road aerodynamic characteristics, wind tunnels are commonly used. Although wind tunnels offer advantages of repeatable conditions in an easily-documented environment, several modelling parameters that should, in theory, be simulated are usually ignored. Turbulence experienced by vehicles has generally not been simulated, nor are its effects well understood and examining types of turbulence and the possibility of tunnel simulation are the main objectives of this paper. The RMIT Vehicle Aerodynamics Group will be investigating this at the new Joint Vehicle Centre at Monash University.

Turbulence can arise from a variety of causes including changes in vehicle speed and direction. However, these latter causes will not be considered and the vehicle speed will be assumed constant. Generally the vehicle will be traversing turbulence from:

a. The atmospheric wind;
b. The wakes of local roadside objects (e.g., trees, bridges and buildings) in the atmospheric wind and;
c. Wakes from other road users, from vehicles passing in the same, or opposing, directions.

Turbulence will effect drag and stability of cars. For drag estimation, average wind conditions and average effects are required, i.e., a few extreme cases of wind conditions will have negligible effect on a vehicle's overall drag coefficient.

Stability and safety considerations only require data on the peak forces and moments. These arise from the worst-case combination of inputs (i.e., a sudden gust, or change in wind conditions that produces the largest variation in force or moment). There is a distinct difference between the wind environment needed to test for drag and stability considerations.

2. VEHICLE DRAG

The long-term average drag force or coefficient has a considerable effect on the fuel economy of a vehicle and is normally calculated with mathematical models. Inputs include a mean atmospheric windspeed, the vehicle speed, the (yaw) angle between the vehicle and the relative wind and experimental drag coefficients as a function of yaw angle, traditionally measured in smooth flows. Such models include the method of Wind Averaged Drag (Buckley, et al., 1978) and other models proposed using the American Duty Cycles. The effects of turbulence will be to change the experimentally-determined drag coefficient. Tests have been performed in turbulent streams and it has been found that on commercial vehicles, the drag coefficient can be substantially influenced by turbulence (eg., Cooper and Campbell, 1971 and Watkins et al., 1986). Smaller effects are generally found on more streamlined vehicles.

The atmospheric wind varies in direction and speed continuously, as characterised by spectral analysis on long-term wind records. Simulation of the full spectrum is not practical in wind tunnels. It is generally considered that the effect of long-term changes in windspeed and direction (macro-meteorological changes) can be considered as quasi-static.

An understanding of what can be considered as quasi-static (and hence modelled by changes in vehicle yaw angle in the tunnel and implemented in mathematical models as mean wind-speed changes) is needed but this area for vehicle-type shapes is not well understood. Short-term changes in wind characteristics are generally thought to be of a sufficiently small scale such that they interact directly with parts of a vehicle's flow field thus they cannot be satisfactorily modelled by quasi-static measurements. Bearman and Morel (1983) suggest three possible areas:

a. Large-scale turbulence that can be considered to have quasi-static effects;
b. Turbulence with scales approximately equal to the size of the vehicle interacting directly with the flow field and;
c. Small-scale turbulence which influences boundary layers on the vehicle and which may change separation points.

Generating the complete spectrum in the tunnel may not be required. A possible method to investigate this is to use aerodynamic admittance, e.g., see Davenport et al. 1975.

2.1 Mean Atmospheric Windspeeds

Mean wind data have been obtained from records on a site between Melbourne and Geelong in Victoria. As is commonplace the data were recorded at a height of 10m, see Fig.1.

An examination of the data revealed that for approximately 95% of the time the windspeed is less than 10 m/s with the most common windspeeds being 4-5 m/s. (Using a suitable profile law to factor the speed for the reduction in mean windspeed with reducing height, led to the conclusion that for 98% of the time the speed at typical

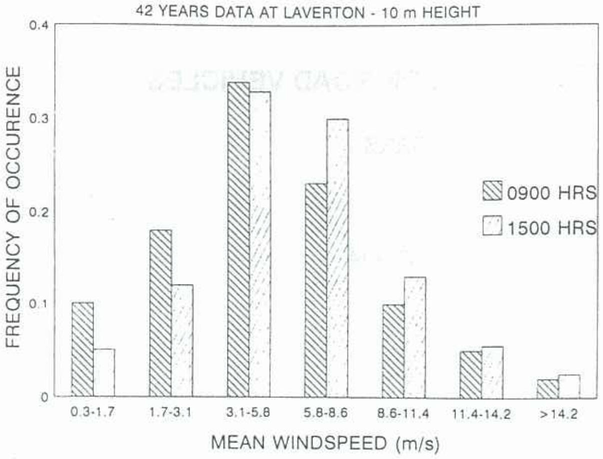

Fig.1 Frequency Distribution of Mean Windspeed

vehicle heights would be less than 10 m/s.) At speeds of less than 10 m/s much of the large body of data collected for wind engineering purposes may be of limited use since the data are usually obtained under periods of strong winds, which are defined as winds of greater than 10 m/s. It is now recognised that the mean atmospheric speed influences turbulence characteristics (e.g., the correction in ESDU 85020 for the variation in turbulence intensities and scales under low windspeeds). Under light winds, the effects of thermal stratification will influence the data and for much of the data gathered during strong winds for wind engineering purposes, these effects will not have been included. Since low windspeeds are predominantly encountered, the levels of turbulence will be low and when driving in traffic, the wakes of other vehicles will be significant. For stability work, wind engineering data are more useful.

2.2 Intensities And Spectra Of Turbulence

From measurements taken via hot-wire and propeller-vane anemometers mounted on a vehicle moving at 100 km/h, intensities and spectra have been calculated. The road had a smooth upstream fetch (very low grass) for approximately 2 km, no local upstream obstacles and no traffic, thus all the turbulence was from the atmospheric wind. Typical non-dimensional spectra are presented in Figs. 2 and 3. The data were obtained under the following atmospheric conditions of mean velocity, V_w; direction relative to the road Φ and average longitudinal and lateral intensities I_u and I_v:

$$V_w = 6.9 \text{ m/s}, \ \Phi \approx 126°, \ I_u = 0.16, \ I_v = 0.11$$

It is apparent that peak energy occurs at approximately 1 Hz. This frequency of maximum energy did not shift significantly with wind orientation to the road nor atmospheric wind speed since generally the atmospheric windspeed is low compared to typical road vehicle speeds. It is interesting to note that in building aerodynamic work on 3-D shapes, small changes in length scales make relatively little difference to forces and moments.

However, typical turbulence intensities can vary from 0 to approximately 10% with differences in wind conditions. Also the ratio of longitudinal to lateral intensities depends upon Φ. Further details can be found in Watkins, et al. (1989) and Watkins (1990).

To simulate the correct (and numerous) variations in longitudinal and lateral intensities in wind tunnels is difficult with passive means (e.g., grids) and it is further complicated since the turbulence scales (particularly lateral) are restricted by size of grid and size of tunnel. To overcome this, some researchers are using active turbulence generation by either moving the vehicle or the airstream.

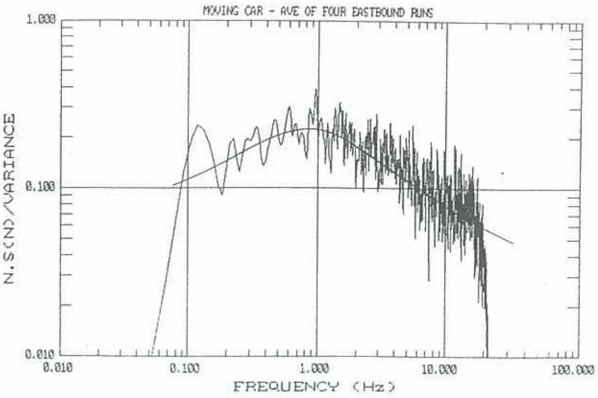

Fig.2 Typical Longitudinal Spectra - Vehicle Moving

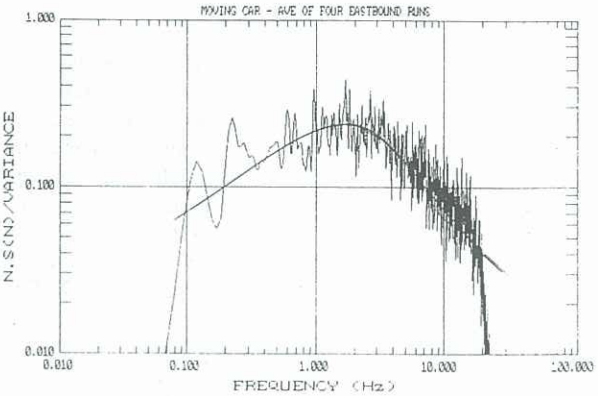

Fig.3 Typical Lateral Spectra - Vehicle Moving

Large yaw angle variations are a characteristic of turbulence near the ground. Garry and Cooper (1986) rotated an instrumented truck model at different yaw rates to simulate the changes in yaw angle due to the turbulent environment. It was found that for between 0.25 to 64°/second (the maximum range of yaw rates tested) the rotating model experienced similar drag coefficients to those obtained at fixed yaw angles. However, a considerable phase shift in yaw angle was noted between rotating and quasi-steady results, implying aerodynamic hysteresis. Clearly more work is needed in this area.

3. VEHICLE STABILITY

A vehicle's lateral deviation is mainly affected by sudden changes in the side force and yawing moment and hence in yaw angle or velocity. A large range of conditions can generate such a change. The largest rate of change of yaw angle is found when the vehicle passes from a road section that is shielded from the atmospheric wind into a road section that is not, or the converse. Possible scenarios include tunnel entering or exiting. A single point on the vehicle experiences a rapid change in yaw angle and velocity, when the wind vector V_w changes magnitude or direction. The rate of change depends upon the vehicle speed V_T the atmospheric windspeed V_u and the rate at which V_w changes. Since a rapid change in V_w occurs usually due to shielding from a local roadside object, the rate depends upon the horizontal shear in V_w. The shear layer thickness depends upon the roadside obstacle that offers the shielding and also on the distance from the obstacle. Generally the closer the vehicle is to the obstacle, the thinner the shear layer and the greater will be the rate of change of yaw angle and velocity. It then becomes necessary to consider which value of the wind angle Φ between the wind and the road will give the greatest change in forces and moments on the vehicle. Initial considerations show that the largest yaw angle that can be generated occurs when the relative wind V_R and the atmospheric wind V_w are orthogonal, as shown by the dotted lines in Fig. 4, but in this case, the relative velocity (V_r) and hence the dynamic pressure are not maximum. Assuming a linear relationship between side force and yaw angle for the vehicle i.e., SF = $K(\psi)$ (which is true for many vehicles up to high yaw angles, see Takanami et al., 1976) the maximum force that can be generated occurs when $\frac{1}{2}\rho V_R^2 K(\psi)$ is maximised as a function of Φ as shown in Fig.5. Considering the geometry from Fig.4.

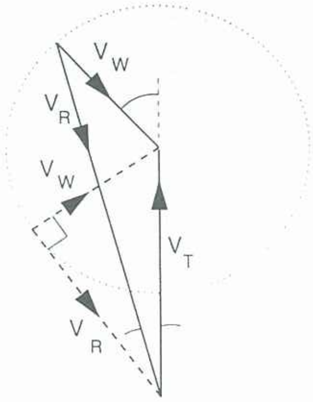

Fig.4 Vector Diagram for a Moving Vehicle

$$V_R^2 = V_T^2 + V_w^2 + 2V_wV_T\cos\Phi \text{ and}$$

$$\psi = \tan^{-1}\left[\frac{V_w / V_T \sin\Phi}{1 + \frac{V_w}{V_T}\cos\Phi}\right]$$

Fig. 5 shows $V_R^2\,\psi$ (normalised with respect to the maximum value) plotted as a function of Φ for various atmospheric windspeeds and a constant vehicle speed. It can be seen that $\frac{1}{2}\rho V_R^2 K(\psi)$ is generally a maximum when Φ is about 75 to 80°.

A similar argument is used by Kramer et al., 1991 in obtaining the angle between the road direction and a crosswind gust generator to maximise forces on vehicles driven through the crosswind.

A typical scenario is a vehicle passing through a discrete wake from a roadside object, see Fig.6. On the extreme right-hand side is a typical wake. The left-hand column shows the flowfield incident on the vehicle before it reaches the wake. Subsequent columns show the flow incident on the vehicle as it moves past the wake. As can be seen the change in the crosswind strength introduces curvature dependent on the width of the shear layer.

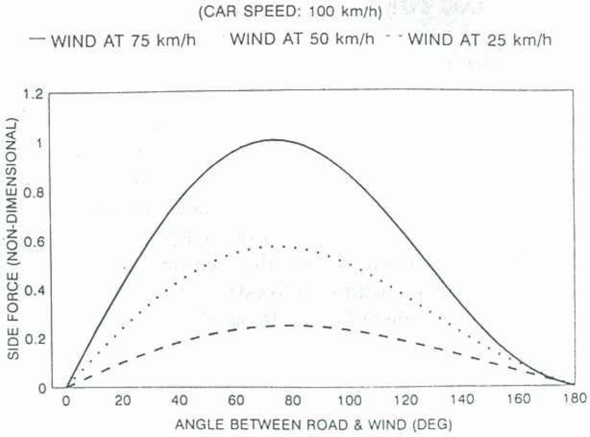

Fig.5 Variation of Side Force with Wind Angle Φ

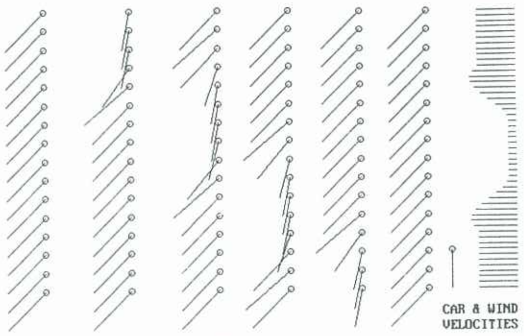

Fig.6 Vector Diagram for a Vehicle Moving through a Wake

4. METHODS OF GENERATING OR SIMULATING THE SIDE GUSTS

There are currently several methods used:

a. Full-scale road testing utilising crosswind generators - the vehicle is driven across a change in crosswind and the deviation is measured.
b. Model testing utilising models propelled across wind tunnels - this allows the correct simulation of turbulence in the tunnel. It can allow more than one model thus offering the possibility to study interactions between two or more vehicles.
c. Wind-tunnel tests with models or full-size vehicles, where the vehicle is held stationary in a turbulent airstream, moved within the confines of the test section or a combination of the two.

Whilst method (a) allows "driver-in-the-loop" testing, it is difficult to conduct systematic research in repeatable conditions and measure the aerodynamic forces and moments to pinpoint sources of problems.

The second method may suffer from uncertainties due to Reynolds number effects and is not practical for full-size vehicles.

The third method appears to be a convenient way of simulation and this is discussed in more detail.

5. MOVING THE VEHICLE IN A WIND TUNNEL

Consideration of the reproduction of rapid yaw angle changes has led to work that has rotated the model, usually about a point close to the centre of the vehicle e.g., Garry and Cooper (1986) and work at Texas Tech. University (unpublished). Such a technique needs to obtain values of the inertial forces with no wind on, to later remove them as a tare reading from test results. Consider points located on the vehicle centreline whilst the vehicle is undergoing continuous rotation with zero freestream velocity, as shown on the left-hand side of Fig. 7. It can clearly be seen that to the front of the vehicle a 90° yaw angle is generated whilst to the rear the yaw angle is similar, but of opposite sign. When this is added vectorially to a tunnel freestream velocity V the effect is to generate streamline curvature along the length of the vehicle which varies as a function of time as the vehicle is being rotated. On Fig. 7, velocity vectors are plotted as the vehicle is yawed from -45 to 0 deg. with varying rates, while the tunnel speed is reduced so as to keep the velocity component along the vehicle (the road speeds) constant. If the columns were viewed from right to left, a streamline curvature would be perceived as experienced by a vehicle exiting a tunnel at constant speed into an open region of crosswind. However, the wind-tunnel time sequence is from left to right and when the columns are thus viewed, it would appear that the vehicle is leaving an open zone of crosswind to enter a tunnel, but with the rear end "seeing" the disturbance first! No combination of yaw angle, yaw rate and tunnel speed can produce the correct sequence. Hence the simulation is not correct for gust penetration and exiting. The method of rotating models in wind tunnels is common for aircraft which do not encounter passing problems but do need stability derivatives to examine their stability and control.

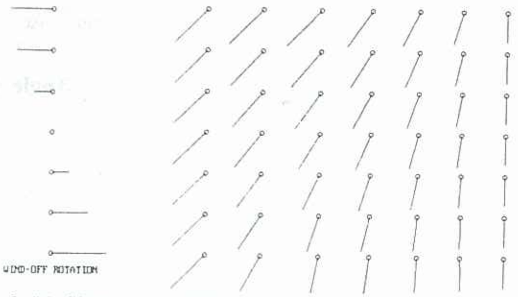

Fig.7 Vector Diagram for a Vehicle Rotated in the Wind Tunnel

For vehicles, a more general approach is to consider rotation and translation of the vehicle via a force balance platform that can be moved accordingly in the tunnel. This has been considered in full scale but has currently been rejected due to the complexity of implementation. It offers considerable aerodynamic advantages due to the ability to simulate large-scale longitudinal and lateral disturbances useful for drag as well as stability studies. This may be considered in model scale as an adjunct to the full-size facility.

The above methods of moving the vehicle generate only large scales of turbulence; larger than the vehicle dimension. If this is implemented in addition to grid - generated turbulence it seems possible to generate a more complete turbulence spectrum and could be used to study the drag as well as stability of vehicles. This could also be useful in the study of building aerodynamics to generate a wider spectrum than current testing methods permit.

6. CONCLUSION

The turbulence characteristics relevant to drag and stability consideration have been discussed.

It was concluded that rotating the vehicle in a wind tunnel will not simulate correctly a common passing problem. However, a combination of grid turbulence and vehicle movement offers the possibility of generating a more complete spectrum than has currently been possible.

7. ACKNOWLEDGMENTS

The authors wish to thank the efforts of Ms Shob Narayan in assembling this paper and the assistance of the Ford Motor Companies of America and Australia.

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