

A Novel Technique to Determine Free-Stream Velocity from Ground-Based Anemometric Measurements During Track Tests

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ABSTRACT

A novel method was developed to predict the free-stream velocity experienced by a traveling vehicle based on track-side anemometric measurements. The end objective of this research was to enhance the reliability of the prediction of free-stream conditions in order to improve the accuracy of aerodynamic drag coefficient (C_D) assessments from track tests of surface vehicles. Although the technique was applied to heavy-duty vehicles in the present work, it is equally applicable to any vehicle type. The proposed method is based on Taylor's hypothesis, a principle applied in fluid mechanics to convert temporal signals into the spatial domain. It considers that the turbulent wind velocity fluctuations measured at one point are due to the "passage of an unchanging pattern of turbulent motion over the point". The method is applied to predict the wind velocity that the vehicle will experience as it encounters a wind pattern detected earlier by an anemometer located upwind. The proposed technique has the potential to enhance the accuracy of free-stream velocity predictions aimed at calibrating a vehicle-mounted anemometer. A sensitivity analysis highlights the errors on the predicted free-stream speed and yaw angle that result from errors in the evaluation of the terrestrial wind speed and direction. Moreover, considering that a surface vehicle travels through the atmospheric boundary layer, it is demonstrated that using track-based anemometers to calibrate a vehicle-mounted anemometer installed at a different height leads to incoherency and can cause substantial errors in the evaluation of free-stream conditions. It is recommended that all ground-based anemometers be installed at the same reference height relative to local ground, as the vehicle-mounted anemometer.

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INTRODUCTION

In the framework of a research collaboration with Environment Canada¹, the Aerodynamics Laboratory of the National Research Council of Canada (NRC) conducted aerodynamic experiments on two tractor-trailer combinations at Ford Motor Company's Arizona Proving Ground (APG). The experiments were conducted in June 2011 in the midst of the Environmental Protection Agency's (EPA) test campaign for the development of the Phase-I regulations to curtail greenhouse gas emissions and fuel consumption of medium- and heavy-duty vehicles (HDV), which led to the Phase-I rules in the USA [1] and in Canada [2]. The experiments and the ensuing analysis conducted by the author were documented in three technical reports². The present article is derived from this research which led to the development of ideas, techniques and procedures aimed at enhancing the accuracy and reducing the uncertainty of free-stream wind predictions and aerodynamic drag assessments from track tests, applicable to any vehicle type.

The Phase-I regulations [1] introduced by the EPA relied on coast-down testing as the primary technique to determine the aerodynamic drag coefficient (C_D) of test vehicles with the possibility of using

alternative methods (wind tunnel testing or CFD³) correlated to coast-down results. The required use of a track-side anemometer during coast-down tests, following recommended practice SAE J1263⁴ [3], was only aimed at determining whether the mean wind speed was below the admissible limit of 16 km/h but this anemometric data was not utilized in the analysis. Thus, the Phase-I regulations focused on the "zero-yaw drag coefficient" without ascertaining that the yaw angle was effectively zero. The proposed phase-II rule [4] introduces the use of a vehicle-mounted anemometer with the intent of taking into account the variation of C_D with yaw angle (Ψ_∞), from which a wind-averaged drag coefficient (C_{Dwa}) is derived by combining with the results from one of the alternative methods. The proposed test procedure is akin to SAE recommended practice J2263 [5] whereby wind velocity measurements from one or several track-based anemometers are utilized to correct the readings of the vehicle-mounted anemometer for "vehicle blockage". However, one major deviation of the proposed rule from standard J2263 is that the terrestrial wind velocity measured by track-based anemometers at vehicle mid-height is used to "calibrate" the vehicle-mounted anemometer sensing the apparent wind at a different

³. Computational Fluid Dynamics

⁴. Note that SAE Recommended practices J1263 and J2263 are not heavy-duty vehicle testing standards. In this paper, reference to these two recommended practices is made because they are currently the only two SAE standards covering road load measurement with the coast-down technique

¹. Now "Environment and Climate Change Canada"

². These reports published in 2011, 2012 and 2013 contain proprietary information and consequently may not be used as references in this paper. Notwithstanding, the author is making their non-confidential content available for the benefit of the readers.

height. The soundness of this approach will be evaluated herein by considering intrinsic properties of the terrestrial wind, which constitutes the operational environment for such tests.

The aerodynamic drag coefficient of HDVs is typically characterized by a pronounced rise with yaw angle. The assessment of the yaw-sensitivity of C_D from track tests requires testing in windy conditions producing large enough free-stream yaw angles to enable the calculation of C_{Dwa} , the wind-averaged drag coefficient. This characterization is important to enable the evaluation of fuel consumption in various wind conditions. In this respect, the pioneering work of Buckley, Walston et al. [6] [7] who developed procedures and analysis methods for coast-down testing in windy conditions has provided valuable insight for the present work. The subsequent work by Buckley [8] has contributed towards the development of SAE recommended practice J2263. Notwithstanding, the methods proposed in reference [8], in SAE standard J2263 [5] and in the proposed phase-II rule [4] to name a few, rely on assumptions that do not take into consideration the turbulent nature of the terrestrial wind for the calibration of a vehicle-mounted anemometer. For instance, one such assumption was exemplified by Buckley [8]:

"The analysis rests on the assumption that the spatial averages of the wind speed and direction along a common section of test track are the same during two successive vehicle passes back and forth along the track ..."

Likewise, many studies aimed at determining the drag coefficient from track tests (e.g. [9]) do not consider the inherent property of the terrestrial wind in ground vicinity, which is characterized by spatio-temporal, turbulent fluctuations with correlation length scales not exceeding several metres [10]. In a specific example pertaining to HDVs [4], the terrestrial wind speed and direction measured in proximity of the test track midpoint are used as reference values to calibrate the onboard anemometer readings taken during the same time interval, irrespective of the vehicle's position along the track. This method rests on the assumption that the terrestrial wind velocity at the vehicle location is equal to the wind velocity measured at the track midpoint during the same time interval, suggesting that the wind is spatially uniform and characterized by temporal variations only.

The first portion of the present paper considers free-stream wind conditions in the context of a surface vehicle traveling through the near-ground turbulent boundary layer and the errors that result from an improper free-stream correction of the apparent wind measured onboard a traveling vehicle. A detailed review and analysis of the turbulent winds experienced by a surface vehicle traveling through the atmospheric boundary layer was presented by Cooper and Watkins [11], emphasizing the large variability of turbulent wind conditions that a vehicle can experience. More recently, McAuliffe [12] reported experimental results characterizing the turbulent environment experienced specifically by heavy-duty vehicles, corroborating the wide range of turbulent wind conditions associated with the surrounding terrain or the presence of nearby vehicles, among other things. In the present work, a novel technique is proposed to predict the free-stream wind velocity from track-based anemometric measurements using "Taylor's hypothesis", a useful

approximation first proposed by British physicist *Geoffrey Ingram Taylor* [13]. This analysis technique is applied to correct the onboard anemometric measurements to free-stream conditions. Moreover, the consideration that a surface vehicle travels through the atmospheric boundary layer is treated analytically to evaluate the effect of the vertical position of a vehicle-mounted anemometer on the prediction of free-stream velocity. Finally, some procedural guidelines are then proposed, to maximize the accuracy and reliability of track tests aimed at characterizing vehicle aerodynamic performance.

SCOPE

The experimental campaign conducted in the framework of the present project was the first such field test carried out by the NRC Aerodynamics Laboratory, contrasting with its primary activity of wind tunnel testing. The experience and the aerodynamic data gathered during these tests motivated the examination of the challenges associated with aerodynamic measurements in the field and the development of ideas having the potential to improve the accuracy and reliability of aerodynamic experiments conducted in an uncontrollable, unsteady environment. This first implementation of the proposed methods is illustrated by applying them to the limited data set acquired during these experiments. Further testing with optimized experimental arrangements would enable the improvement and refinement of the proposed techniques.

CONTEXT AND EXPERIMENTAL ARRANGEMENT

The experimental campaign was commissioned by the EPA in the context of the development of its Phase-I regulations for limiting GHG emissions from medium- and heavy-duty vehicles [1]. In the midst of this test program, NRC was granted access to two tractors each coupled to a 28-foot trailer⁵ to conduct a distinct set of aerodynamic experiments involving the measurement of static pressure distributions on the tractors and trailers. NRC conducted constant-speed runs to acquire static pressure signals using its own on-board instrumentation system and coast-down runs for evaluating the vehicles' aerodynamic drag. The static pressure experiments will be the focus of a separate publication.

The experiments were conducted at Ford's Arizona Proving Ground located in Wittmann, approximately 65 kilometres north-west of Phoenix, Arizona. A satellite view of the test track is shown in [Figure 1a](#). The lower plot displays in red the itinerary followed by one of the test vehicles during several runs, as acquired by the onboard GPS receiver. Two propeller-vane anemometers were installed on the windward side of the straightaway to measure the wind speed and direction, at positions prescribed by the EPA. They are labelled AN_1 and AN_2 in [Figure 1b](#). A measurement station was also located next to anemometer AN_1 to record the barometric pressure, temperature and humidity of the air required for calculating the density and viscosity of the ambient air. The data from both sites were recorded with two GPS data loggers at a rate of 10 samples per second. Each vehicle tested was equipped with a similar propeller-vane anemometer

⁵. 28-foot trailers were used because the same tractor-trailer combinations were previously tested in the NRC 9m x 9m Wind Tunnel, which cannot accommodate larger vehicles in its test section.

protruding 2.4 metres ahead of the vehicle nose at the end of a boom, sensing the wind speed and angle that were also recorded by an onboard GPS data logger. Details on the characteristics and accuracies of the instrumentation used are provided in the [Appendix](#).

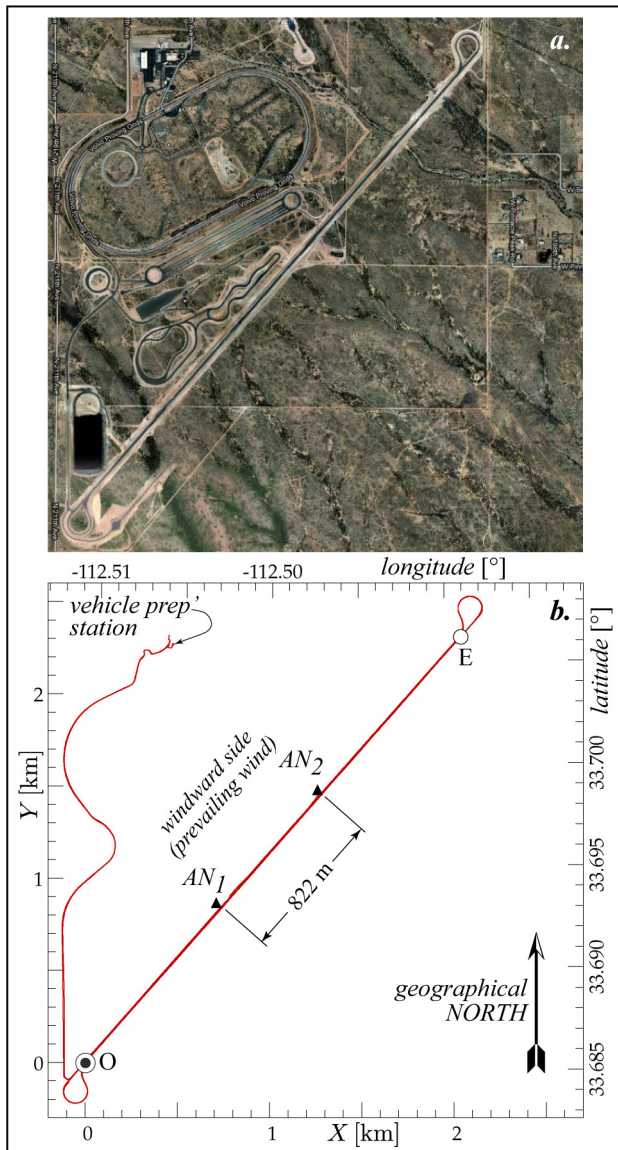


Figure 1. a. Aerial view of the APG straightaway and b. GPS map of the vehicle trajectory recorded during the tests.

The GPS latitudes and longitudes were converted to orthogonal cartesian coordinates by using the equations defining the WGS84 ellipsoid [14] as an approximation to the earth's shape, the standard representation used on current GPS devices. As shown in the lower plot of [Figure 1](#), the north end of the southern hairpin was defined as the origin of the test track ($X, Y = (0, 0)$) (labelled 'O'), whereas the south end of the northern hairpin was defined as the end of the track (labelled 'E'). Based on the GPS data, the useful track length, i.e. distance OE , is approximately 3.078 km. The results from a survey of the straightaway indicates a maximum elevation difference of approximately 64 millimetres over a distance of more than 3 km, as determined from a set of 100 measurement points. The flatness of this track ensured that gravitational loads could be neglected in a

coast-down analysis. The track consisted of a single lane⁶ that was traveled back and forth in both directions. The flatness of the land surrounding the track with a minimal number of obstacles was favourable in terms of wind conditions. The long fetch over which the wind profile develops with minimal obstruction is indeed conducive to stabler winds.

ON THE CRITICAL IMPORTANCE OF FREE-STREAM CONDITIONS

The coefficient of aerodynamic drag C_D is the ratio of the drag force D experienced by a traveling vehicle to the force that would result from applying a pressure differential equal to the free-stream dynamic pressure q_∞ across a surface of area A , typically the vehicle frontal area:

$$C_D = \frac{D}{q_\infty A} = f(\Psi_\infty, Re_\infty) \quad (1)$$

$$\text{where } q_\infty = \frac{1}{2} \rho U_\infty^2 \quad \text{and} \quad Re_\infty = \frac{U_\infty w}{\nu} \quad (2)$$

The accuracy in quantifying C_D , the measure of a vehicle's aerodynamic efficiency, depends critically on the ability to determine the approach flow conditions 'at infinity (∞)', that is, sufficiently far, in the free-stream zone where the flow field is unperturbed by the vehicle's presence. In a wind tunnel, where the flow conditions are controlled, the flow field around the test vehicle is distorted by the tunnel-specific configuration⁷, when compared to operating conditions in 'open air'. The associated challenge is to predict the corresponding free-stream values by applying empirical blockage-corrections. To reduce the implicit errors, it is advisable to minimize these approximate corrections by combining a vehicle model with a wind tunnel test section producing a minimal area ratio A/C while satisfying the minimum Reynolds number constraint $Re_\infty > Re_{min}$, as achieved with the experimental configuration described in [15] for testing HDV models.

The analogous challenge for aerodynamic experiments on test tracks is distinct. In this case, unlike in a wind tunnel simulation, the flow conditions are realistic, but the zone where perturbation-free wind conditions exist is too far from the vehicle nose for probing with a conventional boom-mounted anemometer, typically sensing the apparent wind velocity within a few metres forward of the nose of a HDV. This phenomenon was demonstrated by means of a wind tunnel experiment⁸ whereby the PIV⁹ technique was applied to measure the flow field forward of the nose of a generic HDV model in a horizontal plane at model mid-height. The results are schematized in [Figure 2](#). An anemometer sensing the wind velocity forward of the vehicle at point *a* measures a wind speed that is lower than the unperturbed wind speed U_∞ and a wind angle larger than Ψ_∞ by virtue of the

⁶. The facility has since been upgraded with the addition of a separate second lane.

⁷. e.g. solid boundaries for closed test section wind tunnels and nozzle-collector configuration for open-jet wind tunnels.

⁸. This research conducted by the author was documented in an R&D report containing proprietary information.

⁹. Particle Image Velocimetry

presence of the solid obstacle downwind distorting the flow field. Relying on this information to determine the drag coefficient can lead to significant errors:

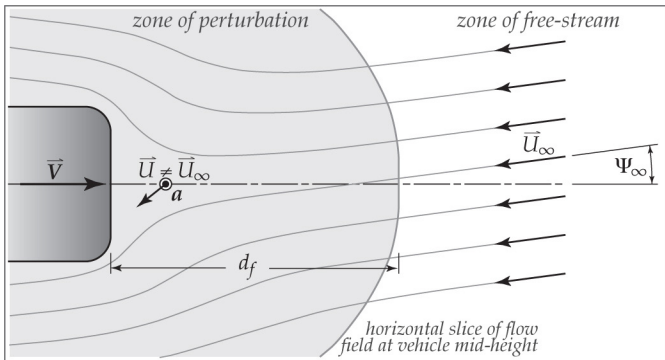


Figure 2. Schematic diagram of the perturbed velocity region surrounding a traveling vehicle.

$$\epsilon(C_D) \approx -2 \epsilon(U_\infty) \quad (3)$$

Equation 3, which was obtained by differentiating equation 1, indicates that the relative error on C_D is twice the relative error on U_∞ . Walston et al. [6] reported that an anemometer located 3 metres forward of the nose of a 1970's HDV measured a speed approximately 10% lower than the free-stream value. Based on equation 3, this would result in an overestimate of C_D of the order of 20%. The impact on the curve $C_D(\Psi_\infty)$ of a biased measurement of the velocity $\vec{U}_\infty$ within the perturbed zone ahead of the vehicle is depicted in Figure 3. At zero degrees of yaw, the bias in the measured wind speed causes a vertical shift of C_D from point A to point B. For non-zero yaw angles, the C_D shift is accompanied by a yaw angle bias (e.g. from point C to point D) resulting in the observed vertical shift and flattening of the $C_D(\Psi_\infty)$ curve.

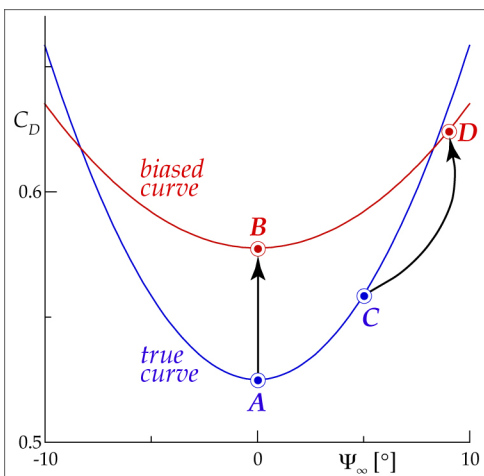


Figure 3. Schematic illustration of the C_D -bias caused by measuring the apparent wind in the perturbed zone.

In the context of quantifying the aerodynamic drag coefficient of a surface vehicle on a road, the determination of the free-stream speed U_∞ and yaw angle Ψ_∞ presents a major challenge. The general concept consists in calculating the vectorial difference between the

vehicle velocity $\vec{V}$ and the unperturbed terrestrial wind velocity $\vec{W}$ experienced by the vehicle to produce the free-stream velocity vector $\vec{U}_\infty$. These values are then used to apply a "free-stream calibration" to the anemometric data sensed by a boom-mounted anemometer measuring the biased apparent wind at point *a* (see Figure 2). The technical challenge is related to the fact that the terrestrial wind measurement is made at a single specific point in space, some distance away from the vehicle trajectory. Thus, the spatial resolution is non-existent. However, the 100 ms temporal resolution of the anemometers used in the present study, is small relative to the time scales of the turbulent motions. This will be capitalized on in the analysis to follow.

FRAMEWORK

A schematized plan view of the zone of interaction between a traveling vehicle and the measured terrestrial wind is shown in Figure 4. The track-based anemometer (labeled *AN*), located a distance L from the centreline of the vehicle's trajectory, measures the terrestrial wind velocity vector $\vec{W}(t)$ which is oriented at angle $\gamma(t)$ relative to the vehicle travel direction. An important consideration is that the height of the anemometer sensing point relative to the local ground must be the same as the height of the vehicle-mounted anemometer above the test track, as will be demonstrated below. The anemometric information measured at point *AN* propagates over a distance F (the fetch) to reach point *c* some time after the measurement was made. The measured 'wind front' and the vehicle's boom-mounted anemometer meet at point *c* at a unique instant in time. The vectorial difference between the terrestrial wind and vehicle velocities at that precise space-time instant yields the sought free-stream velocity vector $\vec{U}_\infty$:

$$\vec{U}_\infty(t) = \vec{W}(t) - \vec{V}(t) \quad (4)$$

By expressing this vectorial equation in terms of magnitude and direction, we obtain the free-stream wind speed¹⁰ and direction:

$$U_\infty(t) = V(t) \sqrt{1 + 2\sigma(t) \cos \gamma(t) + \sigma^2(t)} \quad (5)$$

$$\tan \Psi_\infty(t) = \frac{\sigma(t) \sin \gamma(t)}{1 + \sigma(t) \cos \gamma(t)} \quad (6)$$

$$\text{where } \sigma(t) = \frac{W(t)}{V(t)} \quad (7)$$

Examining Figure 4, the position of the weather station on the windward side of the track is conducive to a prediction of the unperturbed terrestrial wind velocity that will combine with the instantaneous vehicle velocity at point *c* to yield the free-stream wind velocity experienced by the vehicle at the instant it crosses that point. However, if the wind direction were shifted 180°, with the weather

¹⁰. Throughout this paper, the word "velocity" (e.g. $\vec{V}$) refers to a vector whereas "speed" (e.g. V) refers to the magnitude (scalar) of the velocity.

station now located on the leeward side of the track, the anemometer would then be located downwind of point **c** and consequently, it would sense some wind velocity originating from point **c** at some time after the passage of the vehicle through that point. This wind velocity is not equal to the *unperturbed* terrestrial wind velocity experienced by the vehicle at point **c**. Instead, it is a perturbed wind velocity corresponding to the "signature" of the vehicle's passage at point **c**. The utilization of a wind velocity sensed by an anemometer installed on the leeward side of a test track to calculate the free-stream wind velocity experienced by a traveling vehicle introduces a bias in the aerodynamic analysis.

Examples of suggested configurations for terrestrial wind measurements are shown in Figure 5. Under conditions of a prevailing wind direction whereby the same side of the track is consistently to windward (Figure 5b), then all available anemometers would be installed on that side¹¹. This situation is optimal since all anemometers provide useable wind data at all times, from which a substantial database of calibration points can be created with efficiency. On the contrary, when the wind direction is unpredictable and can alternate on either side of the track in the course of a test campaign, then a pair of anemometers should be installed at each measurement station, one on either side of the track, as shown in Figure 5a. In this case, only the anemometric data from the windward anemometers is used for the calculations, so half as much valid data as in the former case will be collected per unit of time.

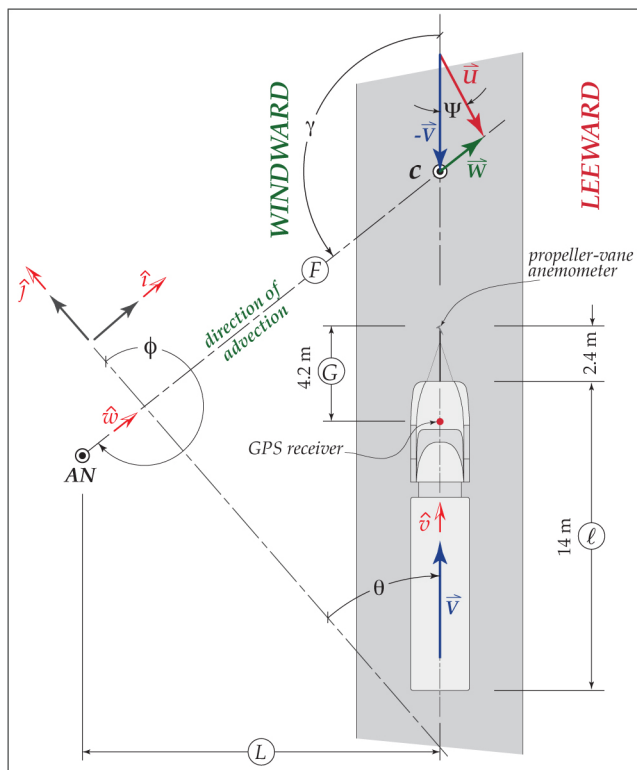


Figure 4. Schematized plan view of the interaction between the measured wind and the traveling vehicle.

COASTING THROUGH THE ATMOSPHERIC SURFACE LAYER

The schematics of Figures 2 and 4 only portray a simplified bird's eye view of the conditions that a vehicle is subjected to during a track experiment. It is important to recognize that the vertical distribution of the terrestrial wind velocity has a fundamental impact on the flow field that a traveling vehicle experiences and consequently on the approach used to evaluate the reference wind velocity vector $\vec{U}_\infty$. The "natural wind" has fundamental characteristics that may affect the aerodynamic loads experienced by a travelling vehicle, as shown by Watkins and Cooper [16]. One such characteristic is the variation of the wind velocity with elevation. The atmospheric surface layer (ASL) is defined as the layer of air in the immediate vicinity of the earth's surface within which the mean wind speed increases monotonically from zero at ground level to an outer value at the edge of the layer. This layer is turbulent, that is, the velocity at any point in space fluctuates relative to the local mean, with velocity variations in all three spatial directions. In general, it can be said that the time and length scales associated with these fluctuations are a function of the height z , of the topology and roughness of the surrounding terrain (see reference [11]) and of the external forcing by temperature and pressure gradients, among other things.

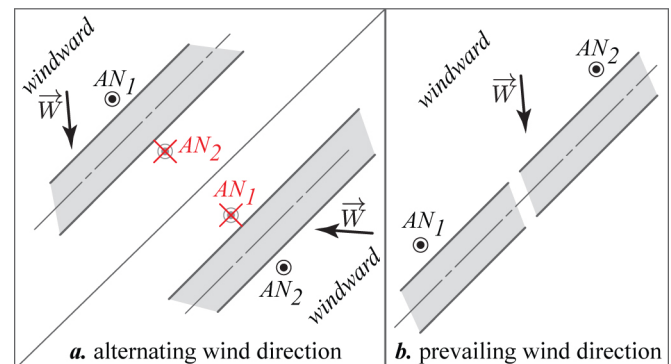


Figure 5. Schematic of acceptable configurations for terrestrial wind measurements

Turbulent boundary layers have been studied extensively in laboratory wind tunnels but the ASL has received less attention, due to the technical challenges involved. However, recent experiments conducted at the SLTEST research facility in Utah [17] [18] have confirmed the similarity between the structure of the near-neutral¹² ASL and canonical, zero-pressure-gradient boundary layers studied in wind tunnels. The results of these investigations are consistent with Von Kármán's "law of the wall" (see reference [19]), a logarithmic function relating the mean velocity distribution to the shear stress (τ) at the solid boundary. In particular, it was shown in [17] that the validity of the "law of the wall" spans the lower 15% of the near-neutral ASL, which is reported to have a thickness of 80 ± 8 metres. Hence, any surface vehicle is totally immersed within the logarithmic wind velocity profile that extends up to about 12 metres from the ground. The "law of the wall" for a fully developed turbulent boundary layer on a flat plate is given by:

¹¹. This was the case for the present experiments

¹². In a neutrally-stable ASL, shear-driven turbulent energy production overwhelms buoyancy-driven production caused by thermal gradients

$$\frac{W(z)}{U_\tau} = \frac{1}{\kappa} \ln \left(\frac{z U_\tau}{\nu} \right) + B \quad \text{where} \quad U_\tau = \sqrt{\frac{\tau}{\rho}} \quad (8)$$

Where U_τ is the skin friction velocity, κ is the Von Kármán constant ($\kappa \approx 0.4$) and B is a parameter characterizing the roughness of the boundary. In practice, for the atmospheric surface layer, an equivalent and more practical relationship (e.g. in [20]) is used to capture the surface roughness effects, as follows:

$$W(z) = \frac{U_\tau}{\kappa} \ln \left(\frac{z}{z_o} \right) \quad (9)$$

Where z_o is an empirical constant called the "characteristic roughness height" whose value has a large impact on the mean velocity distribution. z_o is not a direct measure of the height of terrain roughness, rather a measure of its capacity to withdraw momentum from the flow near the ground. Its value is obtained through field experiments. For the present analysis, it was more practical to rewrite equation 9 in terms of the value of the mean wind speed W_{ref} prevailing at the reference height¹³ z_{ref} :

$$W(z) = W_{ref} \frac{\ln(z/z_o)}{\ln(z_{ref}/z_o)} \quad (10)$$

Figure 6 presents two mean wind velocity profiles for the lower 6 metres of the ASL, based on equation 10. The fuller profile ($z_o = 5 \cdot 10^{-4}$ m) corresponds to the ASL developing over a flat desert whereas the other mean speed distribution ($z_o = 5 \cdot 10^{-2}$ m) is characteristic of the wind blowing over a field with tall grass. These empirical parameters were obtained from reference [20]. Both profiles were calculated for a consistent mean wind speed of 25 km/h at the vehicle mid-height point ($z_{ref} = 2.057$ metres for a typical tractor-trailer) depicted by the bull's eye symbol. This value is within the limits prescribed in the SAE recommended practice J2263 for coast-down testing [5]. The figure emphasizes the marked variation of mean wind speed with height and the dramatic effect of terrain roughness on the velocity gradient.

For a given wind direction γ and vehicle speed V , one can calculate the variation in apparent mean wind speed and yaw angle as a function of height z by applying equations 4 to 7 and 10. Figure 7 depicts the apparent wind profiles that a vehicle would experience when traveling at 60 and 120 km/h in the presence of a terrestrial wind characterized by equation 10 and blowing at $W_{ref} = 25$ km/h, at 30 degrees from the travel direction, for both terrain roughness conditions. The upper two plots (a, b) correspond to the vehicle traveling against a headwind and emphasize the speed deficit in the near-ground region and the monotonic increase of free-stream speed and yaw angle with height. For the rougher terrain and a vehicle speed of 120 km/h, the yaw angle increases from about 6° to 10° between heights $z = 0.5$ m and $z = 4$ m. The corresponding lower plots (c, d) display the profile for the vehicle traveling in the opposite

direction, with a tailwind blowing at $\gamma = -150^\circ$. In this case, because the tailwind component reduces the magnitude of $\vec{U}$, the yaw angle variations are exacerbated, with a rise from approximately 4° to 9° between the same heights of 0.5 and 4 metres. It is noteworthy that the apparent wind speed increases monotonically towards the ground level, in this case. The distinct shapes of these velocity profiles indicate that coast-down runs in opposite directions in the presence of terrestrial winds are different in character and ought to be treated as distinct objects of analysis. Besides, the variation of velocity with height warrants special attention with respect to prescribing the height at which the vehicle-mounted anemometer measures the apparent wind.

The plots presented in Figure 8 were created to investigate the effect of varying the vertical position z_{an} of the vehicle-mounted anemometer on the correspondence between the apparent wind speed U_{an} measured at that height and the speed U_{ref} that would be sensed if the anemometer were positioned at the reference height z_{ref} . The control parameters are shown in the inset of Figure 8a, with z_{ref} corresponding to the mid-height of a typical HDV. The data was produced by varying the vehicle speed V , much like during a coast-down run. As expected from the previous examination of the velocity profiles, if the anemometer is positioned above the reference height, then U_{an} exceeds U_{ref} for the headwind run whereas the converse is true for the tailwind run. For example, for a speed of $U_{ref} = 60$ km/h and the anemometer located 3 metres above the reference position, i.e. $z_{an} = z_{ref} + 3$ m = 5.057 m, the measured speed is about 12% higher than U_{ref} for the headwind run. On the contrary, for the tailwind run, U_{an} is approximately 8% lower than the reference speed U_{ref} , an overall difference of 20% between headwind and tailwind runs with the same value of U_{ref} . When the test anemometer is positioned below z_{ref} , the trend is reversed.

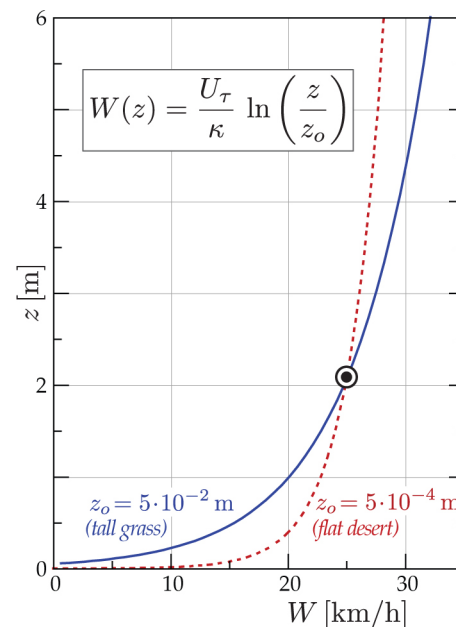


Figure 6. Typical mean wind profile of the near-neutral ASL.

¹³. Here, the reference height z_{ref} is defined as the height above ground at which both the terrestrial wind and the apparent wind velocities should be measured. It is common practice (e.g. in SAE J2263 to set $z_{ref} = h/2$, the vehicle mid-height