

Cross Winds and Transients: Reality, Simulation and Effects

2011-01-0172

Published
04/12/2011David Sims-Williams
Durham University

Copyright © 2011 SAE International

doi:10.4271/2011-01-0172

ABSTRACT

This paper provides a published counterpart to the address of the same title at the 2010 SAE World Congress.

A vehicle on the road encounters an unsteady flow due to turbulence in the natural wind, due to the unsteady wakes of other vehicles and as a result of traversing through the stationary wakes of road side obstacles. This last term is of greatest significance.

Various works related to the characterization, simulation and effects of on-road turbulence are compared together on the turbulence spectrum to highlight differences and similarities. The different works involve different geometries and different approaches to simulating cross wind transients but together these works provide guidance on the most important aspects of the unsteadiness.

On-road transients include a range of length scales spanning several orders of magnitude but the most important scales are in the 2-20 vehicle length range. There are significant levels of unsteadiness experienced on-road in this region and the corresponding frequencies are high enough that a dynamic test is required to correctly determine the vehicle response. Fluctuations at these scales generate significant unsteady loads (aerodynamic admittance typically 0.6-1.4) and the corresponding frequencies can adversely affect vehicle dynamics.

The generation of scales larger than the scale of the vehicle is impractical with passive grids and so active turbulence generation systems are preferred. These can be classified into lift and drag-based devices. Lift-based devices provide better control of the turbulence but can only just reproduce the smaller scales in the 2-20 vehicle length range. Different

moving model approaches are also discussed. CFD offers real advantages through its ability to allow arbitrary time-varying boundary conditions.

INTRODUCTION

This paper provides a published counterpart to the address of the same title presented at the 2010 SAE World Congress.

A vehicle on the road encounters an unsteady flow due to turbulence in the natural wind, due to the unsteady wakes of other vehicles and as a result of traversing through the stationary wakes of road side obstacles. A review by Watkins and Cooper [1] concluded that there is evidence that turbulence can significantly affect the aerodynamics of some road vehicles.

Increasing effort is going into better understanding this on-road aerodynamic environment and a key observation is that a wide range of diverse conditions are experienced. On-road transients and turbulence include a range of length scales spanning three to five orders of magnitude but the greatest proportion of on-road turbulence occurs at scales of several meters.

The paper reviews work undertaken to characterize the on-road environment and its effects on road vehicles, including recent work and enduring contributions. This paper overviews the unsteadiness present on-road, its effects, and the capabilities of different simulation tools.

The approach adopted is to present published research in terms of the scales investigated, helping to clarify the diversity of different works. This work seeks to place these various approaches together on the turbulence spectrum to highlight differences and similarities. Different works use different approaches (eg: yawing the flow, rotating the model

etc) and test properties of very different geometries and scales are included. While individual results will be specific to the geometry and approach, together these works provide guidance on the most important aspects of the unsteadiness to consider as part of the vehicle development process. With this in mind, the various simulation techniques are considered in terms of what they have to offer in the future.

CHARACTERIZATION OF ON-ROAD CONDITIONS

STEADY CROSS WINDS

The flow seen by a car on the road will be the vector combination of the natural wind and the reciprocal of the vehicle's velocity over the ground, as illustrated in [Figure 1](#). Different wind strengths and directions and different vehicle speeds result in a range of different yaw angles (and resultant velocities) seen by the vehicle. A typical yaw angle probability distribution for highway driving is illustrated in [figure 2](#).

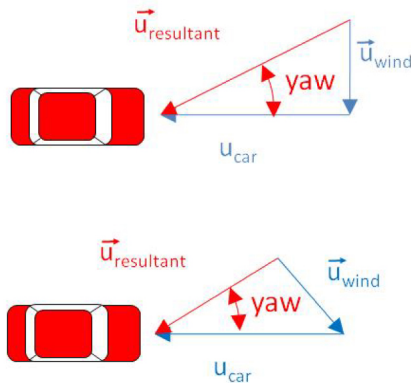


Figure 1. Vector combination of vehicle velocity and natural wind

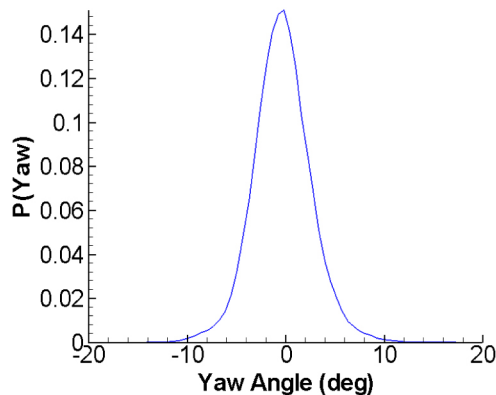


Figure 2. Yaw Angle Probability Distribution (from Lawson et al [2])

TIME VARYING FLOWS

The natural wind and the driving speed and direction will, of course, both be time-varying functions. The vector combination of [Figure 1](#) will therefore be time dependent, described by:

$$\frac{D\vec{u}_{resultant}}{Dt} = \frac{\partial \vec{u}_{car}}{\partial t} + \frac{\partial \vec{u}_{wind}}{\partial t} + \vec{u}_{car} \frac{\partial \vec{u}_{wind}}{\partial x} \quad (1)$$

The first term on the right hand side of [equation 1](#) represents the vehicle seeing transients due to changes in vehicle velocity. This term can dominate for race cars where driving speed is high compared to the natural wind and where vehicle speed varies rapidly over a wide range. For road cars however this term is generally negligible. The second term on the right hand side represents the temporal variation in the natural wind at a point fixed in space. Some early work on large scale turbulence impacting on cars often focused on this term, using knowledge of natural wind turbulence at a stationary point from wind engineering and completing a vector addition with a constant vehicle velocity. This term could also include the effect of unsteady wakes from other vehicles travelling at the same speed. The final term represents the car traversing through steady spatial variations in the natural wind, for example due to natural wind deficits behind road side obstacles, as illustrated in [Figure 3](#). While the spatial field may be steady in an absolute reference frame, the moving vehicle will experience it as a transient. This is generally the most important term for road vehicles and it can only be determined by making spatially distributed measurements, for example from a moving vehicle.

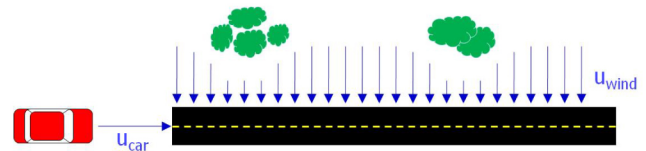


Figure 3. Illustration of vehicle experiencing time-variation due to traversing through a steady spatial variation in the natural wind

Previous reviews of the on-road environment include Howell [3] and Cooper and Watkins [4]. While the strongest focus of [4] was on atmospheric turbulence (ie: term 2 in [equation 1](#)), this paper highlights the importance of the wakes of stationary objects and other vehicles. The assessment of the transient conditions experienced by a moving vehicle was pioneered by Watkins [5] and, for example Watkins, Saunders and Hoffmann [6]. Similar assessments have been included in Lawson et al [7], [2], Lindener et al [8], Oettle et al [9] and Wojciak et al [10]. The definitive work is that of Wordley [11] including [12], [13]. Some of these studies sought to investigate the vehicle's aerodynamic or

aeroacoustic response to transients ([2], [7] and [8], [9] respectively) and hence needed a measurement of the onset flow without unduly disrupting the flow around the vehicle, this inevitably compromises the measurement of the onset conditions. The works of Wordley and Wojciak et al [10] benefitted by focused specifically on measuring the conditions experienced by the vehicle and hence placed the measurement instrumentation upstream of the vehicle approximately on the stagnation streamline, as shown in Figure 4.



Figure 4. Probes mounted upstream of the vehicle for on-road measurement of flow conditions (from Wordley [11])

Wordley [11] represents the conditions on-road through spectral bands. This communicates the wide range of different scales that the vehicle experiences and the variation in their levels between different weather, road and traffic conditions. Figure 5 illustrates his results for the transverse (cross-wind) velocity component. This is typical of natural wind spectra in that it shows a roll off at higher frequencies.

Wojciak et al [10] used a similar measurement approach but with a focus on individual extreme crosswind gust events. They suggest that considering gusts with scales of 2 m to 200 m would comfortably cover the important range for vehicles, with scales of 10 m to 80 m being of greatest relevance.

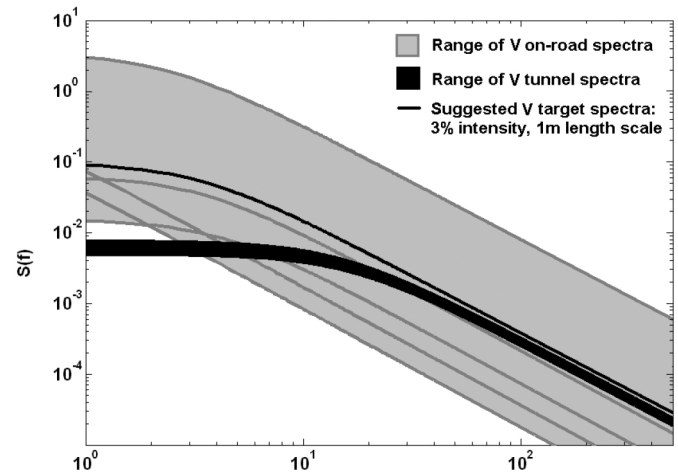


Figure 5. Cross-flow spectral range experiences on-road (from Wordley [11])

SIMULATION AND EFFECTS

Where changes in the onset flow occur sufficiently slowly the vehicle's aerodynamic response will be quasi-steady. For example, if yaw angle is changing sufficiently slowly then the side force at an instantaneous yaw angle of 10° will be indistinguishable from the side force at a steady yaw angle of 10° . As the yaw angle transient becomes faster, the flow around the car at a particular instantaneous yaw angle will differ increasingly from its steady state counterpart. The reduced frequency is often used to characterize the rate of change in a transient in a non-dimensional way (discussed, for example, in [14]). Reduced frequency is defined as:

$$K = \frac{\omega L}{u} = \frac{2\pi fL}{u} \quad (2)$$

$$K = \frac{2\pi L}{\lambda}$$

$$K = \frac{2\pi (\text{Time to Convect Length of Vehicle})}{\text{Turbulent Time Scale}}$$

where ω is angular frequency (rad/s), f is frequency (Hz), L is a characteristic dimension of the geometry (vehicle length is used throughout this paper), u is free-stream velocity and λ is the turbulence wavelength (length scale). Care is required as some works define reduced frequency to be exactly half of the value defined here. On occasion it is even defined simply based on frequency, dimension and velocity (more usually referred to as the Strouhal number). For this paper all values have been translated to the definition of equation 2 to allow comparison.

Reduced frequency as used here will always treat a cycle as 2π radians, irrespective of the yaw amplitude, although there

would be an argument for basing ω on the rate of change of yaw angle.

It is typically assumed that the flow will be quasi-steady for reduced frequencies less than 0.1 and that the flow will not be quasi-steady for reduced frequencies greater than 1.0. This is approximately equivalent to saying that transients with wavelengths of more than 60 vehicle lengths will allow the flow to fully develop at each instantaneous yaw angle but that if the wavelength is less than 6 vehicle lengths then the higher rate of change of the flow will mean that the instantaneous flow will not be the same as for the corresponding steady state condition. For a 4 m vehicle at 30 m/s this translates to the flow being expected to be quasi steady at time scales greater than about 8 s and it will not be quasi-steady for time scales less than 0.8 s. The aerodynamic response of smaller geometry elements on the vehicle will remain quasi-steady to shorter length and time scales. Obviously different geometries will behave differently and the precision of these rule-of-thumb values for the quasi-steady boundary should not be overstated; the 0.1-1.0 rule-of-thumb estimates the quasi-steady boundary only within an order of magnitude. Figure 6 illustrates these values superimposed on a spectrum of on-road conditions based on Wordley [11]. This figure illustrates the spectrum simultaneously in terms of frequency (the norm) but also the corresponding time scale and length scale (assuming a velocity of 30 m/s).

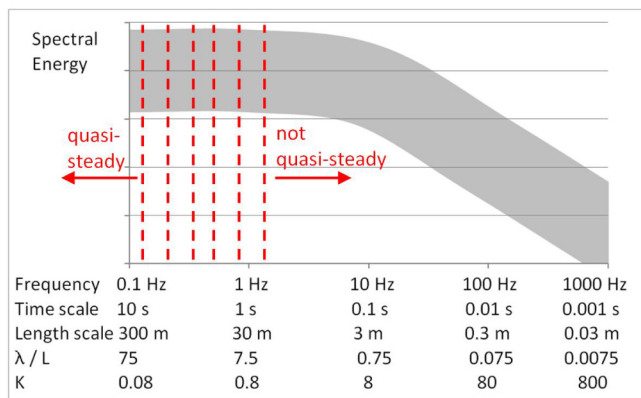


Figure 6. Expected bounds for quasi-steady flow superimposed on spectrum based on [11]

Care needs to be taken in comparing length scales reported from different sources. Calculation of length scale by different methods (autocorrelation vs Von Karman spectral fitting), with different low pass filtering and with different record lengths can yield different scales by a factor of two or more. A 20 Hz low pass filter and 20 s record length (0.05 Hz high pass filter) is recommended as a standard approach, in part as this seems to provide consistency between autocorrelation and Von Karman methods [15].

Care is also needed when comparing effects due to turbulent length scales quoted for broad-spectrum, statistically stationary, turbulence with length scales associated with those of isolated transient events or single harmonics. When autocorrelation or Von Karman scales are quoted these values represent a notional mean length scale where, in reality, many scales are present. The scale responsible for causing an observed aerodynamic effect could be an order of magnitude away from the “mean” length scale quoted.

Effects of unsteady aerodynamic excitation are often quantified by the aerodynamic admittance, defined at a particular frequency f as:

$$\chi^2(f) = \frac{S_C(f)}{\left(\frac{dC}{d\beta}\right)^2 S_\beta(f)}$$

where C represents an output variable (eg: yaw coefficient), β represents an input variable (i.e. yaw angle) and $S_C(f)$ and $S_\beta(f)$ represent the spectra of C and β respectively at frequency f . The derivative $\frac{dC}{d\beta}$ is based on steady state conditions and so the admittance should, by definition, tend to unity when f is zero. However, the results reported many researchers fail to demonstrate this. An admittance indistinguishable from unity is synonymous with a quasi-steady response. Admittance values greater than unity indicate that the transient vehicle response (eg: yawing moment) will exceed that expected from a quasi-steady analysis. The aerodynamic admittance and transfer function are closely related, the latter omitting the non-dimensionalisation to unity at $f = 0$ but, as a complex function, including phase as well as amplitude information. The transfer function can be defined as:

$$H(f) = \frac{\hat{C}(f)}{\hat{\beta}(f)}$$

where $\hat{C}(f)$ and $\hat{\beta}(f)$ represent the Fourier transforms of C and of β at frequency f .

STEADY CROSS WINDS

A quasi-steady aerodynamic response does not diminish the importance of the externally-imposed unsteady flow. The aerodynamic response of a vehicle to steady cross winds is evaluated routinely by yawing the vehicle in the wind tunnel or by CFD simulations at a range of steady yaw angles. It is possible to compute a “wind averaged” drag coefficient by combining the drag coefficients measured at different yaw angles weighted by the probability (frequency) of each yaw angle being experienced on the road. To be correct this approach must also consider the effect of different wind