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Theoretical Study of the Effect of Weather Conditions on Vehicle Aerodynamic Properties †

Brúnó Péter [1,*] and István Lakatos [2]

[1] MouldTech Systems Kft., H-8900 Zalaegerszeg, Hungary
[2] Department of Road and Rail Vehicles, Audi Hungarian Faculty of Vehicle, Széchenyi István University, H-9026 Győr, Hungary; lakatos@sze.hu
* Correspondence: peter.bruno@sze.hu
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Abstract: One of the most widely researched fields within the automotive industry is the effect vehicles place on the environment. To achieve a sustainable transport system, reducing the pollution of vehicles is an essential issue. The aim of this paper is to examine how weather conditions influence a vehicle's operation. The study examines potential methods to evaluate the effect of different weather conditions on the aerodynamic parameters of a vehicle. Aerodynamic properties can be measured with the help of computational fluid dynamics (CFD), a wind tunnel and test-track measurements. On-board diagnostics are also examined to collect data on aerodynamics. These methods can monitor several parameters to measure and visualize the effects of weather conditions. The theoretical background to the related aerodynamic parameters is summarized.

Keywords: sustainable mobility; weather; pollution; road vehicles' aerodynamics; energy efficiency; computational fluid dynamics; wind tunnel; test-track measurement; on-board diagnostics

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1. Introduction

Electric vehicles and climate change are transforming mobility in several ways. Regulations have been introduced regarding the construction of internal combustion engines, emissions, and vehicle types in metropolitan areas. The purpose of these regulations is to reduce the impact of vehicles' emissions on the environment. The present paper focuses on the impact of vehicles on the environment from an aerodynamic point of view. It investigates the effects of weather conditions on the aerodynamic parameters of a vehicle, which is in close connection with emission and energy efficiency. Methods to examine the effects of weather conditions and important aerodynamic parameters are compared.

The impact of vehicles and traffic on the environment is an important research field. Examinations of electric vehicle batteries are being carried out to investigate, for example, how environment temperatures influence batteries, the efficiency of the regenerative break [1–4], and the optimalization of energy efficiency in the case of electric vehicles [5–9]. Optimization is achieved using artificial-based networks or real-world driving data.

Vehicle aerodynamic parameters are also widely studied. The most accepted work on road vehicle aerodynamics is 'Aerodynamics of Road Vehicles' written by Wolf-Heinrich Hucho [10]. It contains data, legal regulations and useful facts on road vehicles. Several other important research papers have been written on the topic [11–14]. Aerodynamic forces, simulation methods and additional elements that affect a vehicle's aerodynamic properties have been analyzed in these studies.

2. Methods

Several methods are known and used to measure the aerodynamic parameters of a vehicle. Each method has its advantages and disadvantages. In order to find the most appropriate method, a detailed analysis is necessary.

2.1. Computational Fluid Dynamics (CFD)

CFD is one of the most cost- and time-efficient methods. CFD was first used in 1920 [15]. The method is based on partial differential equations (PDE) and equation systems with numerical methods. The computational volume is discretized, and fluid mechanic parameters are calculated using these discrete points [16].

Using CFD simulations, several parameters can be measured. CFD is the simplest way to identify the aerodynamic parameters of a vehicle. Pressure and velocity distribution plots can be obtained easily, whereas in a wind tunnel or a test-track measurement, parameters can be measured using less points. In CFD simulations, different weather conditions can be created. In the case of test-track measurement, weather conditions cannot be changed, thus proper planning is essential to investigate different weather conditions. CFD can be used to analyze complex problems because the software can calculate two or more phase flows.

Besides wind, which affects a vehicle's aerodynamic parameters the most, precipitation modifies these parameters as well. Rain intensity, raindrop size, humidity and air temperature also affect energy efficiency. To examine these parameters, CFD simulation is a suitable method.

2.2. Wind Tunnel Measurement

The use of a wind tunnel is one of the most traditional ways to examine a vehicle's aerodynamic parameters [17]. The basis of this method is using an open tunnel in which the examined vehicle is placed (Figure 1). Air is circulated in the tunnel by a fan. Flow parameters can be precisely set and modified during measurements. Therefore, wind tunnel measurement data are widely accepted and valid if the measurement report meets certain criteria.

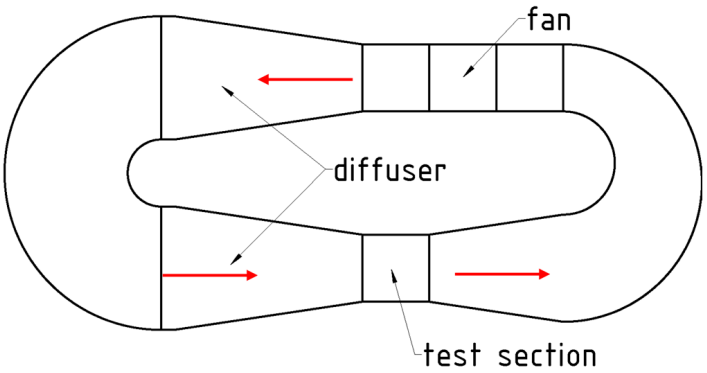


Figure 1. Operating principle of wind tunnel.

On the other hand, wind tunnel measurements are circumstantial. One of the most regular problems of examining a vehicle in a wind tunnel is the size of the vehicle. A wind tunnel has a maximum size of vehicle that can be placed inside it, depending on the tunnel's dimensions, maximum flow rate, etc. [18]. If the vehicle is bigger than the maximum capacity of the wind tunnel, a scaled model must be used. Creating such a model is a time-consuming process with high costs. For the measurements, lots of sensors and certified measuring equipment are needed, which increases the costs. Also, detecting a vehicle, collecting, filtering, and evaluating the data is time consuming. Despite these difficulties, wind tunnel measurements produce valid and precise data.

2.3. Test-Track Measurement

The final measurement tool used in the research process is test-track measurement. This measurement involves the highest costs but simulates real traffic situations the most precisely.

Measuring parameters on a test track is similar to wind tunnel measurements. Sensors and certified equipment are needed to obtain adequate data. For instance, the energy efficiency of a vehicle can be measured using a fuel flow sensor, while a wind anemometer

can be used to measure the actual wind speed around the vehicle. A test track is also needed, which constitutes a significant portion of the costs.

Test-track measurement gives the most precise data, but it involves the most preparation. Final decisions in connection with development processes are usually based on test-track measurements.

2.4. On-Board Diagnostics (OBD)

Using OBD tools to measure the aerodynamic parameters of a vehicle is essential today. Aerodynamic parameters cannot be measured directly in this way, but the data provide important information during measurement. Data on energy efficiency, fuel consumption and length changes of the damper can be monitored and controlled with the help of OBD [19]. Real-time data can be stored for later evaluation.

2.5. Summary of the Methods

In the previous sections, the possible measuring methods were described. In the following matrix (Figure 2), the discussed measurement tools and the measurable parameters are presented. The darker the cell in the matrix, the more efficient the measurement for the parameter. This use of color helps to visualize and understand what tools should be used for different data collection processes.

	Wind	Rain	Temperature
CFD Simulation			
Wind tunnel measurement			
Test-track measurement			

Figure 2. Measurement tools and measurable weather condition parameters in matrix form showing the effectiveness of the pairs: the darker the cell color, the more efficient the method.

3. Theoretical Study of Vehicle Aerodynamics

To describe how a vehicle operates in different driving conditions from an aerodynamic point of view, it is important to examine the aerodynamic force acting upon it. This force consists of two parts: pressure differences and shear stress [20]. If these forces act on a unit area (Figure 3a), the aerodynamic force can be calculated as follows:

$$F_{aero} = \int_A \left(p - p_{inf}\right) d\underline{A} + \int_A \tau_0 \vec{e} \, |d\underline{A}|, \quad (1)$$

where p is local pressure, p_{inf} is the pressure in the free-stream zone, τ_0 is local shear stress, and $\underline{e}$ is a unit vector. In the first part of the equation, pressure difference is integrated in the unit surface, so the force acts perpendicular to the unit surface. The second part of the equation calculates the force from shear stress by integrating the multiplication of local shear stress and the unit vector, which gives the direction of the force.

In vehicle aerodynamic applications, the aerodynamic force is divided into three components (Equation (2)): drag force, side force, and lift force (downforce) (Figure 3b).

$$\underline{F}_{aero} = \underline{F}_x + \underline{F}_y + \underline{F}_z, \quad (2)$$

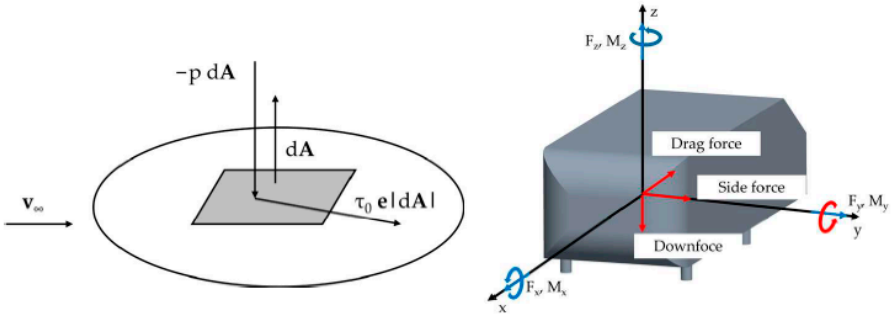


Figure 3. (**a**) Aerodynamic force acting on a unit surface. (**b**) Components of aerodynamic forces and moments.

As well as the force components, there are three moments to consider: roll moment (x axis), pitch moment (y axis), and yaw moment (z axis).

From the aerodynamic forces, the drag and lift coefficients can be calculated as:

$$c_{D/L} = \frac{1}{2} \cdot \rho \cdot A \cdot F_{D/L} \cdot v^2, \tag{3}$$

where c_D is the drag coefficient, c_L is the lift coefficient, ρ is the density of the flow, v is the velocity in the free-stream zone, and A is the projection of the vehicle (Figure 4). Using these forces, moments, and coefficients, the basic aerodynamic behavior of a vehicle can be described and predicted.

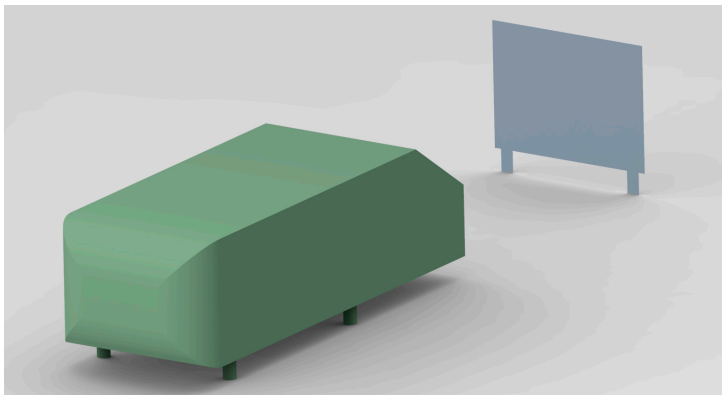


Figure 4. Explanation of projection area (gray surface) of a vehicle; in this case, that of the Ahmed body (green body).

4. Relevance

According to a number of publications in the field of energy efficiency in electric vehicles, examining the effect of weather conditions on a vehicle's aerodynamic parameters is highly important and relevant today. Different weather effects should be analyzed. The influence of rain droplet size, humidity and mass flow on the drag coefficient is to be studied further. Air temperature can affect the drag coefficient as well. Cumulative states of precipitation and wind effects that influence energy efficiency should also be researched.

Based on preliminary studies, weather conditions can affect a vehicle's aerodynamic properties. There is a lack of studies in this area, but detailed examinations could prove and support this fact.

5. Summary

In this paper, the connection between weather conditions and vehicle aerodynamic properties has been studied. The results support the thesis that there are connections between weather conditions and aerodynamic properties. Possible measurement methods have been examined and relevant aerodynamic forces have been defined. Based on theoretical research, it has been proven with high probability that there is a connection between weather effects and aerodynamic properties. Further investigations are essential in this field.

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