

A System for Simulating Road-Representative Atmospheric Turbulence for Ground Vehicles in a Large Wind Tunnel

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ABSTRACT

Turbulence is known to influence the aerodynamic and aeroacoustic performance of ground vehicles. What is not thoroughly understood are the characteristics of turbulence that influence this performance and how they can be applied in a consistent manner for aerodynamic design and evaluation purposes. Through collaboration between Transport Canada and the National Research Council Canada (NRC), a project was undertaken to develop a system for generating road-representative turbulence in the NRC 9 m Wind Tunnel, named the Road Turbulence System (RTS). This endeavour was undertaken in support of a larger project to evaluate new and emerging drag reduction technologies for heavy-duty vehicles.

A multi-stage design process was used to develop the RTS for use with a 30% scale model of a heavy-duty vehicle in the NRC 9m Wind Tunnel. This paper documents this process, which included 1) an on-road measurement campaign to identify that target wind characteristics, 2) small-scale concept-development efforts to identify a passive approach to the problem, and 3) commissioning of the full-sized RTS in the NRC 9m Wind Tunnel. The wind-spectrum generated by the RTS is a good match to the target road measurements. Using a 30%-scale model of a heavy-duty vehicle, comparison of measurements in smooth and road-representative turbulent wind conditions were performed. The measurements show differences in the drag characteristics of the vehicle, and show differences in the drag-reductions associated with add-on devices such as side-skirts and boat-tails, highlighting the importance of representative turbulence for ground-vehicle aerodynamic evaluations.

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INTRODUCTION

Transport Canada's ecoTECHNOLOGY for Vehicles Program [1] and the National Research Council Canada (NRC) are investigating the aerodynamic performance of current and emerging drag reduction technologies for heavy-duty vehicles (HDVs). The goal is to provide Transport Canada and its stakeholders with data on the performance of various drag reduction technologies for HDVs in Canada. A wind-tunnel investigation has been undertaken with the objective to provide the most reliable evaluation of drag-reduction-technologies possible. To do so, it was deemed important to simulate the effects of relative motion between the vehicle, the ground and the wind, and to simulate the turbulent wind characteristics near the ground encountered by heavy vehicles on the road. The approach selected was to use a 30% scale model of a tractor-trailer combination in the NRC 9 m Wind Tunnel using the Ground Effect Simulation System (GESS [2]), consisting of a boundary-layer suction system and a rolling road, with the addition of representative free-stream turbulence.

Watkins and Cooper [3] provide a review concerning the effects of turbulence on the aerodynamic performance of road vehicles. They discuss that drag reductions for commercial vehicles have been shown to be smaller in turbulent flows than smooth flows, implying that it may be more difficult to reduce the drag of HDVs in flow conditions representative of the turbulent terrestrial winds experienced on the road. The measurements they described are a combination of road-to-windtunnel comparisons and comparisons between different turbulence conditions in a wind tunnel, all with older-style vehicles that have poor aerodynamic performance compared to today's HDVs. The measurements also suffer from high uncertainties in the road measurements, or were performed at much lower Reynolds numbers than are generally accepted today [4]). Recent measurements performed by the NRC for a 5% scale tractor-trailer model, designed to behave in a high-Reynolds number regime, demonstrated the sensitivity of a streamlined modern tractor shape to turbulence [5]. Turbulence has also been shown to reduce the Reynolds number sensitivity of bluff bodies and increase the effective Reynolds number of the flow conditions through a forced transition process, which can improve the simulation of scaled-model experiments [4]). As such, a requirement for the current HDV drag-reduction effort was to replicate road-representative turbulence conditions in the wind tunnel.

GENERATING TURBULENCE FOR VEHICLES ON THE ROAD

Terrestrial winds play an important role for the aerodynamics of road vehicles, but are often not replicated in a sufficient manner in wind tunnels. For HDVs, the basic effects of wind speed and wind direction are assessed through the evaluation of a wind-averaged drag coefficient. This approach is based on combining the ground speed of the vehicle with a mean terrestrial wind speed that is equally probable to be blowing from any direction [6].

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 not only affect the magnitude of the drag experienced by a tractor-trailer combination, but can also affect the characteristics of the drag mechanisms and how they vary with wind direction [7, 3].

The field of wind engineering has been simulating turbulent atmospheric flows in wind tunnels for decades. In fact, appropriate turbulence is a must for characterizing the aerodynamic and aeroelastic performance of large structures [8]. 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 on the order of 100 m to 1000 m and more. In many cases, wind fluctuations on these largest scales are not necessary to reproduce because the body of interest will behave in a quasi-steady manner for these scales. This is in contrast to wind-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 local flow-field surrounding the vehicle.

Sims-Williams [9] discusses the importance of turbulence length scale on the aerodynamic performance of ground vehicles. He suggests that turbulence scales on the order of 2-20 vehicle lengths are most important for characterizing the change in aerodynamic performance of a vehicle. His study was directed more at transients related to gusts and cross-winds and their effect on vehicle dynamics. For the purpose of examining drag reduction technologies and the change in long-term, or steady-state, aerodynamic performance, length scales larger than one HDV length may not have a strong influence but there is insufficient evidence in the literature to support this argument.

Several techniques have been used to simulate the fluctuations of terrestrial winds in a wind tunnel. Sims-Williams [9] reviews some of these techniques and shows that for length scales much greater than the vehicle size, active technologies are required for turbulence generation, meaning some energy input is required. Active technologies typically have moving systems that require mechanical forcing through hydraulic or electrical systems, and are therefore costly to develop, use, and maintain, especially if used in a large wind-tunnel such as the NRC 9 m Wind Tunnel. For automotive testing, the Pininfarina Wind Tunnel [10, 11, 12] has an advanced system for turbulence generation. It uses a set of flapping devices that

are similar to the triangular spires used in wind-engineering work. Other techniques are available such as sets of flapping or pitching airfoils [13, 14] or screens of spinning plates [15, 16]. At NRC in the 1980s, an active method was demonstrated using an oscillating grid with hinged plates that were driven by either white noise or sinusoids of various frequencies [7]. These active techniques are effective at increasing the length scales of the turbulence, by introducing low-frequency fluctuations into the flow, while maintaining turbulence intensities of adequate magnitude to represent road conditions.

To ensure a reasonable cost and time-frame for the current project, it was recognized early that a passive technology would be required to generate turbulence in the NRC 9 m Wind Tunnel. Spires, turbulence screens, and turbulence grids have been used in the wind tunnel for wind engineering applications (for example, [17]) but the scales of turbulence are small relative to ground vehicles used in the wind tunnel, either full-scale or model-scale. These techniques also generate high turbulence intensities (often in excess of 5%) relative to what is commonly encountered by vehicles on the road. As a result of the high ground speeds relative to the terrestrial wind speeds, ground vehicles experience lower turbulence intensities. As an example, 20 km/h winds with a 10% turbulence level relative to the stationary ground would be expected to have approximately 2% turbulence intensity as seen by a vehicle travelling at 100 km/h. This lowering of the effective turbulence intensity with increasing ground speed is advantageous when considering techniques to generate turbulence passively. Behind obstacles such as spires or grids, turbulence intensities decay with downstream distance and turbulence length scales increase with downstream distance. Wind tunnels designed specifically for wind engineering purposes have a very long fetch to allow the generation of sustained large-scale wind structures. The NRC 9 m Wind Tunnel does not have sufficient fetch in the test section to allow the length scales to grow to a sufficient size for large-scale testing. However, NRC and other facilities have placed large obstacles in the settling chambers of wind tunnels, upstream of the test section, which have provided larger length scales for a given turbulence intensity than can be generated by passive devices in the test section. For a companion project performed for Transport Canada examining safety issues associated with boat-tails attached to HDVs, a set of obstacles in the settling chamber with a screen at the test-section inlet of the NRC 2 m × 3 m Wind Tunnel generated turbulence intensity of 4% with length scales on the order of 0.1 m or 40% of the HDV-model width [18]. This was based on efforts to generate appropriate turbulence for sports-engineering projects [19]. The FKFS Model Wind Tunnel in Germany, used primarily for automotive purposes, uses large spires in the settling chamber that generate large the turbulence scales in the test section while maintaining reasonable levels of turbulence intensity. Based on data presented by Schroeck et al. [20], this system provides a turbulence intensity of approximately 3% with length scales on the order of typical model lengths. The challenge with implementing large obstacles in the settling chamber of the NRC 9 m Wind Tunnel is the scale of the required infrastructure, as the diameter of the settling chamber is 25 m.

Although a variety of techniques are available to generate turbulent terrestrial-type flows in a wind tunnel, the actual turbulence characteristics experienced by vehicles on the road must be known. This is typically accomplished by mounting measurement devices to vehicles and measuring the wind experienced on the road. Smith [21] documents a series of road tests with anemometers mounted to the roof of a car to investigate gust events experienced by vehicles on British highways. More recently, Wordley and Saunders [22] performed measurements on Australian roads using an array of four fast-response pressure probes that can measure the fluctuations in the wind to high resolution. Their work was aimed at passenger vehicles and their measurements were performed close to the ground (between 0.25 and 1.0 m from the ground). They suggest a turbulence intensity of 3% and length scale of 1.0 m for the longitudinal and lateral wind speed components, and a vertical wind component intensity of 2% with an associated length scale of 0.5 m. They do not make any recommendations for variations in the mean and fluctuating winds with height from the ground. As noted by Cooper [23], HDVs may see a variation with height in these flow parameters and may also see a variation in wind angle with height (twist) under cross-wind conditions as a result of the variation in wind speed with height of the terrestrial boundary layer.

SYSTEM REQUIREMENTS

The requirements set forth for the development of the RTS were to provide road-representative turbulence levels in the NRC 9 m Wind Tunnel, more specifically to:

- provide wind characteristics in the test section representative of what HDVs experience on Canadian roads;
- use passive technology (no energy input) to avoid an expensive and complex system to build and maintain; and
- develop a system that can be deployed or removed in a time period no longer than five hours (half a test day), to avoid excessive costs during a test program.

To achieve the requirements noted above, an eight-step approach was taken, as follows:

1. Measure the winds that HDVs experience on the road.
2. Examine various passive techniques in a small wind tunnel that may provide the important wind characteristics identified from the on-road measurements.
3. Examine the sensitivity of HDV drag to various unsteady wind characteristics.
4. Select an appropriate turbulence environment and design concept to represent best what was observed on the road, using the results of items 1, 2 and 3 above.
5. Verify the design scaling process and evaluate any influence of wind-tunnel configuration by installing and testing an intermediate-scale version of the RTS in the NRC 2 m $\times$ 3 m Wind Tunnel.
6. Design and build a quick-install version of the RTS for the NRC 9 m Wind Tunnel.

7. Commission the RTS and verify its flow characteristics.
8. Evaluate the influence of turbulence on an HDV model in high-Reynolds number experiments.

This paper provides highlights from this development process.

ON-ROAD TURBULENCE MEASUREMENTS

To provide representative wind conditions in a wind tunnel, the characteristics of the winds experienced by moving vehicles on the road must be known, and such wind characteristics have not been thoroughly studied. The winds near the ground (0.1 to 4 m) are highly dependent on the local terrain (urban, rural, roadside obstacles, etc.). Although some recent high-quality on-road measurements have been performed, described by [22], the study concluded that more measurements are required to assess adequately the winds to be simulated in a wind tunnel. Their study also considered only a few types of local terrain and did not consider some of the terrain environments prevalent on Canadian roads. As a first step towards developing the RTS for the NRC 9 m Wind Tunnel, on-road measurements were performed over Ontario and Quebec highways to measure the winds experienced by HDVs. This on-road wind measurement study is described in detail by McAuliffe et al. [24], and summarized herein.

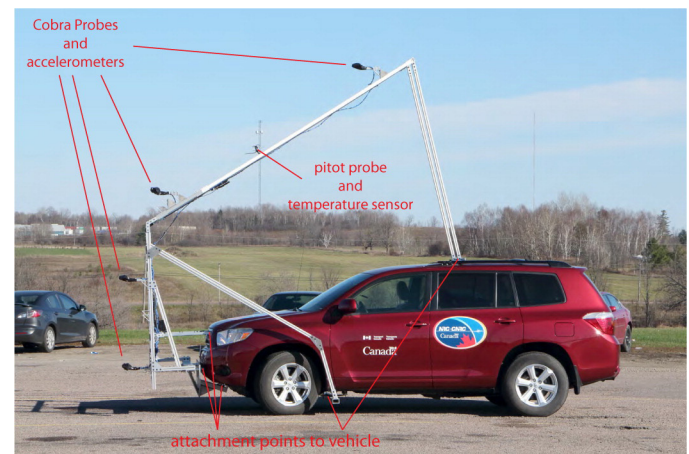


Figure 1. On-road turbulence measurement rig

To measure the winds experienced on the road, a sport utility vehicle (SUV) was outfitted with an array of four fast-response pressure probes that could be arranged in vertical or horizontal rake configurations that provided measurements up to 4.0 m from the ground and spanning a width of 2.4 m (shown in Figure 1). Eight days of testing over a two month period in late 2012 were conducted over roads in Eastern Ontario and Western Quebec, Canada, with dates and test routes selected to provide a variety of conditions. Time-series of on-road turbulence data were segmented and classified based on differences in the terrain roughness, traffic density, and wind strength experienced during the measurements, as inferred by topographical maps, on-board video, and weather-station data, from which wind spectra and spatial correlations were calculated for each condition. 25 such conditions were identified in the data set.

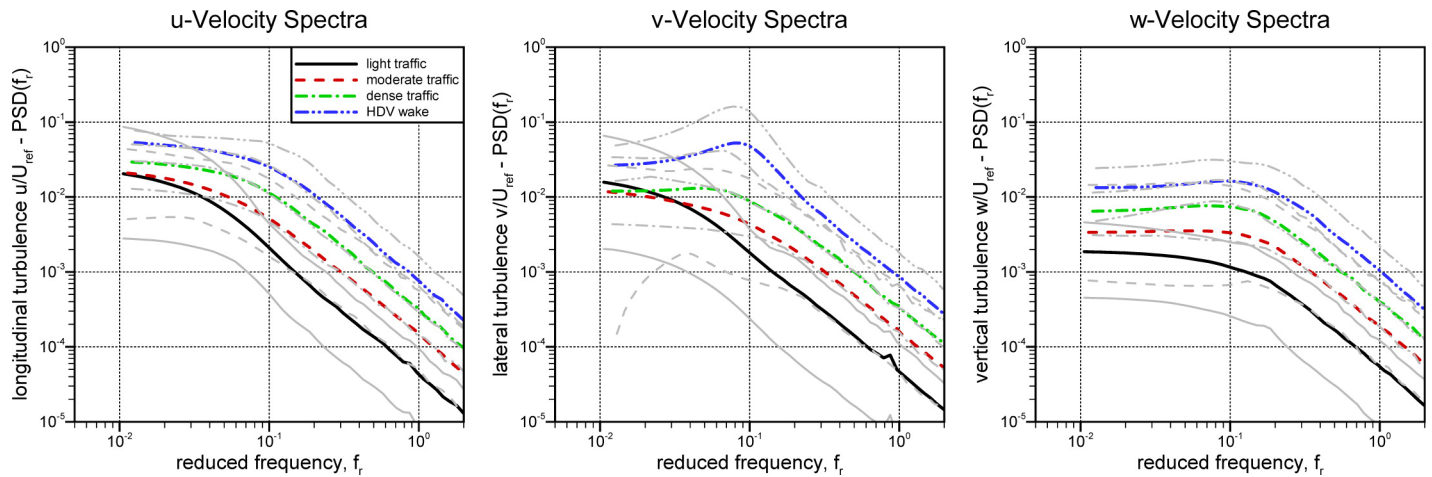


Figure 2. Wind spectra for characteristic conditions encountered on the road, for changes in traffic density with moderate terrain roughness and moderate terrestrial wind strength

Typical wind spectra were developed based on an average of all spectra measured for each defined condition, from which the turbulence intensities (I_u , I_v , I_w) and turbulence length scales (L_u^x , L_v^x , L_w^x) were evaluated. A sample of the characteristic wind spectra defined for different levels of traffic density are shown in Figure 2, representing moderate levels of terrestrial winds and terrain roughness (see [24] for description of terrain, traffic and wind conditions). Each graph shows the wind spectra for the longitudinal (u), lateral (v) and vertical (w) components. The dark coloured lines in each plot represent the averaged on-road spectra, with the minimum and maximum extent of the road-measurement data shown as gray lines with the corresponding line style. The spectra are normalized in such a way that a higher the curve in relation to the ordinate (y-axis) has a higher the turbulence intensity level for the condition. From this data, it has been concluded that the turbulence intensity (total energy content) increases with greater levels of traffic density or the presence of an HDV, and the turbulence length scale (representative frequency/wavelength defining where spectral distributions transitions from constant energy to a decay of energy with frequency) decreases with increasing traffic density.

A target wind spectrum was identified that became the benchmark for the RTS development efforts. Due to its predominance in the number of data segments it represents, and the high volume of heavy-vehicle traffic in the geographic region in which the measurements were performed, the Moderate-Terrain, Moderate-Traffic, Moderate-Winds (M-M-M) condition (see [24] for categorization scheme) has been chosen as the target against which the RTS was designed. This M-M-M condition, which is only one of the 25 specific conditions encountered during the road campaign, represents approximately 20% of data collected and categorized. The wind spectra and correlation distributions for this condition were used as the target for the small-scale development and larger-scale demonstrations of the RTS. Table 1 identifies the target turbulence intensities and length scales for this condition. These are higher than the levels recommended by Wordley and Saunders [22] due to the different environments encountered during the test program.

Table 1. Target turbulence intensities and length scales for FTS development representing the Moderate Terrain, Moderate Traffic, Moderate Winds (M-M-M) condition, at 1.5 m from ground

Component	Turbulence Intensity, I	Turbulence Length Scale, L^x
u	4.0 %	4.7 m
v	3.5 %	1.9 m
w	3.1 %	0.6 m

SMALL-SCALE RTS CONCEPT DEVELOPMENT

Generating turbulence in a wind tunnel to represent terrestrial winds is not a new concept. The field of wind engineering has been making use of such simulations for decades to design large structures such as buildings and bridges to withstand adequately the mean and dynamic wind forces acting on such structures. As noted in the introduction, typical wind-engineering turbulence-generating devices provide too high a turbulence intensity in the test section to be used for tests on full-scale or large-scale models. Obstacles in the upstream settling chamber are a good candidate technique instead of grids or spires for obtaining lower turbulence intensity levels typical of what are experienced on the road.

As a starting point in developing a RTS to generate road-representative turbulence, a concept-deign study was undertaken in the NRC 0.9 m Pilot Wind Tunnel. This wind tunnel was originally a 1/10-scale pilot version of the NRC 9 m Wind Tunnel, but was later adapted to accommodate different test-section arrangements. In the configuration used for this study, the wind tunnel consists of a closed-test-section of dimensions 1.0 m $\times$ 0.8 m with an upstream rectangular-shaped settling chamber with a contraction ratio of 3.6, with a maximum wind speed of 44 m/s. Measurements were performed with the same fast-response pressure probes used in the on-road turbulence study. Three probes were mounted in a vertical-array arrangement on a 3-axis traverse system that allowed measurements over a large range of the test section. Measurements were performed such that a plane of data perpendicular to the flow was surveyed over a range of ± 0.28 m from the centerline of the flow.

floor to a height of 0.45 m, to provide an assessment of the uniformity of the flow fields generated by the various turbulence-generating concepts.

Four types of passive turbulence-generating technique were examined in the study:

- A vertical-bar turbulence grid at the inlet of the test section (shown in top photograph of [Figure 3](#), combined with a screen). This concept has been used previously to generate sub-5% turbulence intensities in the NRC 9 m Wind Tunnel for tall building studies.
- A screen at the inlet of the test section (shown in top photograph of [Figure 3](#), combined with a vertical-bar grid). This is representative of a net concept used in the NRC 9 m Wind Tunnel for various bluff-body-aerodynamics purposes.
- A set of moving spires designed to vibrate under the actions of the wind, tuned to amplify low-frequency turbulence. This concept was conceived to replicate the effects of active turbulence systems that generate constant-frequency forcing.
- Wooden obstacles mounted in the settling chamber, most of which represented triangular spire shapes with the intent to generate a vertical gradient of the turbulence characteristics (sample concept shown in bottom photograph of [Figure 3](#)). This idea was developed based, in part, on previous bluff-body-aerodynamic studies at NRC performed in intermediate-sized wind tunnels.



Figure 3. Turbulence generation concepts tested in the NRC 0.9 m Pilot Wind Tunnel (top - vertical-bar grid and screen combination at inlet of test section, bottom - triangular spire concept in settling chamber)

Preliminary results with the moving-spire concept identified an increase in turbulence over the full-range of turbulent frequencies, rather than just the low-frequencies intended to be amplified, with too-high a turbulence level to represent road conditions. Therefore, no additional consideration was given to the moving spire concept.

A summary of measurements for some of the concepts tested is provided in [Table 2](#), which tabulates the turbulence intensities (I) and longitudinally-correlated turbulence length scales (L^x) for the three directional components of the the wind (longitudinal- u , lateral- v , vertical- w). The “SMTH” case represents the standard smooth-flow conditions of the wind tunnel, the “VB” case represents the vertical-bar grid case, and the “C” cases represent variations of the spire-in-settling-chamber concept. Outside of the boundary layer that develops on the floor of the tunnel, all of these cases show flow uniformity within $\pm 1.5\%$ of mean wind speed, and flow angularity of $\pm 1^\circ$ laterally and vertically. The spire-in-settling-chamber cases show vertical gradients in the turbulence characteristics (turbulence intensity decreasing with height) similar to what was observed on the road, with good uniformity of the mean wind speed in the test section unlike test-section-mounted spire concepts that provide boundary-layer-like flow profiles. Of note is the reduced isotropy of the turbulence for the spire-in-settling-chamber concepts. For these, the lateral and vertical turbulence components are higher than the longitudinal components as a result of shearing and acceleration though the contraction. A similarity in turbulence intensity levels is observed for the VB case and the C6Q case (for the longitudinal components) and the VB case and the C7F case (for the lateral and vertical components) but with distinctly different magnitudes of length scales. The VB case, compared to the C6Q and C7F spectra, has lower turbulence energy at low frequencies and higher energy at high frequencies.

Table 2. Turbulence intensities and length scales of configurations used to evaluate sensitivity of HDV drag to turbulence, measured 0.09 m from the ground

Config.	I_u [%]	I_v [%]	I_w [%]	L_u^x [m]	L_v^x [m]	L_w^x [m]
SMTH	0.6	1.0	1.1	0.098	0.079	0.086
C7F	3.2	3.8	4.4	0.035	0.077	0.117
C6Q	3.8	4.8	5.0	0.036	0.081	0.104
VB	4.1	3.9	3.8	0.016	0.012	0.010
C3W	4.6	6.2	6.0	0.039	0.108	0.082
C3S8	5.5	7.7	7.1	0.047	0.156	0.117

As a secondary step towards identifying a concept for the RTS, the sensitivity of HDV drag to turbulence was evaluated to allow bounds to be placed on the final specifications for the RTS. Two small-scale HDV models were built and tested in the NRC 0.9 m Pilot Wind Tunnel with the RTS concepts summarized in [Table 2](#). One model was a lightweight foam model for use with a dynamic balance to evaluate the drag loads experienced by an HDV in turbulent flow. The second model was instrumented with pressure taps over the surface of the model to evaluate the mean and dynamic pressures that affect the mean and dynamic wind loads.

When designing wind-tunnel models for small-scale testing, care must be taken to ensure the aerodynamics of the model behaves in a representative manner to that of a full-scale vehicle. As such, rather