

Measurement of the On-Road Turbulence Environment Experienced by Heavy Duty Vehicles

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ABSTRACT

Terrestrial winds play an important role in affecting the aerodynamics of road vehicles. Of increasing importance is the effect of the unsteady turbulence structure of these winds and their influence on the process of optimizing aerodynamic performance to reduce fuel consumption. In an effort to predict better the aerodynamic performance of heavy-duty vehicles and various drag reduction technologies, a study was undertaken to measure the turbulent wind characteristics experienced by heavy-duty vehicles on the road.

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. To characterize the influence of the proximity of the vehicle on the pressure signals of the probes, the SUV and its measurements system was calibrated in a large wind tunnel. On-road measurements of the turbulence intensities, turbulence length scales, wind spectra, and spatial correlations were performed. Eight days of testing over a two month period in late 2012 were conducted over roads in Eastern Ontario and Western Quebec, Canada. Dates and test routes were selected to provide a variety of conditions. The 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.

Of the three classification categories, traffic density provided the greatest influence on the measured turbulence characteristics by modifying the strength of the high-frequency/small-scale turbulence structures in the wind. Conversely, the strength of the terrestrial winds provided a strong influence on the low-frequency/large-scale turbulence. In the near-ground region of the current study (0.5 to 4.0 m), which represents the vertical extent of typical heavy duty vehicles on the road, the turbulence length scales showed a much greater sensitivity to vertical distance than did the turbulence intensity, resulting from damping of the large-scale/low-frequency wind fluctuations near the ground.

Based on the frequency of the various conditions experienced on the road, a target set of wind conditions, (intensities, length scales, spectra, correlation lengths) are recommended that differ from previously-published recommendations.

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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 will be undertaken with the objective to provide the most reliable evaluation of drag-reduction-technologies

possible. To do so, it is 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 is to use a 30% scale model of a tractor-trailer combination in the NRC 9m Wind Tunnel using the Ground Effect Simulation System (GESS [2]), consisting of a boundarylayer suction system and a rolling road, with the addition of representative free-stream turbulence.



Figure 1. SUV with support rig for on-road turbulence measurements, measurement probes in vertical-array configuration.

Watkins and Cooper [2] 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-wind-tunnel 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 is to replicate road-representative turbulence conditions in the wind tunnel.

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 studied at length. The winds near the ground (0.1 to 4 m) are highly dependent on the local terrain (urban, rural, road-side obstacles, etc.). Although some recent on-road turbulence measurements have been performed in Australia, as documented by Wordley and Saunders [6,7], they

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 turbulence simulation for the NRC 9 m Wind Tunnel, the NRC has performed on-road measurements over Ontario and Quebec highways to measure the winds experienced by HDVs. A similar approach to that of Wordley and Saunders [6,7] was taken, with measurements over a larger vertical and lateral extent to examine the turbulence characteristics experienced by heavy-duty vehicles.

EXPERIMENTAL SETUP

To examine the winds experienced by HDVs on the road, measurements up to the height of typical HDVs was required (4.1 m). The temporal and spatial nature of the turbulence are both important characteristics to measure for developing turbulence generation capabilities for the wind tunnel. As such, simultaneous measurement of the unsteady winds at various spatial locations was required. To examine lateral variations in the flow, measurement locations spaced as wide as an HDV were also required (2.6 m). Measurements were performed using four fast-response four-hole pressure probes (Cobra probes manufactured by Turbulent Flow Instrumentation Pty Ltd.[8]) mounted to a sport utility vehicle (SUV). These probes allowed measurement of the wind velocity and pressure fluctuations with a frequency response up to 1.5 kHz. For road conditions at 100 km/h, this provides the measurement of turbulence scales down to about 0.02 m which is sufficient given that the most energetic scales of turbulence on the road are on the scale of the vehicle size or larger.

HVs are taller and wider than the SUV used for the investigations, and a large support structure was mounted to the vehicle to position the measurement probes at the various spatial extents necessary to characterize the flow field experienced by HDVs. The SUV with the support structure attached is shown in [Figure 1](#). The lower front part of the support rig was mounted directly to the vehicle frame at five locations: one under the front bumper, two to the tow-hook connections through the front bumper, and two to the upper frame rail at the front of the engine compartment behind the front grille. Additional support was added through a cross beam attached to the underbody aft of the front wheels. This provided roll stability to the large frame overhanging the front of the vehicle. The upper tilted structure was hinged at the front to the vertical front frame, and was mounted to the structural supports for the roof racks.



Figure 2. Horizontal probe-array configuration (with tubing system to zero the probe pressure transducers)

Two basic probe configurations were selected for the test program. The first was a vertical-array configuration with probes mounted at 0.5 m, 1.5 m, 2.5 m and 4.0 m from the ground along the centerline of the vehicle (shown in the [Figure 1](#)). The lowest probe head was located approximately 1 m ahead of the vehicle. The second configuration was a horizontal array configuration. To allow the calculation of lateral turbulence correlations, it was desired to have the largest number of probe spacings. With four measurement probes, an array was made to provide six different correlation distances. The configuration used provided a combination of lateral correlation distances of 0.406 m, 0.813 m, 1.219 m, 1.625 m, 2.032 m, and 2.438 m. For the horizontal array, the probe were mounted to a horizontal bar attached to the front face of the support rig, with the probe tips placed at a height of 1.5 m from the ground, corresponding to one of the vertical array locations.

To measure ground speed and location, a GPS antenna was mounted to the roof of the vehicle and connected to the data acquisition system by routing the cable through the rear-hatch door seal. The GPS unit embedded in the data acquisition system provided speed and position at a rate of approximately

1 Hz which was sufficient for the steady-ground-speed measurements which were the most important during the test program.

The wind speed as measured by the measurement probes requires the ambient barometric pressure and temperature to allow calculation of the air density. [Figure 1](#) shows the location of a bracket on which a pitot probe and a resistance temperature detector (RTD) were mounted for these reference measurements. The static-pressure port of the pitot probe was connected through pressure tubing, to a barometric pressure sensor mounted in the vehicle cabin. A manifold in this reference pressure line was used to provide a reference backpressure for the probes. For the majority of measurements presented herein, the measurement uncertainties for the wind speed and turbulence intensity were within $\pm 1\%$ of measured values, and the flow angle uncertainties were within $\pm 1^\circ$, based on typical repeatability and uncertainty estimates established for these probes through their use at the NRC.

The probe holders were instrumented with three accelerometers each, to measure vibrations in the three probe axis directions. Analysis of the accelerometer results shows some excitations at frequencies above 30 Hz, but of insufficient magnitude to influence the turbulence measurements. In addition, cycling of the vehicle cruise control system provided low-frequency oscillations on the order of 0.1 Hz, but at sufficiently low amplitude that it did not adversely influence the measurements.

A portable 32-channel sample-and-hold data acquisition system was mounted inside the vehicle, to which all the instrumentation was connected. The probes, accelerometers, temperature sensor and pressure sensor were sampled at 2.5 kHz with a 1 kHz low-pass filter. The digital GPS signals were sampled at 10 Hz and up-sampled to 2.5 kHz to provide a consistent data set for data processing. Data acquisition was controlled through a laptop connected to the system. Typical measurement runs were approximately 15 minutes. Periodic zeroing of the probe pressure transducers was accomplished using a manifolded tubing system that was connected to the reference pressure line, with sealed covers placed over the probe heads to ground the pressure system.

To document the terrain and traffic environment, a digital SLR camera with video capability was mounted on a tripod and installed on the front passenger seat of the vehicle. Synchronization of the video with the acquired data has allowed an identification of the conditions experienced which provide context for various patterns observed in the wind measurements, for example the wake of a passing vehicle on the highway.

To allow correction of the wind measurements for offsets in the physical probe angles, due to alignment uncertainty during installation, as well as to characterize the influence of the vehicle on the winds at the measurement locations, the test vehicle was installed over the Ground Effect Simulation System (GESS) of the NRC 9 m Wind Tunnel (shown in Figure 3). This provided a known uniform flow in which to perform yaw sweep measurements with the vehicle measurement system. By comparing probe measurements to the known wind condition as measured by the wind-tunnel data acquisition system, the angle offsets and vehicle influence effects were quantified, and subsequently used for data processing to provide a representative measure of the winds in the absence of the vehicle. Under zero yaw conditions, the probes measured wind speeds of 78%, 86%, 95% and 98% of the blockage-corrected wind-tunnel speed, from lowest to highest, respectively. The probe measurements also showed sensitivity to wind angle, with a decrease in sensed wind speed at 15° yaw of approximately 5% from the zero-yaw values. The lowest probe showed the greatest sensitivity of the sensed wind angle to yaw, with a 5° increase in wind-angle at a yaw angle of 15° (measured 20°). The three higher probes showed an increase in wind angle over this range no greater than 2°.



Figure 3. Test vehicle in NRC 9m Wind Tunnel

Eight days of road measurements were performed between October 11 and November 22, 2012. Test routes extended approximately 150 km from Ottawa, Ontario, Canada to encompass a range of terrain and traffic conditions.

DATA ANALYSIS PROCEDURES

The principles behind the measurement probes and the manner in which the four measured pressures can be converted to wind speed and angles are described by Hooper and Musgrove [8]. The probes are pre-calibrated for the transducer, head, and tubing response. A Matlab-based data reduction software was used for data processing.

A two-pass approach to the detailed data processing was taken, to allow a refinement of the time periods of interest for the final results. During the first pass of data processing, the entire data set for each measurement run was processed.

Synchronized time series were output for ground speed, bearing, barometric pressure, temperature, the three components of motion (acceleration and velocity) for each of the four probe holders, and wind speed, static pressure, and wind angles for each of the four probes. An additional set of time series was exported with these data that represented 10-second means of the full time series. This second set of data allowed a quick assessment of turbulence intensity levels measured by the probes. A sample of the first-pass wind and GPS data is shown in Figure 4 for a data set collected while travelling at 100 km/h on a four-lane divided highway under moderate wind conditions. The temporal variations in vehicle speed and wind velocity magnitude for all four probes are shown in the upper plot, with the temporal variations of lateral and vertical wind angles at 1.5 m from the ground shown in the middle plot. The lower plot shows the 10-second-average turbulence intensities measured at 1.5 m from the ground.

Figure 4 also shows some of the notes made about the conditions experienced during the measurement run, based on the video recording for the run. Of note from the data presented in Figure 4 is the influence of the vehicle on the lower probes which show reduced wind speed magnitude. It is also evident that the presence of other vehicles has a strong influence on the measured turbulence characteristics.

For the second pass of data processing, the initial time-series of data were subdivided into period of interest, based on the notes similar to those shown in the upper plot of Figure 4. The classification system used for the analysis is described later. Periods of constant ground speed were identified, and segments of the measurement runs with specific characteristics were identified, such as the period in Figure 4 from about 40 to 220 s representing low-traffic conditions, or the period from 450 to 980 s representing moderate traffic. For each of the time-periods of interest, post-processing of the data was performed to calculate the mean and rms values of the three wind components, and the corresponding wind spectra represented by the power spectral densities (PSDs).

Low-frequency variations in the wind measurements arose due to some non-stationarity of the conditions encountered on the road. As a result, the low-frequency range of the calculated spectra (<0.25 Hz) did not compare well for similar conditions, despite agreement in the high frequency range. To eliminate any bias in the turbulence intensities as a result of such non-stationary variations, the turbulence intensities quantified herein represent those calculated from an integration of the appropriate spectra for which the energy levels below 0.25 Hz were limited to a value defined by the average energy between 0.2 Hz and 0.3 Hz. In addition, the turbulence length scales were calculated using a best-fit von-Karman distribution to the modified spectra, according to the generic von-Karman spectra defined by ESDU [9].

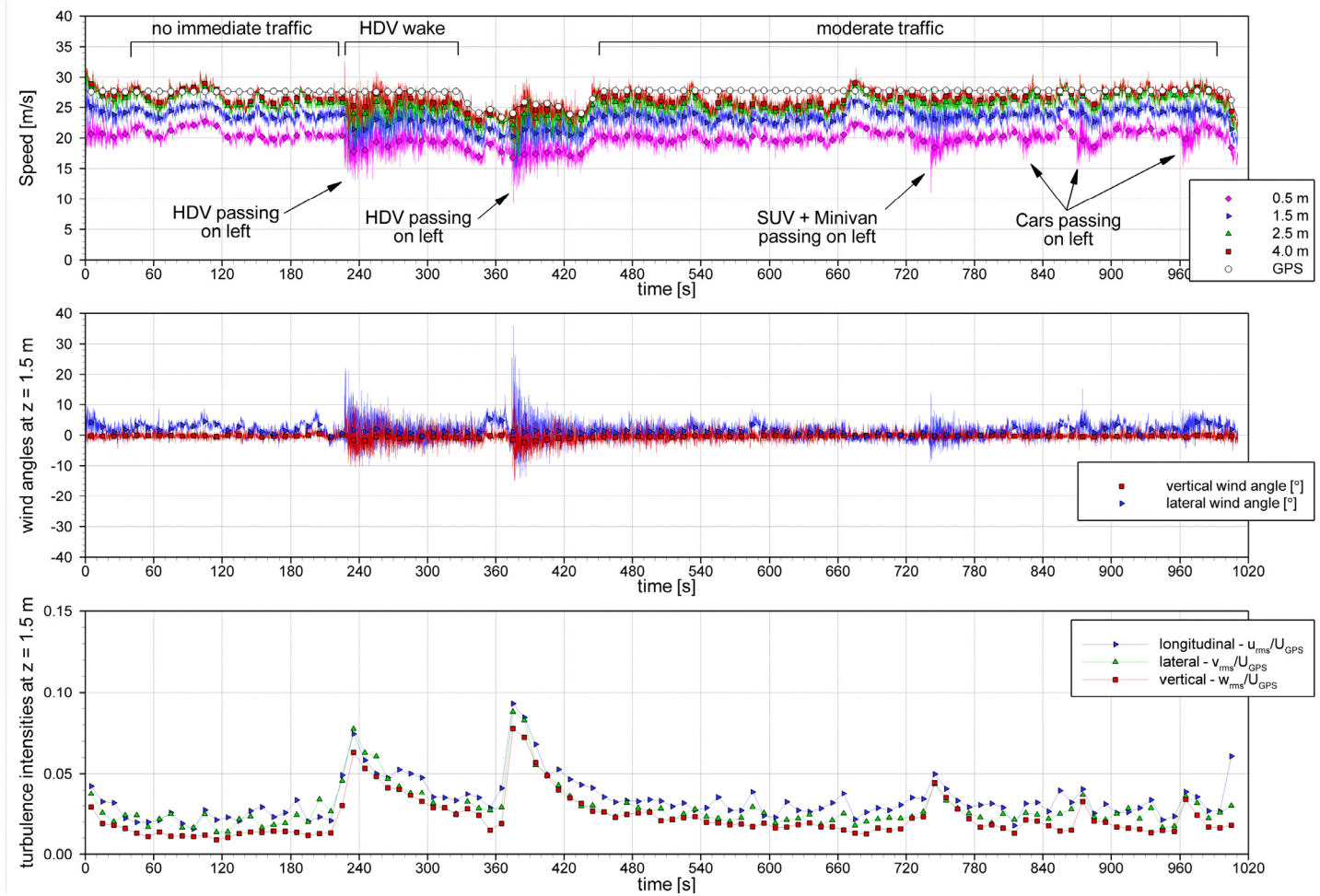


Figure 4. Preliminary processed data for sample measurement run (top - wind speed signals from the four probes and 10s-mean GPS speed, middle - wind angle signals from probe at 1.5 m from ground, bottom - 10s-mean turbulence intensities from probe at 1.5 m from ground)

For each set of conditions defined by the classification system described later, the wind spectra from the associated segments were averaged to provide a wind spectrum representative of that condition. To account for differences in vehicle speed, and to provide a means to compare the on-road data to subsequent wind-tunnel measurements, the wind spectra were normalized. The appropriate frequency scaling is the reduced frequency, defined as:

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

For the on-road data, the reference length scale (L_{ref}) is taken as 1 m. The reference speed (U_{ref}) is taken as the vehicle ground speed. The PSDs are normalized as:

$$PSD(f_r) = \frac{PSD(f)}{U_{ref} \cdot L_{ref}} \quad (2)$$

which ensures that the energy level of the normalized spectra is appropriately scaled for the reduced frequency definition. This normalization was performed prior to averaging of the

wind spectra for a given set of conditions. For each condition, the maximum and minimum of the normalized wind spectra were also identified to provide the bounds within which the turbulence energy for the condition were limited. The minimum, mean, and maximum spectral distributions were smoothed to allow ease of visual comparison.

Spatial cross-correlations between each of the probes were also calculated for each data segment. A correlation value for each probe pair was calculated for the u , v , and w components. To avoid the low-frequency non-stationarity of the on-road measurements, described above, the time series were high-pass filtered with a cut-off frequency of 0.25 Hz prior to the correlation calculations. The spatial cross-correlation for a given spacing (Δx , Δy , Δz) is defined as:

$$R_{ii}(\Delta x, \Delta y, \Delta z) = \frac{\langle u_i(x + \Delta x, y + \Delta y, z + \Delta z, t) u_i(x, y, z, t) \rangle}{\sigma(x + \Delta x, y + \Delta y, z + \Delta z, t) \sigma(x, y, z, t)} \quad (3)$$

where i refers to the velocity component (u, v, w), σ is the standard deviation of the specific component over the full length of the time series, and $\langle \rangle$ represents the time average.

CLASSIFICATION OF THE ON-ROAD WIND MEASUREMENTS

The video and turbulence data for each set of on-road wind-measurement data were analyzed and subdivided into segments representing what appeared to be a constant set of conditions. Each of these segments, which varied in length between 30 seconds and 10 minutes, were subsequently processed and categorized based on three different criteria: terrain roughness; traffic density; and wind strength.

Terrain Roughness

In standard wind-engineering practice, the characteristics of the winds are categorized by the terrain type over which the winds prevail [10]. It was anticipated that the turbulent wind characteristics experienced by road vehicles will therefore also be correlated with terrain roughness.

For each of the segments extracted from the on-road wind measurements, a relative measure of the local terrain roughness was assigned based on observations from the video data combined with examining topographical maps of the route travelled. The terrain roughness was classified into four categories, for which a sample video frame is shown for each in Figure 5. The four categories are:

- Flat: Regions with little or no infrastructure and obstacles. Predominantly vast stretches of farmland.
- Moderate: Regions with vegetation such as forests or mixed farmland-and-forests.
- Rough: Urban infrastructure.
- Complex: Forested Regions with large hills.

Traffic Density

The wake of a road vehicle is highly unsteady and affects the wind characteristics experienced by trailing vehicles on the road. The high turbulence in the wake also decays with distance from its source vehicle, such that the strength of the turbulence experienced by following vehicle is dependent on the spacing between the vehicles. It is therefore anticipated that traffic density will have an impact on the turbulent wind characteristics experienced by HDVs on the road, with higher turbulence levels experienced in dense traffic conditions.

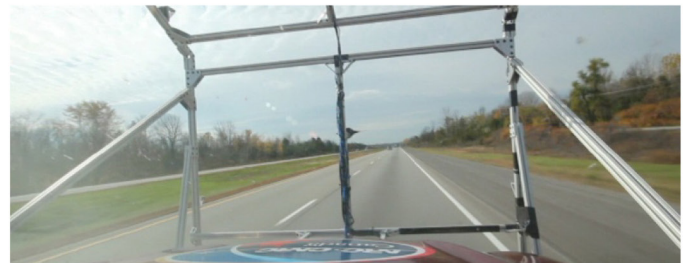
For each of the segments extracted from the on-road wind measurements, a relative measure of the traffic density was assigned based on observations from the video data combined with examination of the measured wind fluctuations. The traffic density was classified into four categories, for which a sample video frame for each are shown in Figure 6. The four categories are:

- Light - Very little traffic with no vehicles immediately ahead. Long stretches between vehicle passings.
- Moderate - Increased number of vehicles with inter-vehicle distances greater than about 20 m. Wind data shows signatures of ambient terrain and wind conditions for part of the time (30-70%), and signatures of vehicle wakes for remainder of the time.

- Dense - Many vehicles in multiple lanes in which measured winds are dominated by vehicle wakes.
- HDV Wake - In the wake of an HDV, the wind fluctuations are often dominating by a vortex-shedding phenomenon that causes high lateral fluctuations at a frequency on the order of 2 Hz. Under these situations, the turbulence is dominated by the effect of the HDV.



a - Flat terrain



b - Moderate terrain



c - Rough terrain



d - Complex terrain

Figure 5. Examples of terrain roughness conditions experienced during the on-road measurements