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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, ¾ 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°, 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 ±8° steady state, extending to ±11° 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 ±10°.

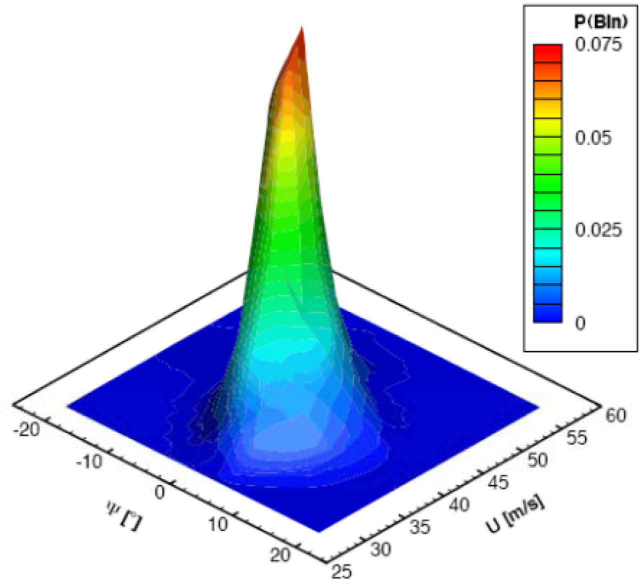

Figure 1. Probability distribution of yaw angle and resultant velocity experienced on road, from [6]

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.

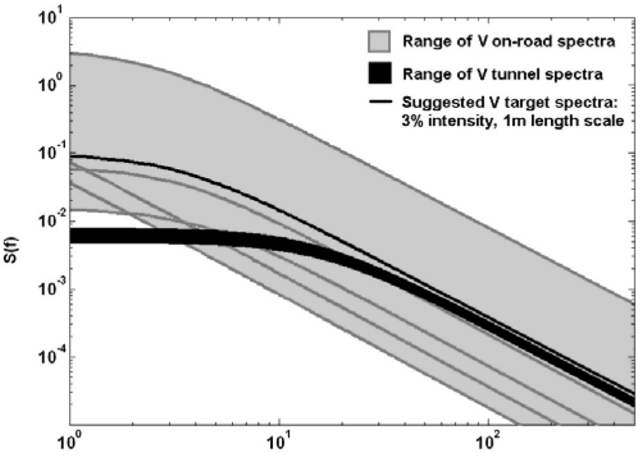

Figure 2. Lateral velocity spectrum experienced on-road, from Wordley [1]

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.

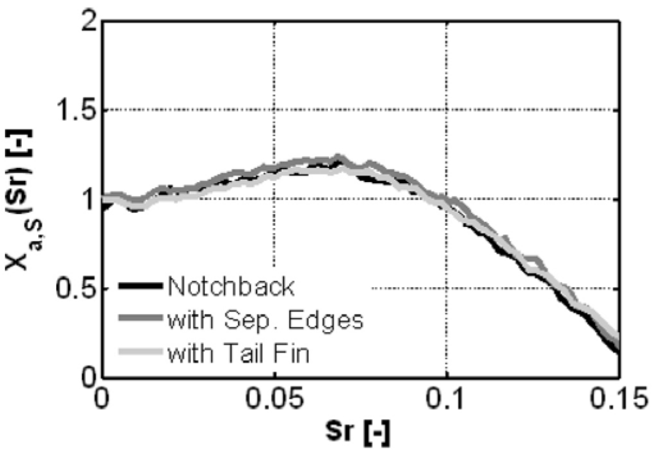

Figure 3. Admittance function for impact of transient yaw on sideforce, from [15]

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 be 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.

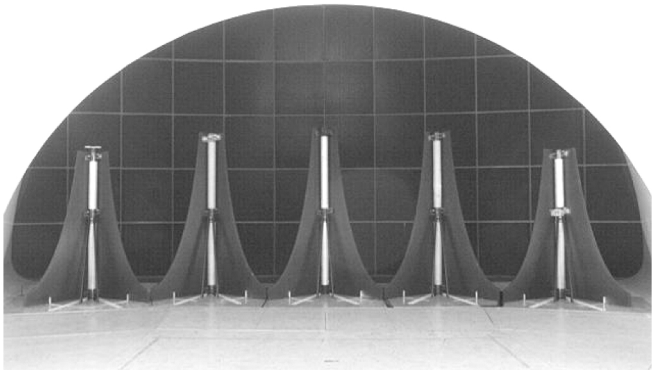

Figure 4. Pininfarina Turbulence Generation System Upstream of the Contraction, from Cogotti [21].

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.

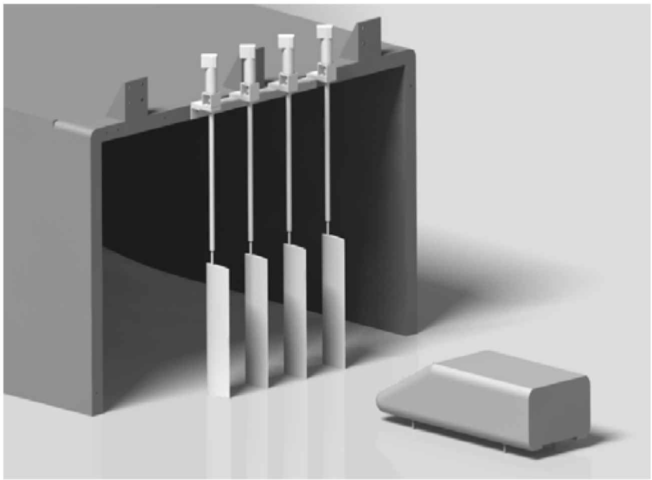

Figure 5. Turbulence generation system from Schrock et al [26]

2. TURBULENCE GENERATION SYSTEM DESIGN AND IMPLEMENTATION

The turbulence generation system was to be installed in the Durham University 2m Wind Tunnel. This is ¾ open jet, open return (Eiffel) wind tunnel with a nozzle area of 2m^2. The tunnel operates either with a wide-belt moving ground with the model supported from overhead, or in fixed ground with turntable and balance below the test section floor. Further details of the facility are available in [27], [28].

2.1 Aerodynamic Design

Following the analysis of the introduction, the turbulence generation system was designed to achieve yaw angles up to 6-8°, equating to a lateral turbulence intensity of 8-10%. The frequency range was to extend up to 10 Hz.

2.1.1 Aerofoil

It was desired to be able to completely control the turbulence impacting on the vehicle and so a lift-based design was adopted, based principally on vertical airfoils at the upstream end of the test section. This lift-based approach essentially avoids the mix of higher unsteady frequencies generated by bluff shapes. Contrasting with previous designs, it was considered desirable to avoid wakes from the devices impinging on the model in order to avoid any risk of specific interactions between an aerofoil wake and a sensitive region on a detailed model. Connected with this, it was considered important to minimize the transition time between conventional tunnel operation and operation in TGS mode and so being able to keep the airfoils permanently installed was preferable. It would be unacceptable to have aerofoil wakes impinging on the model in routine, steady-state, operation of the wind tunnel. Ultimately it was possible to use a pair of airfoils at the periphery of the jet, with the airfoils effectively providing a continuation of the walls of the wind tunnel contraction. Aerofoil sizing and the required angle range was selected with the aid of CFD simulations using Exa PowerFLOW, with the aerofoil unsteady motion modeled using rotating mesh zones. The final design incorporates an aerofoil chord of 600 mm and an angle range of ±15°. Figure 6 illustrates the PowerFLOW simulation domain including the measurement volume around the model installation location. These simulations were also used to predict aerodynamic loads on the airfoils under static and dynamic operation conditions, to aid in the mechanical design of the system.

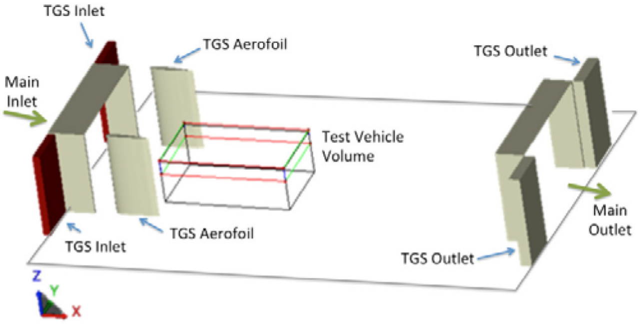

Figure 6. PowerFLOW Simulation Domain showing candidate design with airfoils for yaw angle control.

2.1.2 Shuttered TGS Outlets

The yawing of the whole wind tunnel jet really requires correct handling at the downstream end of the test section. The Durham tunnel has a relatively long non-dimensional test section length (~4 jet hydraulic diameters) which makes the lateral jet deflection at the end of the test section particularly significant. Hence additional, controllable, outlets were incorporated to control collector width and effective location. The locations of these outlets are labeled in Figure 6. Each of these outlets is closed by a set of 4 shutters. These are controlled individually to open/close in a cascade as the jet is deflected. The shutters open to a set angle which is designed to capture and turn the yawed flow. The additional TGS outlets lead to their own diffusers that ultimately feed into the main wind tunnel fans, with the flows mixing after being diffused to low velocity in order to minimize mixing losses. When the tunnel is operated in conventional (non-TGS) mode, the shutters at the test section outlet are all closed and the downstream end of the associated TGS diffusers is also closed using an actuated door between the ducts. This allows an uncompromised wind tunnel diffuser geometry during conventional operation.

2.1.3 Shuttered TGS Inlets

As the jet deflects, the distance between the shear layer edge and the model would be reduced; this is an issue in particular at the rear corners of the model. While the model would remain inside the jet under the full range of yaw angles the proximity to the jet edge would be a concern. Also, the deflected jet would not fill the width of the collector. Therefore additional, shuttered, inlets were incorporated at the upstream end of the test section, as labeled in Figure 6. The 5 shutters on the appropriate side open in a cascade as yaw increases, with the shutters set to open to an appropriate angle. Figure 7 schematically illustrates the flows from the main nozzle and additional inlet to the main collector and additional outlet. Note that this figure illustrates a steady state viewpoint. In dynamic operation there is an increasing phase difference between the flow at the upstream and downstream ends of the test section and the shutter operation is programmed accordingly. At the highest frequencies of operation two complete cycles are present within the length of the test section.

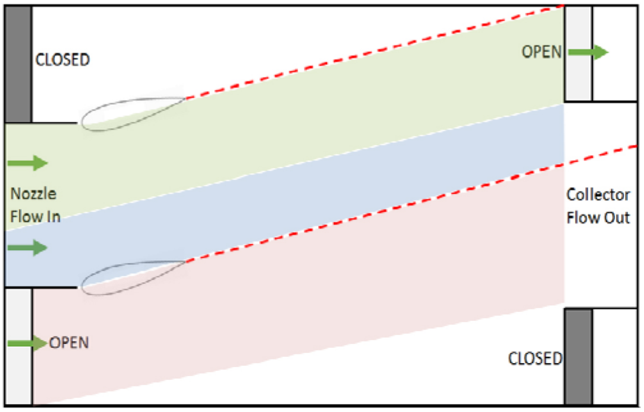

Figure 7. Schematic illustration of the use of shuttered inlet at outlet at extreme yaw (not to scale).

The Eiffel configuration of the tunnel means that the inlets can be simply fed from their own trumpet-style inlets and then provide a stagnation pressure matching that of the main tunnel flow. When the tunnel is operated in conventional, non-TGS mode the shutters are closed and an airtight seal is applied across the trumpet inlet as shown in Figure 8.

Figure 8. TGS Inlet trumpet sealed shut for conventional operation of wind tunnel without TGS.

2.1.4 Vertical and Longitudinal Turbulent Components

While the lateral (yaw) component was the unsteady component of primary interest, the control of vertical and longitudinal components was also incorporated into the system design. As a research facility at model scale, an aim of the work overall is to provide a facility to research the merits of different features and capabilities.

A vertical unsteady component can be introduced by a horizontal aerofoil at the test section inlet across the top of the inlet flow. As for the other components, this aerofoil has an a total angle range of 30°.

Longitudinal unsteady components can be introduced by a set of shutters within the throat of the main collector. Normally these would be in an open position but by dynamically closing them it is possible to dynamically throttle the tunnel.

These additional controls were incorporated in part as a contingency that could be used to control any unwanted artifacts that might occur during dynamic yaw (e.g.: unwanted fluctuations in longitudinal velocity) but they have not been required in this capacity.

2.2 Implementation

While the system aerodynamic specification and design was undertaken principally as a PhD project within Durham University, Labman Automation acted as main contractor for the electro-mechanical design, manufacture and installation of the turbulence generation system, including writing the control software.

To minimize tunnel downtime for installation, the system was built on a test frame and undertook the first round of acceptance tests offsite. Following sign-off, the system was broken down into sub-assemblies for transport, was installed in the tunnel and then performed the final acceptance tests.

The most significant loads within the system originate from acceleration forces on the moving aerodynamic components, in particular the main airfoils and hence the airfoils and all shutters were manufactured in carbon fiber.

The airfoils are operated by servo-motors through a crank arrangement, illustrated in Figure 9. Each aerofoil is driven by two servo motors and associated cranks. This allows harmonic motion of the aerofoil with the motors rotating continuously. Varying the phase of the two motors makes it possible to achieve continuously variable amplitude of aerofoil motion and this can be varied in operation. Operating the motors in this mode means that the frequency of aerofoil oscillation is unaffected by motor rotor inertia. Operating in this mode allows operation at up to 10 Hz with aerofoil amplitude continuously variable up to ±15°.

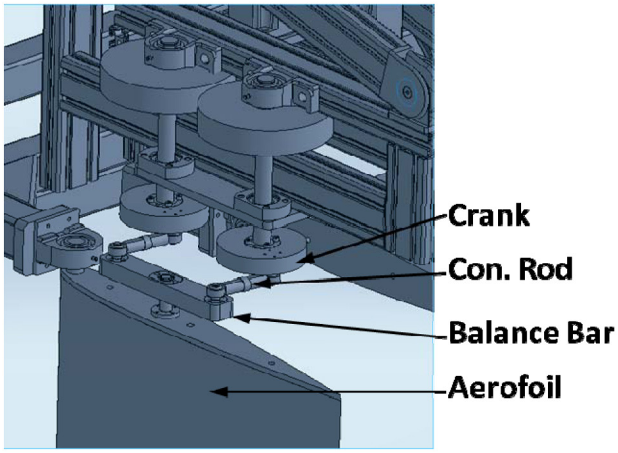

Figure 9. Crank arrangement operating dynamic yaw aerofoil.

Mankowski et al [29] showed that non-linearities in bluff body response mean that it is not sufficient to consider yaw harmonics individually and independently. Therefore incorporating programmed non-harmonic motion was important in the specification and implementation of the system. The system can be operated with the servo motors providing a programmed motion, undertaking partial revolutions, and the ability to achieve programmed non-harmonic motions.

The cascading shutters controlling the additional TGS inlets and outlets and the shutters in the collector throat providing dynamic throttling are all controlled by rotary solenoids. Each of the 22 shutters can be controlled individually, although in general each is programmed to open and close at a predefined yaw angle, with an additionally programmed time delay between the yaw angle at test section inlet and the actuation of the shutters at test section outlet. This allows for the propagation of yawed flow from the inlet to the outlet of the test section. The achieved shutter opening/closing time is less than 30 ms.

The wind tunnel shutdown for the installation of the TGS and its associated systems provided an opportunity to undertake other improvements. Inverter drives, motors and fans have been up-rated, making it possible to maintain or increase tunnel velocity despite the increased jet width with TGS inlets open.

3. COMMISSIONING

3.1 Empty Test Section

Commissioning focused on measurements of the steady and time-varying flow in the empty test section using a pressure probe on the wind tunnel's gantry probe traverse. Measurements were made at the location of the centre of a hypothetical model in the test section, as well as at the nominal corner locations of a 40% scale model. The probe used was a selective laser sintered 5-hole probe (shown in Figure 10) which has an acceptance angle range of ±50° in pitch and yaw angle and dynamic response exceeding 100 Hz, achieved through transfer function correction (as described in [30], [31], [32]).

Figure 10. SLS Stainless 5 Hole Probe

Initial steady-flow tests at a range of aerofoil angles and configurations of open and closed shutters determined which shutters to have open for each yaw angle in order to achieve the best uniformity across the area occupied by the model. The maximum steady state yaw angle range was ±8° with uniformity better than 0.5°. Vertical velocity components corresponding to pitch angles of −5° to +2° were achieved at the nominal model centre position; but obviously pitch angle range in ground proximity strongly depends on the distance from the ground.

For dynamic operation the range of parameters to set is extensive, as each shutter opening can depend on both the instantaneous aerofoil (yaw) angle, operation frequency and tunnel velocity. It was confirmed that opening the inlet shutters could be based on aerofoil angle and opening the outlet shutters could be based on aerofoil angle with a time delay corresponding to test section length divided by test section axial velocity. Under harmonic operation it was possible to achieve slightly larger instantaneous yaw angles than for steady operation, up to ±11° at the highest frequencies.

As discussed, the ability to achieve non-harmonic dynamic conditions was seen as an important capability. An example time-trace measured from a vehicle driving on the road on a moderately windy day was selected as a test case. The turbulence generation system was programmed to reproduce the same yaw vs. time trace. For the unsteady flow in the tunnel it is necessary to scale time according to test section velocity and model scale. In this case this resulted in time being shortened by a factor of approximately 2 (so that 32s on-road scales to 15s in the wind tunnel). With a small number of iterations it was possible to achieve conditions in the tunnel which closely replicated the specific conditions experienced on-road. Figure 11 illustrates the example time trace measured from a vehicle on the road and that achieved in the wind tunnel. The yaw is recorded on road with a probe above the vehicle roof and so the wind tunnel measurement was made with a 40% scale model of the same vehicle with the measurement made using a probe in the same relative location. This approach provides the ability to test different vehicle geometries when subjected to the same particular on-road unsteady events.

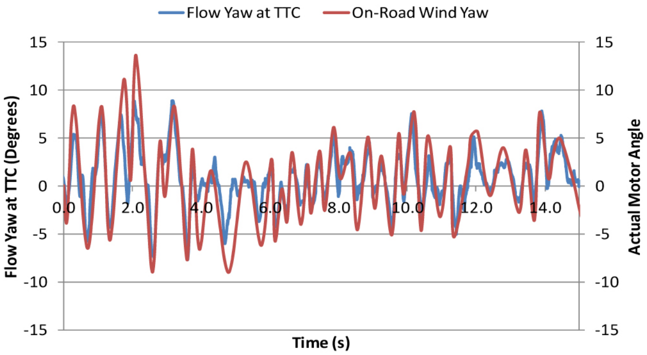

Figure 11. Yaw angle time trace measured on-road and in the wind tunnel. Time scaled to model test time.

Figure 12 illustrates the spectrum for this programmed example trace as reproduced in the wind tunnel and compared with the spectrum for the original on-road measurement. The tunnel spectrum is scaled to on-road time and velocity. While this is the spectrum for a specific, short duration, sample of unsteady data it is consistent with spectra typically observed on-road.

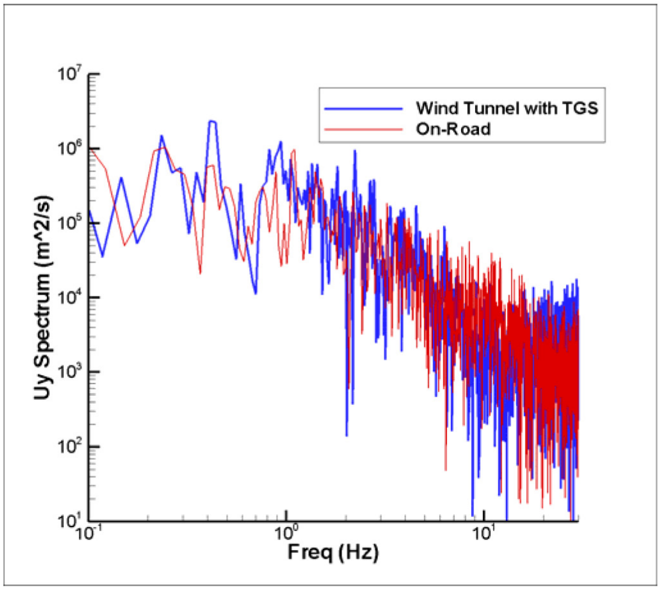

Figure 12. Spectrum of crosswind velocity component (Uy) above vehicle roof on-road and in the wind tunnel with TGS (scaled to road time and velocity).

3.2 Tests on a Vehicle Model

Preliminary tests were conducted with a vehicle model in the test section. Model details are summarized in Table 1. The model was CNC machined from high-density foam tooling block with mounting from the wheel positions to the underfloor balance (tunnel in fixed ground condition). The front sideglass was rapid-prototyped on an Objet Eden machine so that pressure tappings could be installed. The model has a representative underfloor but no engine bay flow, wing mirrors, windshield wipers etc. Area blockage was 15%.

Table 1. Rover 200 (R3) Model Parameters

Scale	40%
Frontal Area	0.308 m^2
Height	555 mm
Width	568 mm
Length	1588 mm
Mass	112 kg

Steady forces were measured with the tunnel in conventional (non-TGS) configuration with the model rotated to a range of yaw angles. Forces were also measured with the turntable set at zero yaw and with steady yawed flow provided by the turbulence generation system. This allows an evaluation of any flow quality impacts in TGS mode on vehicle forces.

Figure 13 illustrates the resulting drag and lift forces measured using these two separate approaches. The agreement, although not universally within the conventional facility repeatability of 0.002 on C_D, is very good considering how different the approaches are. Note that presentation of data requires consistency in terms of reference velocity and force direction projection, because both the airflow and test property reference frames rotate. The reference velocity used here was resultant velocity magnitude, based on the a plenum-method calibration in conventional operation. Figure 14 provides the corresponding side force and yawing moment coefficients.

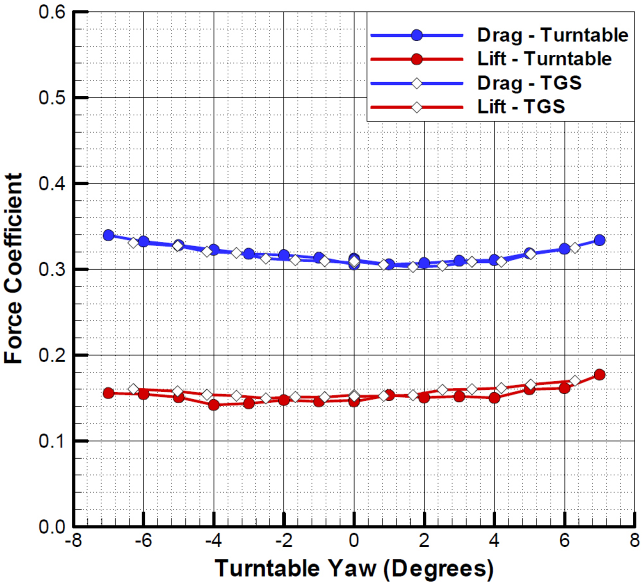

Figure 13. Drag and Lift vs. Yaw achieved with Turntable and TGS

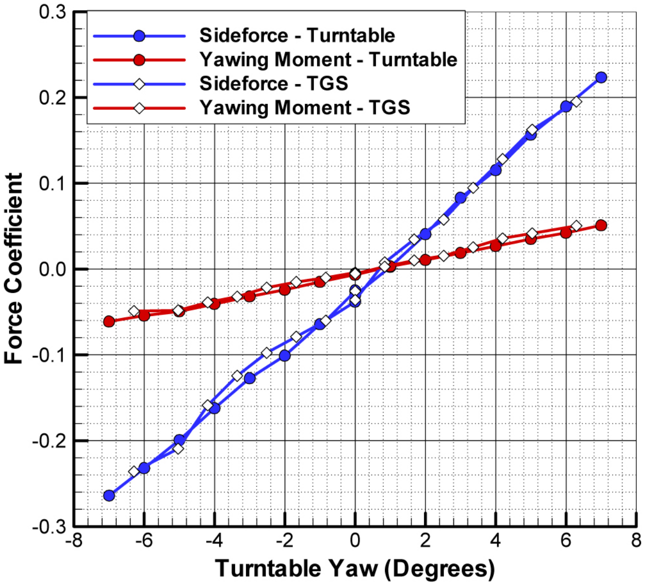

Figure 14. Side force and yawing moment vs. Yaw achieved with Turntable and TGS

CONCLUSIONS

This paper outlines the creation of a facility for simulating on-road transients in a model scale wind tunnel.

Probably the most important source of unsteadiness experienced by a vehicle on-road derives from traversing through spatial non-uniformities in the natural wind, typically rated by the combination of a cross wind and roadside furniture. This places a particular emphasis on cross-wind transients.

Based on conditions experienced on road, and the frequency range of greatest interest in terms of vehicle response, the turbulence generation system was designed to achieve yaw angles up to 6-8°, equating to a lateral turbulence intensity of 8-10% with a frequency range extending up to 10 Hz.

To generate controlled unsteadiness a “lift-based” system was adopted, based principally on a pair vertical airfoils at the upstream end of the test section. The airfoils were positioned so that their wakes would not impinge on the model.

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 ±8° steady state, extending to ±11° 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.

Preliminary tests were conducted with a vehicle model in the test section demonstrating that the same steady forces are measured whether yaw is provided using the wind tunnel turntable or using the TGS.

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DEFINITIONS/ABBREVIATIONS

TGS - Turbulence Generation System