

Accurate Fuel Economy Prediction via a Realistic Wind Averaged Drag Coefficient

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ABSTRACT

The ultimate goal for vehicle aerodynamicists is to develop vehicles that perform well on the road under real-world conditions. One of the most important metrics to evaluate vehicle performance is the drag coefficient. However, vehicle development today is performed mostly under controlled settings using wind tunnels and computational fluid dynamics (CFD) with artificially uniform upstream conditions, neglecting real-world effects due to road turbulence from wind and other vehicles. Thus, the drag coefficients computed with these methods might not be representative of the real performance of the car on the road. This might ultimately lead engineers to develop design solutions and aerodynamic devices which, while performing well in idealized conditions, do not perform well on the road. For this reason, it is important to assess the vehicle's drag as seen in real-world environments. An effort in this direction is represented by using the wind-averaged drag. The wind-averaged drag coefficient is obtained by weighting the vehicle's drag under different yaw conditions. However, being computed in idealized environments with low level of turbulence (both wind-tunnel and CFD) it neglects the natural variability of the wind experienced on the road. High yaw angles are only possible in strong crosswind and are therefore more sensitive to natural wind variability. Therefore, it is fair to say that the current wind-averaged drag relies on unphysical test conditions (high yaw angle and low level of turbulence) to assess the vehicle's performance.

In this paper, unsteady aerodynamics simulations based on the Lattice Boltzmann Method (LBM) are used to assess the aerodynamic performance of a detailed SUV vehicle. Using a surface response method, the drag coefficient of the vehicle is fully and efficiently characterized for different yaw angles and turbulence intensities of the environment. This information is then fed into a driving-cycle calculation and show that the increase in the drag coefficient with yaw and turbulence intensity leads to a reduction of the vehicle's fuel efficiency. A simple loss model is proposed which enables the computation of the energy consumption in real world by pragmatically taking into account the variation of the drag with wind speed, yaw and turbulence intensity. This provides a way to evaluate vehicle designs early in the development cycle and to identify those which are likely to perform well across a wide range of on-road conditions and not just in idealized conditions.

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INTRODUCTION

On-Road Performance

Automobiles and trucks are meant to be driven on the road. On the road, vehicles experience a non-uniform and unsteady flow environment due to the presence of natural wind and other close-by vehicles. The road environment is characterized by a wide range of length- and time-scales which fully encompass the length and time-scales relevant for vehicle aerodynamics. On one hand, the slow and large-scale variations in natural wind can generate a local prevailing crosswind and, on the other hand, the fast and small-scale flow structures represent wind gusts and turbulent eddies. The combination of these structures give rise to a constantly changing environment with significant level of turbulence in which the vehicle experiences a variety of yaw angles. This is remarkably different from the test conditions in modern wind-tunnels which generally

provide an environment with low level of turbulence and are most often used at zero yaw. During the typical process of developing vehicles in wind tunnels to meet aerodynamic targets, body shape parameters, the sizes and angles of aerodynamic devices, and the effectiveness of various measures such as underbody panels, are all determined using idealized conditions. The resulting vehicle design will naturally be tuned to these conditions. Thus, off-design conditions such as crosswind and turbulence typical of on-road driving are highly likely to degrade the aerodynamic performance in such a way that these design changes are no longer the most effective. Engineers need a way to make these design decisions with data showing their effectiveness in more representative realistic conditions.

Probability Distribution of Wind Conditions

Based on simple assumptions and on-road measurements [1] it can be verified that conditions similar to those tested in wind-tunnels are quite rare on the road. First, the most probable yaw angle, even at highway speed, is not zero and, moreover, on-road turbulence is always present. This is clearly shown in Fig.1, which represents the probability of experiencing a given value of yaw and turbulence intensity while driving on the road at 110 km/h. In Fig.1, the green circle and magenta rectangle indicate the regions in parameter space most often tested in wind-tunnels experiments. We note that both regions are unlikely to be experienced on the road where the most probable condition is 5 degrees' yaw and 4% turbulence intensity. The assumptions and procedure used to obtain Fig.1 will be detailed in the "Approach" section.

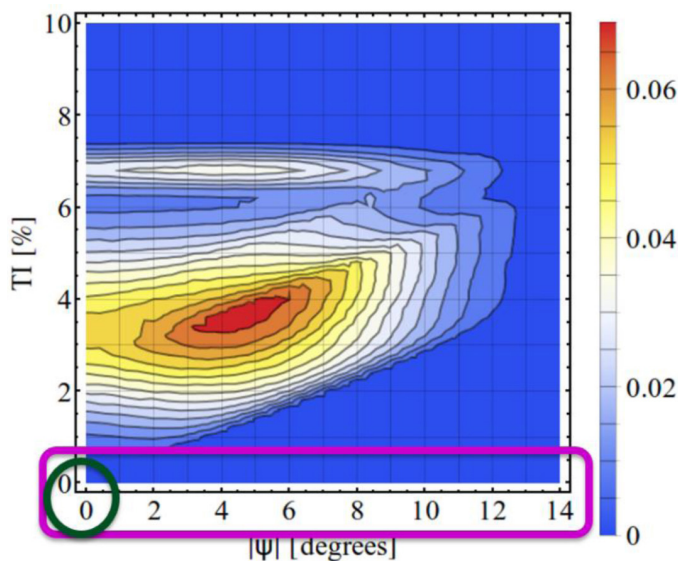


Figure 1. Probability of experiencing a given value of yaw, Ψ , and turbulence intensity, TI [%], while travelling at highway speed of 110km/h. The green circle indicates the region in parameter space most often tested in wind-tunnels experiments. The magenta block indicates the parameter range normally used in wind-averaged drag assessment. The contours are evenly spaced between 0.05 to 0.065 in 0.005 increments.

Wind and Drive Cycles

Aerodynamicists are aware that many differences exist between the conditions tested in wind-tunnels and those experienced on the road. However, it is extremely difficult to quantify the effect of each of these known differences on the aerodynamic performance of the vehicle, and therefore, practitioners must rely on complementary approaches to assess the real-world performance of a vehicle. Two of these approaches are the wind-averaged drag and the driving-cycle. The wind-averaged drag is an effective drag value obtained by averaging the vehicle's drag measured under different yaw conditions. The driving-cycle is a prescribed time variation of vehicle speed which represents a characteristic driving scenario and it is used to estimate the fuel economy of a vehicle. The idea behind both these two approaches is that, to estimate the real-world performance, the vehicle needs to be tested in a variety of conditions. However, these two efforts have not normally been combined. The wind-averaged drag approach neglects the driving cycle since it assumes a constant

vehicle velocity. See for example references [2, 3, 4, 5]. On the other hand, the driving cycle most often ignores the effect on the fuel economy of different yaw angles. Furthermore, both approaches neglect the presence of on-road turbulence.

As will be shown in this paper, these two approaches can be combined with one another and can additionally take into account the presence of on-road turbulence, leading to a more realistic assessment of the fuel economy of the vehicle under real-world conditions.

BACKGROUND

In recent years, many authors have investigated the effect of turbulent flow conditions on the aerodynamic performance of vehicles using experimental, theoretical and computational methods. Experiments include both on-road coast down testing [6–7] and tests in wind-tunnels equipped with passive and active systems which are designed to simulate the unsteady conditions that are experienced on-road, see [8] and references therein. A theoretical method has been introduced by Howell [9–10] to assess the impact of unsteady aerodynamics on the vehicle's drag. Computational fluid dynamics (CFD) methods using unsteady aerodynamic simulations are the most straightforward approach for these investigations, since turbulence can be introduced in the simulation domain upstream of the vehicle [11, 12, 13].

The general picture which emerges from these studies is that unsteady wind-conditions from natural wind and other vehicles tend to increase the aerodynamic drag and reduce fuel efficiency. It has also been recognized that on-road turbulence affects the mechanism responsible for the drag production [14,15]. The deterioration in performance in an unsteady environment is dependent on the vehicle's shape and is bigger than the one predicted in a quasi-static approach, i.e. an approach in which the drag coefficient in a transient flow field is approximated by the drag coefficient measured in a steady flow field at a yaw angle equal to the instantaneous yaw experienced by the vehicle [8]. This means that unsteady effects are important and cannot be neglected if the accurate real-world performance of the vehicle is to be assessed. This suggests that the current methodology to compute the wind-averaged drag [2, 3, 4, 5] might underestimate the real vehicle drag since it is based on a steady state yaw sweep measurements and therefore ignores unsteady effects.

Because vehicles are regularly optimized under smooth and ideal wind conditions using wind tunnels or CFD, some vehicle improvements found will be less effective than expected (or not effective at all) on the road. For example, in [11,13] it was shown that front tire deflectors optimized using idealized conditions reduced vehicle drag by $\Delta C_D = -0.016$. Aerodynamic simulations showed that in these conditions the wake of the front wheel deflectors shielded the front tires, reducing the front half drag on the vehicle by $\Delta C_D = -0.008$. The resulting front tire wakes created a shielding effect straight behind the front wheels, and partially shielded the rear tires from flow impingement. Using simulations with on-road turbulence typical of driving in traffic, however, the lateral mixing of the flow around the front tire reduced the effectiveness of the deflectors to a total

improvement of $\Delta C_D = -0.008$ entirely on the front half of the vehicle. The tire deflectors were no longer able to protect the rear tires and all the benefit at the rear of the vehicle was lost.

On the other hand, it is natural to expect that vehicle improvements made while considering realistic wind effects will lead to a more robust design which performs better in on-road drag and overall fuel economy. In the example above it is natural to consider if a different front tire deflector design could have retained some benefit at the rear of the vehicle, or alternately if the front tire deflector could have been designed to produce lower drag on the front of the vehicle, not expecting that it would have any benefit on the rear tires in more realistic flow conditions. With this type of performance data, these scenarios can be considered in the design process.

A step in the right direction is to use yawed flow results in vehicle design. The wind averaged drag has become an important tool, especially in the truck industry, since, for trucks, the yaw sensitivity is much larger than for passenger cars and neglecting it can lead to wildly incorrect predictions for the real-world fuel economy which is of paramount importance in the truck industry.

As described later, the current wind averaged methodology can be improved to consider unsteady effects coming from natural wind variability. The first step is to precisely characterize the wind experienced by car moving on the road. While there is an enormous amount of data available about wind characteristic in the atmospheric boundary layer, less is known about the flow structure experienced by vehicles on the road. Some on-road turbulence measurements have been performed in Australia [16-19] and in Canada [1]. These studies come to similar conclusions regarding the turbulent length scale and intensities experienced on the road and the few differences in the findings of these studies can be attributed to the different geographical regions where the measurements were collected and to differences in the experimental setup.

These datasets can be analyzed using standard tools in the field of wind engineering [20] which are introduced here for completeness. First, it is well accepted that the natural wind spectrum plotted against frequency shows a spectral gap in the range between 10 minutes and 2 hours [21]. This gap separates the macro-meteorological conditions (passage of storms, breeze associated with night-day transition) from the micro-meteorological conditions (gusts or turbulence of natural wind). This spectral-gap provides a natural temporal scale to compute the mean wind speed. It is customary to set this scale to 1 hour but any other value lying within the spectral gap will give similar results. The wind speed $U_w(t)$ can be decomposed as:

$$U_w(t) = \overline{U_w} + u_w(t) \quad (1)$$

where $\overline{U_w}$ is the average hourly wind speed:

$$\overline{U_w} \equiv \frac{1}{T} \int_0^T dt U_w(t) \quad (2)$$

with T equal to one hour and $\mu_w(t)$ are the instantaneous fluctuations around the hourly speed. In the following, we will refer to $\overline{U_w}$ as the average wind speed, $\mu_w(t)$ as the wind fluctuations and $U_w(t)$ as the wind speed.

The average wind speed is a random variable and, in the field of Wind Engineering, the average wind is often described by a Weibull distribution [20] with a scale parameter λ and shape parameter k :

$$P(x)dx = k \frac{x^{k-1}}{\lambda^k} e^{-(x/\lambda)^k} dx \quad (3)$$

The values of λ and k depend on the site where the measurements are performed. High/low values of k correspond to sites with smaller/greater wind variability around the mean, respectively. The scale parameter λ is simply related to mean speed by the relation $U_{avg} = \lambda \Gamma\left(1 + \frac{1}{k}\right)$ where Γ is the gamma function.

The wind fluctuations can be characterized by the Turbulence Length Scale (TLS) and the Turbulence Intensity (TI). The TLS can be determined separately for each velocity component, *e.g.*, TLS_x , TLS_y , TLS_z , commonly using the time autocorrelation of the velocity fluctuations and the wind speed, for example used by Wordley and Saunders [18,19] and as described by the Engineering and Sciences Data Unit (ESDU) [22]. Since the wind fluctuations can be considered Gaussian, they are characterized by the standard deviation σ of the wind fluctuation. Instead of reporting the standard deviation directly, it is common to report the turbulence intensity defined as:

$$TI_\alpha = \frac{\sigma([u_{w,\alpha}(t)])}{V_{ref}} \quad (4)$$

where $\alpha = x, y, z$, $\sigma(a)$ is the standard deviation of quantity a and V_{ref} is the reference velocity which, in the field of Wind Engineering, is usually taken to be the average wind speed, *i.e.* $V_{ref} = \overline{U_w}$. With this choice of the reference velocity, the turbulence intensity is found to be almost independent of the average wind speed which in turn means that the wind fluctuations are proportional to the average wind speed:

$$TI_\alpha = \frac{\sigma([u_{w,\alpha}(t)])}{\overline{U_w}} = const \rightarrow \sigma([u_{w,\alpha}(t)]) \propto \overline{U_w} \quad (5)$$

This can be understood from the fact that the spectrum of wind fluctuations is largely universal and increasing the average wind speed necessarily leads to a corresponding increase of the wind fluctuations, see Ref. [20]. In our case the turbulence intensity is measured with respect to the vehicle speed, not the average wind speed. It then follows that:

$$TI_\alpha \equiv \frac{\sigma_\alpha}{V_{car}} = \frac{\sigma_\alpha}{\overline{U_w}} \frac{\overline{U_w}}{V_{car}} = c_\alpha \frac{\overline{U_w}}{V_{car}}$$

i.e. the Turbulence Intensity measured with respect to the vehicle speed increases with increasing wind speed and decreases with increasing vehicle speed. The fluctuations in the longitudinal and lateral direction ($\alpha = x, y$) usually have similar strength and are larger than the fluctuations in the vertical direction ($\alpha = z$) which get suppressed close to the ground. The total turbulence intensity is defined as:

$$TI \equiv \sqrt{\frac{1}{3}(TI_x^2 + TI_y^2 + TI_z^2)} \quad (7)$$

APPROACH

Numerical Simulations using the Lattice Boltzmann Method

In this paper, we perform unsteady aerodynamics simulation of a fully detailed SUV vehicle using PowerFLOW, a commercial CFD unsteady solver based on the Lattice Boltzmann Method (LBM) as described in [23-26]. PowerFLOW uses a Very Large Eddy Simulation (VLES) approach to model turbulence, in which the small scales are accounted for using a two-equation turbulence model, and the large scales are simulated on the computational grid. Kotopati [27] provides a review of LBM and describes capabilities for aerodynamics, thermal and aeroacoustics applications for production vehicle development. Examples of published validation studies are shown in [28-36].

Since PowerFLOW is an unsteady solver, it is possible to add to our simulations the needed unsteady real-world flow conditions, using an appropriate time- and space-varying boundary condition upstream of the vehicle [11-13]. This approach is similar to the one used in large-eddy simulation (LES) studies in which grid-resolved turbulence must be added into the simulation via the boundary conditions so that it can be properly simulated. The theoretical approach for generating such turbulent conditions has been pioneered by Kraichnan [37] and others. This approach is very powerful since it allows one to prescribe an arbitrary turbulence profile at the inlet. In particular, the TI and TLS for each velocity component can be separately prescribed. Moreover, as in other standard CFD software, any yaw angle can be simulated by rotating the vehicle inside the simulation domain. Therefore, PowerFLOW is an ideal tool to study real-world aerodynamics since any combination of yaw, TI and TLS can be simulated.

Representing On-Road Wind

The values of yaw, TI and TLS which are important to predict the behavior of the vehicle on the road can be inferred from the existing literature. In particular, a recent study by McAuliffe [1] contains a comprehensive dataset of measured on-road turbulence. There, the values of TI and TLS along the longitudinal, lateral and vertical directions experienced by a vehicle travelling at 100 km/h are reported as a function of the terrain type (which is categorized as Flat, Moderate, Rough, Complex) the wind strengths (which is categorized as Light, Moderate and Strong) and the traffic density (which is categorized as Light, Moderate, Dense, and Heavy-Vehicle Wake)

together with the probabilities of experiencing each condition. It was found that Moderate Terrain, Moderate Wind Strength and Moderate Traffic were the most probable scenario representing about 20% of the specific conditions experienced on the road. Based on this, the authors recommend a target value for TI and TLS which are representative of the most probable condition encountered on the road. The findings in [1] are similar to those reported in [18,19], despite being measured in different geographical area and with different experimental setups. This leads us to believe that the conclusions in [1] are somewhat general and should be applicable with minor modifications to other geographical region and experimental conditions.

The TLS experienced on the road are in the range of 0.1m - 10m, with the vertical TLS being smaller than both the longitudinal and transversal length scales. The ratio of TLS and Vehicle Length (VL) determines whether the phenomenon is quasi-steady or fully transient. The very large TLS lead to quasi-stationary phenomena while the very small TLS do not influence the vehicle aerodynamics much since they are not very energetic. The length scales which are most likely to interfere with the vehicle aerodynamics are the intermediate ones whose size is comparable to the vehicle size. Previous studies [12] have also shown that the vehicle drag depends weakly on the value of TLS suggesting that the precise value of TLS might not be important. We therefore assume that TLS is constant and equal to the target values specified in [18,19]:

$$TLS_x = TLS_y = 1m, \quad TLS_z = 0.5m \quad (8)$$

In [1], the average wind was categorized as Light (<10km/h), Moderate (10-20 km/h) or Strong (>20km/h) with probability 17%, 65% and 18% respectively. As discussed earlier, the distribution of the average wind at a given location is often well described by a Weibull distribution. In lack of more detailed data, it is assumed that the same holds for the distribution of wind measured on the road in a given geographical region. Through a fitting procedure, it was found that the data above can be accurately described by a Weibull distribution with shape parameter $k=3.2$ and a scale parameter $\lambda=16.9$ km/h which corresponds to an average wind speed of:

$$U_{avg} = \lambda \Gamma\left(1 + \frac{1}{k}\right) \approx \lambda 0.895 \approx 15.1 \frac{Km}{h} \quad (9)$$

Finally, the values of TI along the longitudinal, lateral and vertical direction are reported as a function of the traffic density, wind strength and terrain type. Typical values are in the range 2%-8%. It was also found that the value of TI along the longitudinal and lateral components are similar to each other and larger than TI along the vertical component. By applying a linear regression analysis to that data, we could confirm that the measured turbulence intensity is proportional to the average wind speed and to the traffic density. We also observed that, when the vehicle is in the wake of a heavy vehicle the measured value of TI is between 7% and 8% independent of the wind speed and terrain type.