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Cross Winds and Transients: Reality, Simulation and Effects

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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 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.

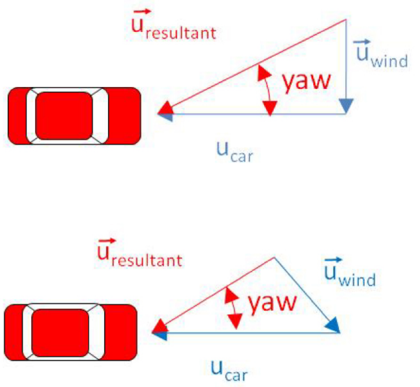

Figure 1. Vector combination of vehicle velocity and natural wind

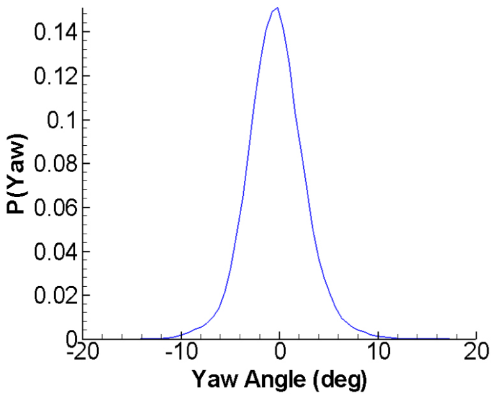

Figure 2. Yaw Angle Probability Distribution (from Lawson et al [2])

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:

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

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.

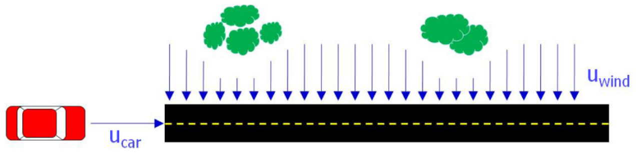

Figure 3. Illustration of vehicle experiencing time-variation due to traversing through a steady spatial variation in the natural wind

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.

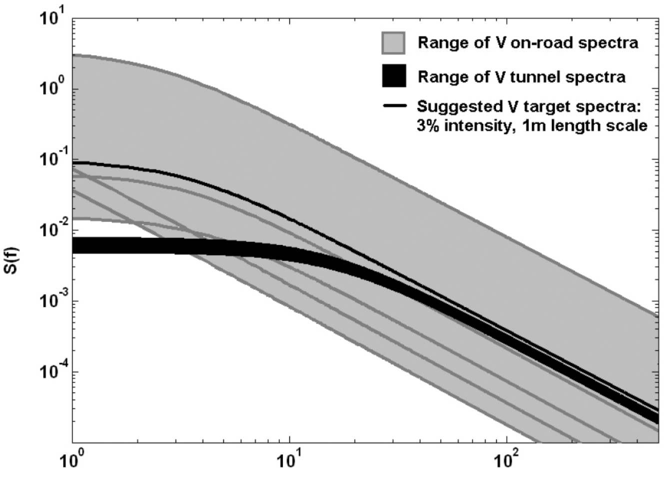

Figure 5. Cross-flow spectral range experiences on-road (from Wordley [11])

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:

$$K = \frac{\omega L}{u} = \frac{2\pi fL}{u} \tag{2}$$

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

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

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).

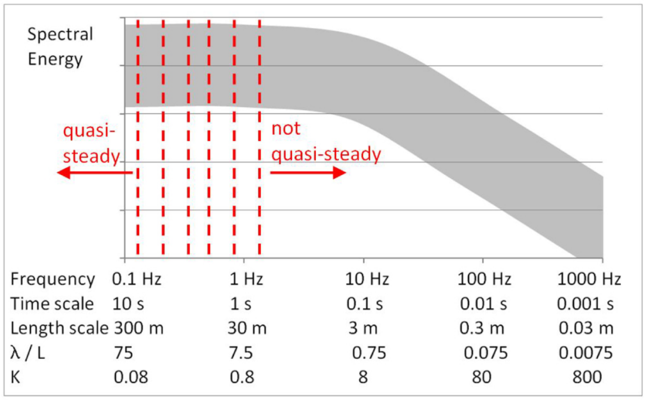

Figure 6. Expected bounds for quasi-steady flow superimposed on spectrum based on [11]

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 strengths and relative directions on the total resultant velocity.

Howell [16] provides a useful estimate of the unsteady loading (sideforce and lift) experience by a vehicle on the road by combining an idealized turbulent flow based on a standard von-Karman wind spectrum with a quasi-steady model of the vehicle response. While much of the work reviewed in the present paper involves trying to assess differences from the quasi-steady response it should be recognized that this quasi-steady analysis provides the baseline for everything else to compare to.

DYNAMIC ROTATION OF TEST PROPERTY

Several studies have dynamically rotated models or full size vehicles while collecting force or pressure data.

Garry and Cooper [17] undertook dynamic yaw sweeps from −40° to +40° using a turntable achieving yaw rates up to 64°/s. This yaw angle range is much larger than that of most other works presented here and so using the time period for the full yaw sweep would generate misleadingly large time and length scales. For comparison, this yaw rate would be equivalent to the peak yaw rate achieved for a ±6° harmonic yaw with a wavelength of 35 vehicle lengths. It is worth noting that, despite the high speed of this turntable, the reduced frequency remains quite low. The tangential velocity at the front of the small scale model used was only about 0.2 m/s or 1% of the free stream velocity. Perhaps surprisingly, significant differences were observed between the instantaneous measured forces compared with those measured under steady state conditions. The drag seemed to lag behind the instantaneous yaw angle such that it varied by ±10% above and below the steady value at the same yaw angle and the side force coefficients were between 0.2 and 0.4 above the steady state values at the same yaw angle. Different but not dissimilar results were obtained at yaw rates as low as 0.25°/s which is very surprising; the free stream flow would then travel some 8000 vehicle lengths within the time require for a ±6° harmonic yaw wavelength. Some similar tests at low yaw rates have shown similar trends [18] while others (eg: [19] - again at very low yaw rate: 2°/s) have shown close agreement with steady state values.

Mansor and Passmore [20], [21] and Baden-Fuller et al [19] used free vibration of the model in yaw using an oscillator rig with variable mechanical yaw stiffness to achieve oscillation frequencies corresponding to reduced frequencies generally between 0.15 and 1.5 [21]. In this work, the rate of change of yawing moment with yaw angle was observed to be amplified by around 20% in the dynamic case compared with the steady case. They showed in [20] that relatively simple geometry changes (adding c-pillar strakes) could be effective in reducing the dynamic yawing moment due to gusts.

Watkins et al [22] show that dynamic model rotation cannot allow the correct reproduction of the conditions experienced by a vehicle traversing a generic cross wind gust. Nevertheless this technique can be instructive in assessing the range of scales of importance.

ISOLATED EXTREME CROSS WINDS

Isolated, extreme transient cross-winds, coupled with the vehicle aerodynamic response, handling and driver reaction, pose a safely risk. This total system has been considered by Wagner and Wiedemann [23] and by Nakashima et al [24].

The traditional tool for evaluating the effect of this type of extreme cross wind is the track-side cross wind generator (see Goetz [25]). However, this approach is generally suitable only late in the development cycle. This approach also makes it difficult to separate the vehicle's aerodynamic response from the chassis dynamics and driver response. These issues have been addressed by a number of researchers using a similar approach but with a small scale model (1/8th or 1/10th) on a track traversing through a wind tunnel jet (eg: Stewart [26], Yoshida et al [27], Kobayashi and Yamada [28], Baker [29], [30], Kramer et al [31], Garry et al [32], Macklin et al [33]). Similar techniques have been used to simulate transient cross-winds for trains (eg: Cooper [34], Howell and Everitt [35], Baker [36]). Slightly apart from other studies in this group, Cooper [34] performed moving model tests in the open air, using the natural wind to provide continuous transients. This work introduces a range of techniques for the analysis of transient data including cross-correlations as well as admittance and spectral fitting. Other model translation techniques have been used, for example to represent the aerodynamic interaction between vehicles through a high-speed overtaking maneuver in a cross-wind (eg: Noger, Regardin, Széchényi [37]).

An alternative approach is the stationary model technique using a moving cross-wind gust produced by opening and closing a set of shutters in sequence (eg: Docton and Dominy [38], Ryan and Dominy [39]). This work showed transient overshoots in surface pressures and body forces when a simple model first enters the cross wind but once the model is immersed more than 7 model lengths in the transient cross wind gust the forces and surface pressures were equivalent to those seen in steady-state conditions. The transient “overshoots” indicate that a quasi-steady analysis would underpredict transient forces. The 7 vehicle length condition is illustrated in Figure 7 and equates to a quasi-steady limit at a reduced frequency of 0.9 which is consistent with the rule of thumb illustrated in Figure 6. A sharp-edged cross wind generator also exposes the vehicle to many high frequency components, although the reality is that the yaw rate will at the start of the cross wind will be softened by the shear layer at the edge of the gust. The estimated range of the scales simulated by a transient cross wind facility are illustrated in

Figure 7, extending into the quasi-steady region at the left hand side and down to length scales of a small number of meters towards the right hand side.

CFD offers the ability to simulate a range of different transient conditions. Recent work includes that of Tsubokura et al [40] and Nakashima et al [24], the former being a simulation of a transient cross wind and the latter extends this by coupling the vehicle dynamics. Gaylard et al [41] in an investigation related to hood flutter, included the simulation of different transient cross-wind conditions on detailed vehicle. Favre and Efraimsson [42] modeled an approximately trapezoidal gust and found that while side force and yawing moment developed quickly, the drag force did not reach a steady state within the 5 vehicle length long gust. Corin et al [43] modeled a vehicle overtaking situation.

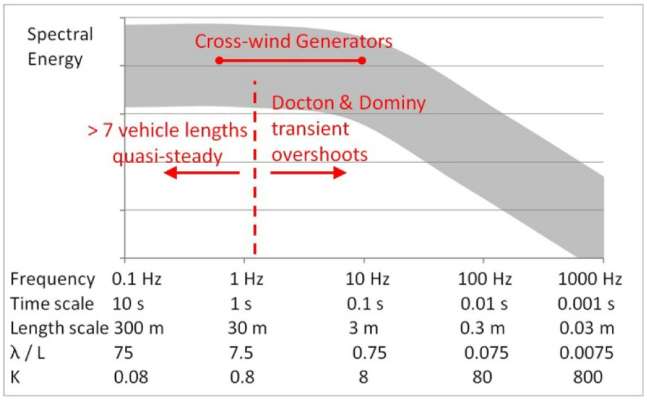

Figure 7. Illustration of Docton 's [44] 7 vehicle length limit for transient overshoots for a model traversing a cross wind gust

STATIONARY TURBULENCE - SMALL SCALES

For shorter turbulence scales it becomes appropriate to consider statistically-stationary turbulence, rather than individual isolated cross-wind events. The further classification “small scales” is used here to represent turbulence scales more relevant to the boundary layers over the vehicle than comparable to the scale of the vehicle itself. The wind tunnel simulation of these scales can be conveniently achieved through the use of passive turbulence generators in the form of coarse grids of bars upstream of the test section. Work of this type includes that of Cooper and Campbell [45], Wiedemann and Ewald [46], Wakins [5], Newnham [47], Howell et al [48] and many others. As reviewed by [48], the introduction of small scale free stream turbulence increases the turbulence inside vehicle boundary layers, producing a consequent delay in separations, for example. Therefore, increased free-stream turbulence can be used to produce a behavior akin to that at higher Reynolds number (eg: as illustrated in Figure 8 from [47]). However, as pointed out in that work, the flow structures (eg: separation) with increased free stream turbulence are not identical to those at increased Reynolds number.

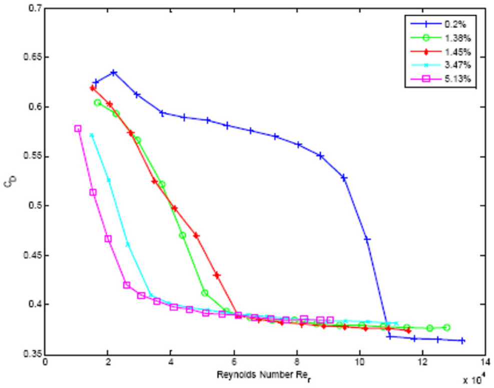

Figure 8. The combined effect of Reynolds number and free-stream turbulence on the drag of a simple body (reproduced from Newnham [47]

The traditional approach in vehicle-related work has been the use of uniform rectilinear grids, occasionally using individual large items to create longer scales (eg: Riegel et al [49]). Some work in other areas has explored the use of “Fractal Grids” to generate a broader turbulent spectrum by including many different scales within the grid (eg: Vassilicos [50]). All of these methods are based on the intrinsic unsteady wake produced behind the bluff elements and these structures will be on the same scale as the individual elements in the grid. These scales will typically be an order of magnitude smaller than the dimensions of the tunnel and model. Figure 9 approximately locates grid generated turbulence within the spectrum of turbulence seen on road. This assumes that the tunnel is sized based on the test property; it is possible to shift the effective range of grid generated turbulence to the left by an order of magnitude by testing a 1/10th scale model in a tunnel sized for a full scale vehicle (similar to [5]).

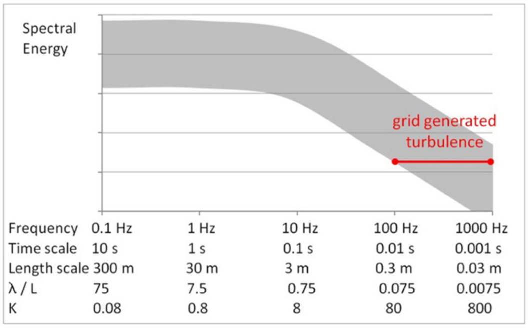

Figure 9. Illustration of approximate scales and effects produced by grid-generated turbulence (scaled to full size)

STATIONARY TURBULENCE - CENTRAL SCALES

The central turbulence scales are of greatest current interest for road vehicle applications and are the most challenging. The term “central scales” is introduced here to represent turbulence scales of approximately the same order of magnitude as the vehicle itself. The work of Wordley [11] shows that while the level of unsteadiness is beginning to roll off at these scales it remains relatively high, suggesting that this is a region of both importance and complexity in terms of the on-road environment. A number of works highlight scales around the 0.2 Hz to 2 Hz region (4 - 40 vehicle lengths) as being of crucial importance (eg: Goetz [25], Watkins and Saunders [51], Riegel et al [49], Passmore and Mansor [20]). At least some of this range of scales are too small (too short in duration) for the vehicle response to be quasi-steady and thus the vehicle response can only be determined by subjecting it to an unsteady onset flow. However, these scales are too large for practical creation with passive bars and grids (ie: except by testing a small scale model in a very large tunnel). Therefore the preferred approach for the experimental evaluation of a vehicle's response to these central scales is to use an active turbulence generator, namely, a device with moving aerodynamic components. Active turbulence generators can be classified as either drag or lift devices (Mankowski [52]).

The term “drag devices” is used to represent devices that generate turbulence in the wake of bluff bodies and hence share similarities with the use of passive grids or upstream bluff shapes, but modify the turbulence by dynamically changing the geometry. Kobayashi and Hatanaka [53], for example, used a system with a moving grid, as well as stationary meshes, to provide an active gust generator, as illustrated in Figure 10. The well known turbulence generator system in the Pininfarina facility, described by Cogotti [54], is principally a drag device with the geometry of the bluff bodies being varied. While drag devices can produce longitudinal scales at the frequency of operation, they simultaneously produce shorter scales from unsteady flow over the bluff geometries. In the Pininfarina TGS (Figure 11) some modes of operation can be used to generate lateral turbulence (Carlino et al [55]) with wavelengths equivalent to approximately 12-100 vehicle lengths. That work reported dynamic yawing moments at particular conditions which were almost 40% greater than would be predicted by quasi-steady theory. This facility has also shown effects on time-averaged vehicle drag at higher reduced frequencies ($K > 10$, length scale equivalent to less than one vehicle length) [15].

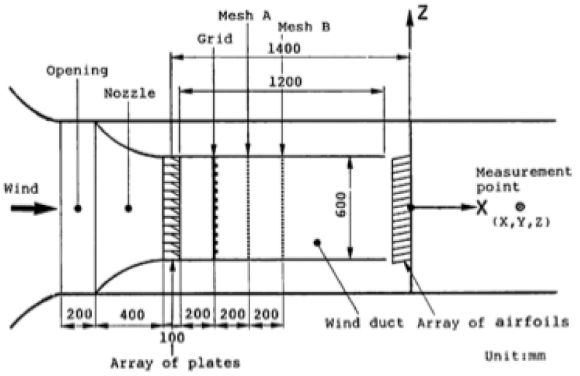

Figure 10. The active turbulence generator of Kobayashi and Hatanaka [53]

Figure 11. Pininfarina turbulence generation system (TGS) upstream of the contraction (from Cogotti [54])

Lift-based active turbulence generation devices generate turbulence through the use of moving lifting surfaces, (eg: aerofoils). In most cases related to vehicles the “lifting” surfaces turn the flow in the transverse (cross flow) direction (see Figure 12 from [56]). This technique has been employed by Gustafson et al [57], Mullarkey [58], [59], Passmore et al [60] and Schröck et al [56]. The system of Knebel, Kittel and Peinke [61] is primarily a lift-based device but the elements may be deflected beyond stall into a drag region.

This approach allows the most direct control of the turbulence generated, the amplitude of aerofoil oscillation controls the turbulence intensity; the frequency of the oscillation controls the turbulent time scale (and hence length scale). With this technique the smaller scales are the most challenging as the devices must move at the frequency desired of the turbulence - which leads to high inertial loads from reciprocating components.

Bearman and Mullarkey [59] tested at wavelengths between approximately 0.5 and 5 vehicle lengths and found aerodynamic admittance values between 0.6 and 1, indicating that the transient forces were smaller than would be predicted by a quasi-steady analysis. Surprisingly, their values of admittance at the longest wavelengths were the furthest from their steady state results.

Schrock et al [56] achieved wavelengths from approximately one vehicle length upward and similarly found aerodynamic admittance values generally below unity but including values up to 1.2 at wavelengths of around 5 vehicle lengths (corresponding to transient forces larger than would be predicted by a quasi-steady analysis). For wavelengths above about 12 vehicle lengths the vehicle response was approximately quasi-steady.

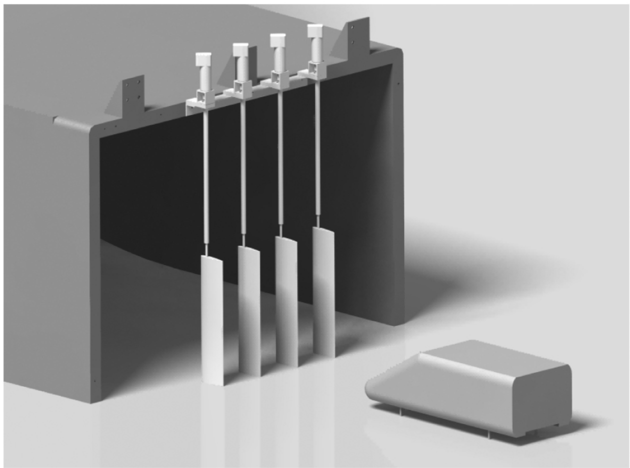

Figure 12. FKFS lift-based turbulence generation system (from Schröck et al [56])

Passmore et al [60] tested at wavelengths between about 4 and 40 vehicle lengths and reported that transient side force was lower than would be predicted by a quasi-steady analysis but that transient yawing moment was higher by up to 30%. They report non-quasi-steady effects for gust wavelengths up to and beyond 35 car lengths (*K* down to 0.18).

Figure 13 illustrates the scales reported by several researchers using active turbulence generation systems of both lift and drag types. Some of their key observations are also included.

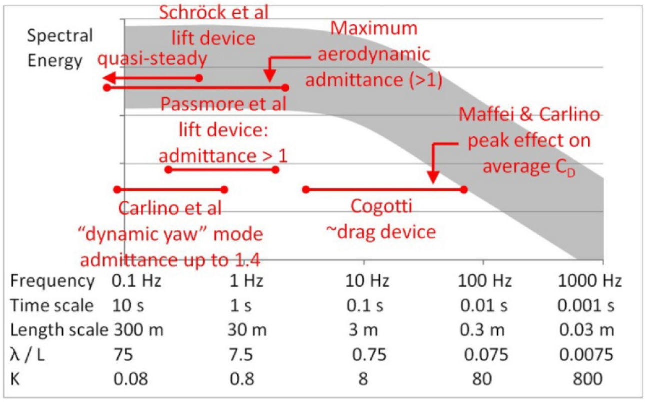

Figure 13. Scales and effects from active turbulence generation systems ([15], [54], [55], [60], [56]) - scaled to full size, 30 m/s

DISCUSSION AND CONCLUSIONS

The on-road wind environment includes a very wide range of conditions. On-road turbulence may stem from vehicle velocity changes, natural wind turbulence and traversing through a steady spatial wind distribution produced by road side-obstacles. For road vehicles this last term is of greatest significance.

This work seeks to characterize the environment and consider the effects on vehicles by considering the scales (wavelengths) of the turbulence relative to the length of the vehicle and by placing different works together on the spectrum for clear comparison. Some care is needed in the use of mean turbulence length scales as these hide the spectral breadth and because their calculation can be sensitive to the details of the method used.

The on-road spectral energy begins to roll off at a few Hz, corresponding to wavelengths of a few vehicle lengths. Scales of 2-20 vehicle lengths are generally seen as the most critical for four reasons:

1. There is a significant amount of on-road spectral energy at these scales.

2. These frequencies are high enough that the vehicle response will not be accurately represented by a quasi-steady analysis. Assessment of the vehicle response therefore requires some form of transient simulation.

3. Fluctuations at these scales generate significant unsteady forces on the vehicle (the aerodynamic admittance is relatively high, often exceeding unity).

4. The frequencies associated with these scales bracket the suspension natural frequency and are important to vehicle dynamics and handling.

Over the most important range of scales, different works show admittance both above and below unity, ranging from

0.6 to 1.4. This indicates that transient loads may be larger or smaller than would be predicted by a quasi-steady analysis by about 20%. Different geometries have been shown to exhibit different dynamic aerodynamic responses and this might explain the differences in the results of different researchers. This indicates that the aerodynamic design of the vehicle affects its sensitivity to transients.

Quasi-steady behavior, characterized by an aerodynamic admittance of unity, should be appropriate for unsteady wavelengths greater than between 6 and 60 vehicle lengths (K>0.1-1.0). In all cases the admittance should go to unity as frequency goes to zero. While the results of many works are consistent with this approximate quasi-steady boundary, many show non-unity admittance at all frequencies evaluated. In particular, some dynamic turntable tests show surprising non-quasi-steady behavior at very long wavelengths.

A key consideration for future work is the suitability of different methods for simulating transients. Passive grids are unable to practically produce turbulence at the most important scales. Active turbulence generation systems are therefore required. Lift-based TGS devices are probably best suited to producing the most important scales, although this is also achieved by transient crosswind simulators. Active drag devices are attractive for producing shorter scales than these but at low operation frequency they begin to behave like passive devices, with the flow dominated by the unsteady bluff body wakes.

While the focus of this work has been on experimental approaches, it should be noted that CFD simulations are able to resolve the range of scales of interest (in terms of computational time-step and total time simulated). The introduction of specific transient boundary conditions in a wind tunnel poses significant challenges but arbitrary, time-varying boundary conditions pose little added complexity for a time-resolved CFD simulation.

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DEFINITIONS/ABBREVIATIONS

C	Output Coefficient (eg: yaw coefficient)
$\hat{C}(f)$	Fourier transform of C at frequency f
f	Frequency (Hz)
$H(f)$	Transfer function at frequency f
L	Vehicle Length (characteristic dimension)
$S_C(f)$	Spectrum (autospectral density) of C at f
$S_\beta(f)$	Spectrum (autospectral density) of β at f
t	Time (s)

u
Velocity (m/s)

x
Position (m)

β
Input variable (eg: yaw angle)

$\hat{\beta}(f)$
Fourier transform of β at frequency f

λ
Turbulence wavelength (length scale)

χ^2
Aerodynamic Admittance

ω
Angular Frequency (rad/s)

CFD
Computational Fluid Dynamics

TGS
Turbulence Generation System

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