

Simulation of Atmospheric Turbulence for Wind-Tunnel Tests on Full-Scale Light-Duty Vehicles

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ABSTRACT

During the past year, a novel turbulence generation system has been commissioned in the National Research Council (NRC) 9 m Wind Tunnel. This system, called the Road Turbulence System was developed to simulate with high fidelity the turbulence experienced by a heavy duty vehicle on the road at a geometrical scale of 30%. The turbulence characteristics that it can simulate were defined based on an extensive field measurement campaign on Canadian roads for various conditions (heavy and light traffic, topography, exposure) at heights above ground relevant not only for heavy duty vehicles but also for light duty vehicles.

In an effort to improve continually the simulation of the road conditions for aerodynamic evaluations of ground vehicles, a study was carried out at NRC to define the applicability of the Road Turbulence System to aerodynamic testing of full-scale light duty vehicles. Using the on-road measurements as a guide, it was concluded that the RTS appears to provide a more representative simulation of on-road conditions for wind-tunnel testing, compared with other passive methods such as with rope nets, spires, large turbulence grids or also with active turbulent generation techniques. Although some differences from the target turbulence conditions were found, all spectra measured behind the RTS were found to be within the range of turbulence energy measured during the on-road campaign. As such, the RTS was subsequently used for measurements of two full-scale light-duty vehicles (a large car and a standard sport-utility vehicle) during a test campaign examining the influence of active drag-reduction technologies. Comparison of these data to the equivalent smooth-flow measurements showed different influences of turbulence on the drag behaviour for each of the two vehicles.

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INFLUENCE OF TERRESTRIAL WINDS ON VEHICLE AERODYNAMICS

The aerodynamic performance of ground vehicles is affected by vehicle-specific and environmental factors. Those factors most pertinent for evaluating the aerodynamic performance and efficiency of such vehicles are:

- Vehicle geometry;
- Vehicle speed;
- Air properties (barometric pressure, temperature, density, humidity);
- Wind speed, which can vary with height;
- Wind direction, which can vary with height; and
- Wind turbulence intensity, length scales, spectra, which can all vary with height.

Terrestrial winds play an important role for the aerodynamics of ground vehicles. However, they are often not replicated in a sufficient manner in wind tunnels. For heavy-duty vehicles, the basic effects of wind speed and wind direction are often quantified through the evaluation of a wind-averaged drag coefficient. This approach is based on the assumption that the mean terrestrial wind speed is

equally likely to be blowing from any direction [1]. The drag-coefficient of a light-duty vehicle does not show a strong sensitivity to yaw angle, at least in the $\pm 10^\circ$ range typically required for wind-averaged-drag evaluations (inferred from [2]), and as such, the wind-averaged-drag concept has not been adopted to the same extent by the light-duty vehicle community.

Although the wind-averaged-drag approach accounts for variations in the mean terrestrial winds, turbulence associated with these winds and from the wakes of other vehicles on the road is usually not simulated in wind tunnel test programs. It has long been recognized that turbulence can affect not only the magnitude of the drag experienced by road vehicles, but can also affect the characteristics of the drag mechanisms and how they vary with wind direction [3, 4]. Naturally, this applies to the effects of drag-reduction technologies, including modern active technologies such as grille shutters and active ride height. A drag-reduction technology may show negligible sensitivity to turbulence when winds are aligned with the vehicle motion, but can show different levels of drag reduction in cross-winds depending on the turbulence environment. Therefore, the characteristics of the turbulence environment are important for adequately assessing the performance of drag-reduction devices for road conditions.

TURBULENCE IN WIND TUNNELS

The field of wind engineering has been simulating turbulent atmospheric flows in wind tunnels for decades. In fact, appropriate turbulence is considered a must for characterizing the aerodynamic and aero-elastic performance of large structures [5]. One of the problems encountered when attempting to simulate the natural wind in a wind tunnel is the inability to replicate the largest-scale wind fluctuations of the atmospheric boundary layer, those associated with turbulence scales of 100 m or more. In many cases, wind fluctuations on these largest scales are not necessary to reproduce because the aerodynamics associated with a body of interest will behave in a quasi-steady manner. This is in contrast to turbulence scales on the order of the size of the body or smaller that can change the steady-state drag coefficient values by nature of the way turbulence affects the shear layer development over, under, and through the vehicle.

Sims-Williams [6] discusses the importance of turbulence length scale on the aerodynamic performance of ground vehicles. Using the definition of "unsteady" versus steady flow for airfoils, he suggests that quasi-steady behaviour can be assumed for length scales larger than 60 vehicle lengths, and cannot be assumed for length scales smaller than 6 vehicle lengths. At scales in between, unsteady effects play an increasing role with decreasing size. Sims-Williams work shows that turbulence scales on the order of 2-20 vehicle lengths are most important, when vehicle dynamics, including gusts and cross-wind behaviour are considered. Cogotti [7] also discusses the importance of larger length scales in the simulation of representative aerodynamics. Sims-Williams suggest that smaller length scales are less important because their energy content is low. However, smaller length scales are known to influence flow separation and reattachment characteristics [8]. Therefore, smaller length scales could significantly influence the development of the separation region behind the vehicle, including around small parts such as mirrors, therefore impacting the drag characteristics.

THE ROAD TURBULENCE SYSTEM

The NRC Road Turbulence System (RTS) was designed for a project undertaken by NRC for Transport Canada between 2012 and 2015 to evaluate aerodynamic fuel-savings technologies for heavy-duty vehicles. Despite claims that an appropriate wind spectrum for road vehicles requires an active turbulence generation system, past experience by the NRC in the fields of wind-engineering, bluff-body-aerodynamics, and sports aerodynamics provided a foundation upon which a passive approach was used for the RTS. The finalized RTS for the NRC 9 m Wind Tunnel (see Figure 1) is a passive system that was designed to provide road-representative turbulence for a 30% scale model of a tractor-trailer combination. To do so, measurements of the turbulence environment within which road vehicles operate were first preformed and subsequently used to define target wind

conditions [9]. Smaller-scale development efforts in the NRC 0.9 m Pilot Wind Tunnel identified settling-chamber-mounted obstacles as an appropriate means to provide the level of turbulence intensity and turbulence length scales found on the road. The development and commissioning of the RTS is documented in a companion paper [10].

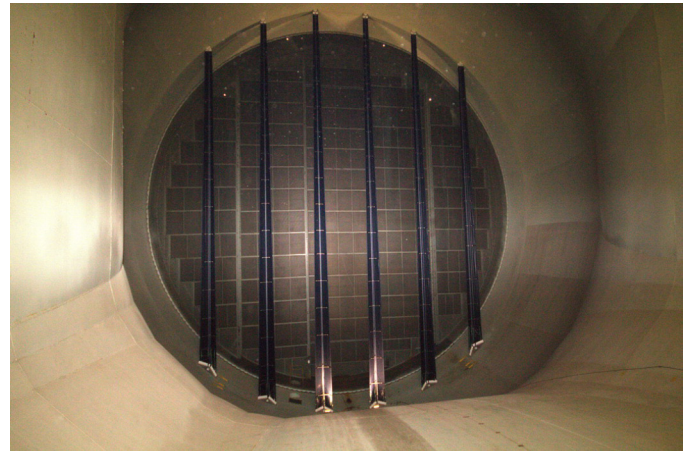


Figure 1. Road Turbulence System (RTS) installed in the 25 m (82 ft) diameter settling chamber of the NRC 9 m Wind Tunnel.

For a heavy-duty vehicle model tested with and without the RTS at a width-based Reynolds number of approximately 2.6×10^6 , the wind-averaged drag was found to be 2% lower in turbulent winds than in the smooth-flow conditions of the standard wind tunnel setup [10]. In addition, the performance of a common drag-reduction device was shown to be over-estimated in smooth flow by up to 1% of total vehicle drag.

FLOW CHARACTERISTICS OF THE RTS FOR FULL-SCALE VEHICLES

Following the success of the RTS for 30% HDVs, it became important to benchmark the technology for use with full-scale light-duty vehicles (LDVs). As part of the RTS commissioning efforts [10], measurements of the flow characteristics in the test section of the NRC 9m Wind Tunnel were performed with the same fast-response pressure probes used to measure the on-road turbulence environment. Some of those measurements are presented here and compared to on-road measurements.

The boundary-layer profile was measured at the leading edge of the turntable using a rake of pitot probes. The displacement thickness was measured to be 4 mm, which is the same for the smooth-flow conditions without the RTS.

Table 1. Comparison of RTS turbulence characteristics with the target on-road condition at a full-scale height of 1.5 m from the ground (moderate terrain roughness, moderate traffic density, moderate winds strength).

Component	Turbulence Intensity, I			Turbulence Length Scale, L^x		
	Road	RTS (30%)	RTS (100%)	Road	RTS (30%)	RTS (100%)
u	4.0 %	3.7 %	3.9%	4.7 m	1.0 m	0.3 m
v	3.5 %	5.0 %	5.4%	1.9 m	2.6 m	0.7 m
w	3.1 %	4.4 %	5.3%	0.6 m	1.3 m	0.6 m

The on-road turbulence measurements demonstrated that a wide-range of turbulence characteristics are encountered by vehicles on the road [9]. A classification system was developed for which the road-measurement data was categorized and typical conditions identified. At a height of 1.5 m from the ground, turbulence intensities over the range of the classifications varied from 2% to 8%, and turbulence length scales varied over two orders of magnitude from about 0.1 m to values in excess of 10 m. The characteristics of the most common condition, which was the moderate-terrain-roughness, moderate-traffic-density and moderate-wind-strength condition, is provided in Table 1 along with the respective measurements for the RTS relative to full-scale and 30%-scale models in the NRC 9 m Wind Tunnel. The turbulence intensities from the RTS system compare well to the on-road measurements, although somewhat lower values for the lateral (v) and vertical (w) turbulence components are found in the road measurements compared to the RTS. The RTS values for v and w more closely match dense traffic conditions that the target moderate traffic conditions.

The turbulence intensities are slightly different between the 30% and 100% RTS conditions because of the different distance from the floor (0.45 m for 30% and 1.5 m for 100%). Figure 2 shows vertical profiles of laterally-averaged Cobra probe measurements, performed at the leading edge of the turntable in the NRC 9 m Wind Tunnel. Each column represents data associated with a particular coordinate direction, with the top row showing the turbulence intensities, and the bottom row showing the turbulence length scales. Over the measurement height (2.0 m) and within the range of the lateral traverse, the mean wind speed varies by approximately $\pm 1\%$ and the lateral wind angle varies by no more than $\pm 1^\circ$. The longitudinal component (u) is nearly uniform with height, both for the intensity and length scale. The lateral component (v) shows minima for both the intensity and length scales in the 0.6 to 1.0 m range with the highest values of each found adjacent to the ground. The vertical component (w) shows a decrease in intensity and length scale as the ground is approached, due to damping of the vertical wind fluctuations in the presence of the ground, as was also observed in the on-road measurements [9]. As shown in Table 1, at 30% scale, the turbulence length scales are of similar magnitude as the road measurements, however at 100% the longitudinal (u) components show a smaller length scale than found on the road. This effect is a combination of change in the parameter with height and the scale.

Although the turbulence intensity and length scale are a basic quantitative measure of the turbulence characteristics of the winds experienced on the road, they are generalizations resulting from a typical wind spectrum. The wind spectrum, represented by the power

spectral density (PSD) which identifies the distribution of turbulent energy across a range of frequencies, provides a detailed characterization of the turbulence and is an important consideration when attempting to simulate turbulent winds in a wind tunnel. The final RTS design was selected through matching of the various component spectra between the on-road data and the concepts evaluated. To compare the wind-spectra measurements of the RTS at any scale to those on the road, for which the physical scale and mean wind speed may be different, the wind spectra have been normalized. The appropriate frequency scaling is the reduced frequency, defined as:

$$f_r = \frac{f \cdot L_{ref}}{U_{ref}} \quad (1)$$

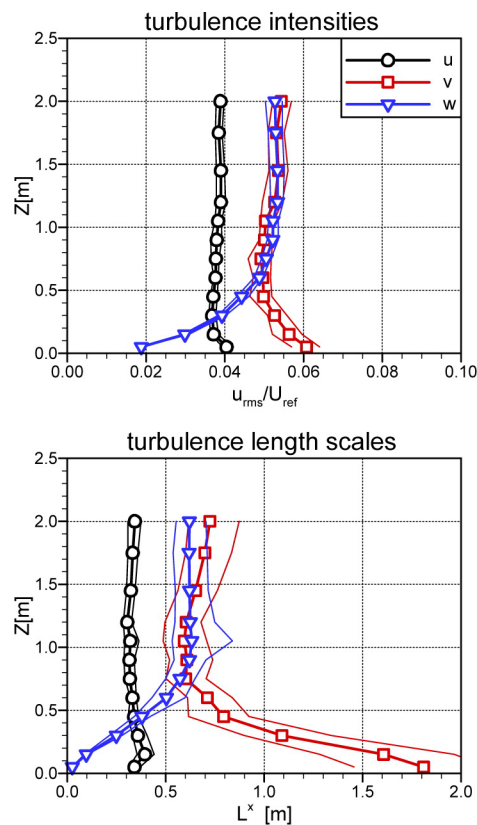


Figure 2. Vertical profiles of RTS turbulence characteristics (thin lines represent maximum and minimum values of laterally-averaged measurement points over ± 1.5 m range from centreline).