

A Wind Tunnel Simulation Facility for On-Road Transients

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ABSTRACT

This paper outlines the creation of a facility for simulating on-road transients in a model scale, $\frac{3}{4}$ open jet, wind tunnel.

Aerodynamic transients experienced on-road can be important in relation to a number of attributes including vehicle handling and aeroacoustics. The objective is to develop vehicles which are robust to the range of conditions that they will experience. In general it is cross wind transients that are of greatest significance for road vehicles. On-road transients include a range of length scales but the most important scales are in the in the 2-20 vehicle length range where there are significant levels of unsteadiness experienced, the admittance is likely to be high, and the reduced frequencies are in a band where a dynamic test is required to correctly determine vehicle response.

Based on measurements of on-road conditions, the aim was for the turbulence generation system to achieve yaw angles up to $6-8^\circ$, equating to a lateral turbulence intensity of 8-10% with a frequency range extending up to 10 Hz. In a wind tunnel, the generation of scales larger than the scale of the vehicle is impractical with passive grids and so an active turbulence generation system is required. The system includes a pair of vertical airfoils at the upstream end of the test section. The yawing of the wind tunnel jet requires correct handling at the downstream end of the test section and hence additional outlets were incorporated with cascading shutters to control collector width and effective location. Similarly, additional, shuttered, inlets were incorporated at the upstream end of the test section. The maximum steady state yaw angle range achieved was $\pm 8^\circ$ steady state, extending to $\pm 11^\circ$ in dynamic operation. The turbulence generation system can be programmed to reproduce specific events as measured on-road, with time appropriately scaled for model testing.

Tests with a vehicle model validated that the turbulence generation system operating in a steady state mode results in the same steady forces as achieved yawing the model on a turntable. The system's ability to model specific on-road conditions was also demonstrated.

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1. INTRODUCTION

This paper outlines the creation of a facility for simulating on-road transients in the Durham University 2m wind tunnel. The Introduction outlines the rationale behind the approach; the design of the system is then presented along with first results from commissioning and vehicle testing.

1.1 The On-Road Environment

A vehicle on the road experiences an externally-imposed unsteady flow. To date the largest original source on the topic is Wordley [1], essentially incorporating [2] and [3]. Recent reviews include Sims-Williams [4] and Cooper and Watkins [5].

The sources of unsteadiness include turbulence in the natural wind and the unsteady wakes of other vehicles and these sources were often the focus of early studies. However,

probably the most important source of unsteadiness experienced by the vehicle derives from the vehicle traversing through spatial non-uniformities in the natural wind, typically generated by the combination of a cross wind and roadside furniture (obstacles). This places a particular emphasis on cross-wind transients which impact both yaw angle and resultant velocity.

Of critical importance to the simulation of unsteady on-road conditions is an understanding of the range of conditions to simulate. [Figure 1](#) illustrates the probability distribution of yaw angle and resultant velocity measured on-road from Oettle [6]. Other sources show a similar distribution of yaw angle, with an approximately normal distribution and with yaw angle generally less than $\pm 10^\circ$.

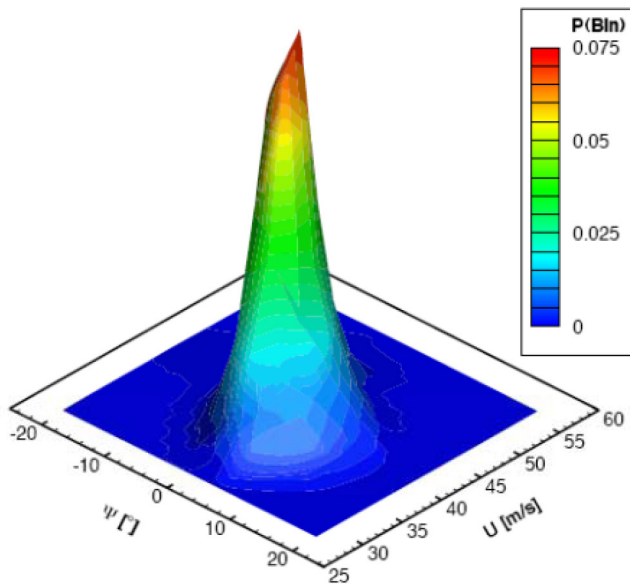


Figure 1. Probability distribution of yaw angle and resultant velocity experienced on road, from [6]

Wordley [1] reports lateral turbulence intensities principally between 2% and 10% according to terrain and traffic conditions. This essentially translates to yaw angles of up to 6-8°. Figure 2 illustrates the spectral range of the cross wind component of velocity experienced on-road for a vehicle travelling at highway speeds, from [1]. This illustrates that the amount of energy on-road rolls off at frequencies above a few Hz.

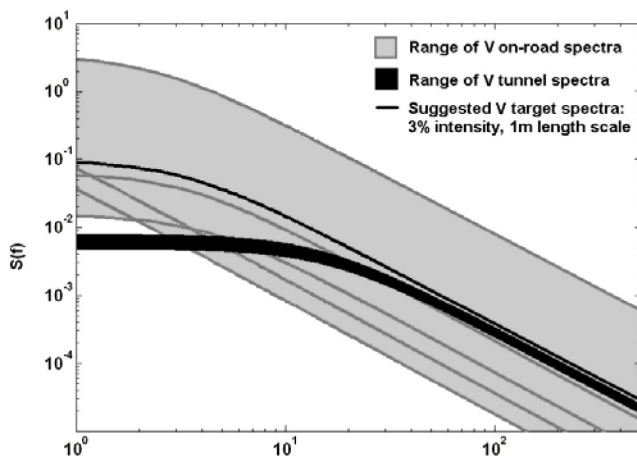


Figure 2. Lateral velocity spectrum experienced on-road, from Wordley [1]

1.2 Aerodynamic Response to Unsteady Flow

On road unsteadiness is important for road vehicles only if it impacts something that the customer cares about. For example handling (e.g.: as investigated by [7], [8], [9], [10]) or cabin noise (e.g.: [11], [12], [13]). This depends on a combination of the onset unsteadiness experienced on-road and the vehicle's response to that unsteadiness.

Aerodynamic response is commonly characterized by a transfer or admittance function which describes the response relative to the input excitation as a function of frequency.

In general, for low frequencies (below perhaps 0.1-1 Hz) the vehicle response will be quasi-steady. The unsteadiness in this frequency range has a good chance of being important but if the response is quasi-steady then it can be adequately assessed using steady-state techniques, for example testing at a range of yaw on a turntable and then calculating the resulting vehicle side force and yawing moment on road using a knowledge of the range of conditions to be experienced. Oettle et al [14] illustrates this approach.

For high frequencies (>5-10Hz) the magnitude of the admittance or transfer function will reduce as these small unsteady scales have a decreasing impact on the overall vehicle's aerodynamics. This is illustrated in Figure 3, from Schröck et al [15], which shows the admittance function for sideforce in response to yaw for an idealized vehicle model (SAE body). The right hand side of the figure corresponds to a frequency of 2.7 Hz for a full size vehicle driving at high speed. In this particular case the admittance has dropped almost to zero at this frequency.

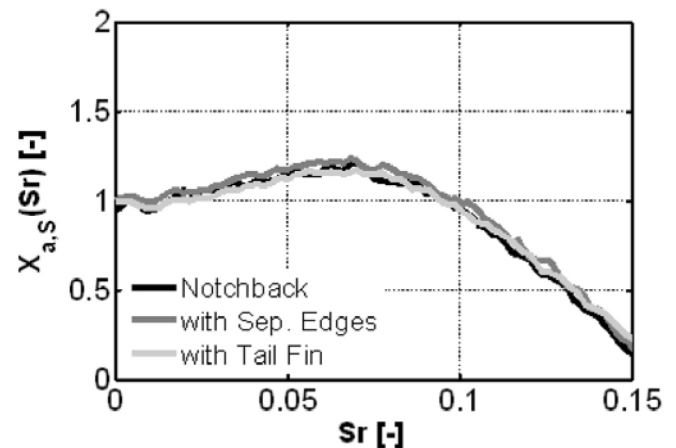


Figure 3. Admittance function for impact of transient yaw on sideforce, from [15]

1.3 Requirements for a Wind Tunnel Simulation of Unsteady Flow

Considering both the range of unsteady conditions experienced on road and previous work on aerodynamic response to unsteady onset conditions makes it possible to identify the range of conditions to simulate using a time-varying methodology such as a wind tunnel turbulence generation system.

Firstly, the cross flow direction is of greatest interest in terms of an unsteady simulation. Simulating yaw angles up to 6-8° is appropriate, corresponding to lateral turbulence intensity of up to 8-10%. A frequency range from perhaps 0.1-0.5Hz up to 5-10Hz is appropriate. At lower frequencies a quasi-steady approach can remove the need for dynamic yaw simulation and at higher frequencies both the amount of energy present

on road and the vehicle sensitivity reduce. It is worth noting that this frequency range encompasses typical vehicle suspension eigenfrequencies (~ 1 Hz) and the noise modulation frequency which humans are most sensitive to (~ 4 Hz - Fastl and Zwicker [16]). On-road turbulence frequencies, and those to be simulated here, span multiple orders of magnitude. On-road this is generally broadband but it is also of interest to be able to simulate discrete frequencies in order to build up an understanding of vehicle response.

1.4 Previous Wind Tunnel Simulation of Unsteady Flow

Turbulence generation in a wind tunnel can be classified into passive and active devices and they can be separately classified as drag-based or lift-based devices. Drag-based devices create unsteadiness as a result of the unsteady separated flow off a bluff body (usually an array of bluff bodies). Essentially all passive devices operate on this methodology. Active devices may be drag-based or lift-based devices. Turbulence generation techniques were reviewed by Watkins and Cooper [17]; a few important examples will be discussed here.

1.4.1 Passive Devices

In many fields, such as wind engineering and turbomachinery aerodynamics, it is possible to generate appropriate turbulent scales using grids or other arrays of bluff shapes upstream of the test section and this approach has also been used for road vehicle aerodynamics however, the turbulent scales required to represent on-road unsteady flows are much larger, in general larger than the vehicle. The generation of scales larger than the scale of the test property is generally impractical with passive grids and so it is generally recognized that some form of active system is required.

1.4.2 Active Drag-Based (Bluff) Devices

Oscillating grids have been employed by Cooper [18] and by Kobayashi et al [19] as a means of achieving longer turbulence length scales than would be achievable with a purely passive device. Cooper shows that these longer scales were in addition to the short length scales that would be generated by the same grid in a passive mode.

The turbulence generation system installed in the Pininfarina wind tunnel (Figure 4), Cogotti [20], [21] is essentially a drag-based (bluff) active device. Varying the width of the bluff spires has some impact on the unsteady scales generated and controlling the relative phasing of the opening and closing of the different spires can even provide an overall dynamic yaw (Carlino [22]). For all drag based devices it is generally difficult to achieve the lower frequencies of interest preferentially over higher frequencies.

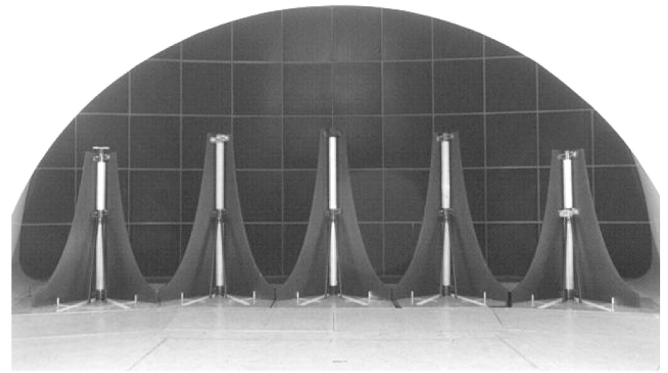


Figure 4. Pininfarina Turbulence Generation System Upstream of the Contraction, from Cogotti [21].

1.4.3 Active Lift-Based Devices

The device Knebel et al [23] is an active array of plates that can be instantaneously operating in either drag or lift mode and while it is not targeted at vehicle aerodynamics or the generation of large yaw angles it is a recent piece of work that offers some good insight.

Active lift-based devices, typically vertical oscillating airfoils at the upstream end of the test section, make it possible to achieve long length scales (associated with the timescale of the aerofoil motion) without simultaneously generating shorter scales associated with the unsteady wake of a bluff body. This approach has previously been explored by Bearman and Mullarkey [24], Passmore et al [25] and Schröck et al [15] [26]. The former studies used a pair of airfoils upstream and outboard of the model and harmonic motion of the airfoils. Schröck's facility (Figure 5) incorporated non-harmonic motion of the airfoils and used 4 airfoils upstream of the model.

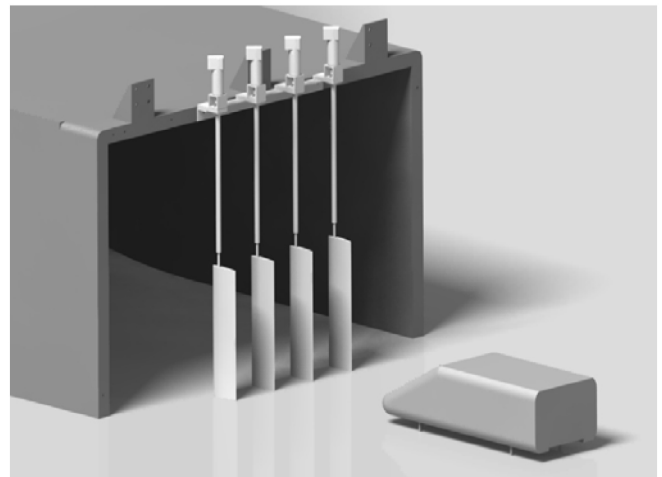


Figure 5. Turbulence generation system from Schrock et al [26]