CFD study of aerodynamic sensitivity to air deviation angle for a hatchback vehicle

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Abstract. Movement is the base of most nowadays activities. For this purpose, vehicles that have specific characteristics for various needs were developed. The current legislation enforces an aerodynamic homologation process to assess a vehicle’s CO\textsubscript{2} footprint. This process has to be done in specific conditions, with airflow at 0 degree deviation. The increasing concerns toward pollution will soon lead to the introduction of new rules meant to closely simulate real life vehicle usage, like the RDE test. The current paper has the purpose to analyse, using the CFD method, the influence of the directionality of the airflow (i.e. front-at 0 degree deviation and at various deviation angles) on the aerodynamic performance of a vehicle. The paper studies the airflow behaviour of a hatchback body type vehicle for airflow direction angles between 0 and 20 degrees, through Cd parameter. The focus of the analysis was on air direction (± angles) and simulating time. Due to vehicle asymmetry, the results were different in case of positive and negative values of the airflow angle. The simulation time leads to slightly different Cd due to different averaging periods. Obtained results indicate the necessity of future investigations towards the optimisation of aerodynamic elements in crosswind conditions.

1. Introduction

The vehicle, with its diversity of shapes, sizes and purposes, is a continuous presence in our lives – an expression of mobility. The constant evolution of the passenger vehicle is an answer to both customer desires and legislation requirements. The vehicle development is strongly linked to the social environment and nowadays, due to climate changes, the focus on CO\textsubscript{2} emissions imposes a shift towards energy consumption reduction [1]. The most common method to achieve this goal is the optimization of all vehicle’s systems. However, reducing the resistance encountered by the vehicle is a viable alternative.

The current paper proposes to continue previous work by studying the vehicle aerodynamics at small deviation angles, with CFD (Computational Fluid Dynamics) tools. The recent introduction of RDE (Real Drive Emissions) test, ancillary to WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure), highlights the great importance of real-world factors, like airspeed and air direction on vehicles’ emissions. CFD is a powerful tool, which is currently used extensively by most of vehicle manufacturers due to its benefits – e.g. time and cost optimisation. Depending on mathematical model and software, errors may occur in comparison with physical test. The errors can be classified in three main categories: numerical errors, coding errors, user errors. In this article the influence of the simulation time factor (part of user error category) is analyzed.
2. Vehicles’ aerodynamic performance assessment

The science of aerodynamics studies the airflow near a body by taking into account the variations of speed, pressure, direction and friction. For vehicles, the main parameter used to assess aerodynamic performance is the drag coefficient, $C_d$, on longitudinal direction. To fully assess the aerodynamic performance, the $C_d$ is multiplied with the projected surface of the vehicle, $A$, measured in square meters. The $C_dA$ represents an input value for CO$_2$ computation and is also used as a parameter to compare the aerodynamic performance of different vehicles [3].

To make a vehicle commercially available, it must be proven that all legislative requirements are satisfied. The current process of aerodynamic homologation consists in doing a physical test, using a wind tunnel – this allows repetitive tests performed in controlled conditions. For homologation, the vehicle is perfectly aligned on longitudinal direction with the air flow [4]. Although this is a well-designed complex process, authorities constantly search other methods to obtain values that reflect real life usage. One example is RDE, which consists in mobile measuring equipment that records emissions when the vehicle is driven on the street, in a real, uncontrolled environment [2]. Vehicle emissions depend on engine load. Along with engine calibration, vehicle mass and tire rolling resistance, the aerodynamic resistance should be also considered due to its role in the total resistance encountered by the moving vehicle (considering the air-flow behaviour that in real world changes frequently).

The vehicle’s shape is developed using both physical tests and virtual tools. The physical test remains a requirement for homologation. However, through the CFD method multiple tests (through iterations) may be conducted in order to achieve the desired aerodynamic performance. This virtual measurement allows a cheaper and faster validation of performances [5].

3. Vehicle aerodynamics in small angle side wind

The sensibility of vehicle aerodynamics in side winds is studied for a hatchback vehicle, at an angle ($\alpha$) between -20° and +20° deviation from vehicle X axis, as graphically described in figure 1. These values were chosen due to high frequency of occurrence in real life, as some studies show [6].

![Vehicle coordinates system definition.](image)

The CFD tool used is based on Lattice-Boltzman mathematical model which provides a good assessment for automotive applications. A first set of results, plotted in figure 2, shows that for $0^\circ<\alpha<2^\circ$, the $C_d$ is relatively constant. This is followed by a gain of 0.025 units for $4^\circ<\alpha<6^\circ$. At approximately 8°, an inflexion is noticed in $C_d$ variation. For $10^\circ<\alpha<20^\circ$, the $C_d$ is increasing in a linear way. The inflexion point, identified at 8°, indicates a significant change in air flow behaviour. The air detachment phenomenon considerably influences the aerodynamic performance and is optimised for 0° wind angles, in accordance with the requirements of the homologation process. For the studied hatchback vehicle, the detachment is changing at $6^\circ<\alpha<8^\circ$, and the energy associated to drag formation is starting to significantly increase. This is reflected by the $C_d$ behaviour for $\alpha>10^\circ$. 


Figure 2. Cd variation with deviation angle, 0°<α<20°.

As stated above, the projected area, A, has a great importance for aerodynamic assessments. The linear dependence between A and α for the studied vehicle is plotted in figure 3 (a), while figure 3 (b) shows the combined effect of the two parameters, together with angle variation. It can be observed that for α<10°, the projected vehicle area induces a different evolution between Cd and CdA parameters, while for α>10° the two parameters’ evolution is very similar.

The air behaviour at small deviation angles is different due to constant increase of the projected vehicle area. This demonstrates why Cd alone cannot indicate the aerodynamic resistance and why for computing CO₂ value, the parameter that has to be measured and considered is the CdA.

Figure 3. Dependence of A and Cd with deviation angle, α.

The drag development significantly varies with the deviation angle value. One CFD parameter that allows the observation of drag shape and intensity is iso-Cpi which stands for total pressure loss coefficient [7], as exemplified in figure 4. The main sources of drag for a vehicle are: front and rear wheels [8], front pillar associated with rear view mirrors and the rear of the vehicle, the latter being also the principal source of aerodynamic energy consumption.

Figure 4. Drag evolution with deviation angle, α.
Having reached the aforementioned conclusion, a new question may be addressed: does the side-wind direction (+α or -α) influence the aerodynamic results? The CFD simulations performed for negative values of α show that, there is in fact a difference for CdA values at +α compared to -α. Figure 5 shows how the CdA varies for -20°<α<+20°. The differences of the CdA values is highlighted by mirroring the results obtained at -α, in the right side of the graphic. The difference is given by the asymmetry of the mechanical parts found under the vehicle’s body. While at α=0° this effect is hardly noticed, in side wind the influence on drag can be easily observed. This aspect is another factor that is not reflected by today’s homologation process.

![Figure 5. Variation of CdA parameter for positive and negative deviation angles.](image)

4. **CFD time simulation influence on results**

When assessing aerodynamic performance, the tools and methodology used may have a great impact on the results obtained. This is the reason why authorities still impose physical tests. While the physical validation is mandatory, the development process was more and more transferred to virtual reality due to reduced costs, possibility of doing numerous iterations and detailed analysis capacity. On the other hand, the mathematical models applied must be carefully chosen depending on the purpose these are used for [9]. Each model has its advantages and disadvantages and of course, each one can give an error value. As the current research is based on CFD tools, it is mandatory to associate the results obtained with an insight of possible sources of error. One important source is the simulating time (i.e. for how long the air passes near the vehicle), which in virtual world is fragmented in many small steps called iterations. The exposure to air-flow should be sufficiently long to allow the drag
shapes to form and stabilise. On the other hand, if the exposure to air-flow is too long, the recorded
data will be too large and the advantage of CFD tool will be decreased. For the current study, the
simulations were performed both at 250,000 iterations and 500,000 iterations and figure 6 shows the
differences obtained. The CFD simulations were prepared using a HP Z420 Workstation and the actual
simulations ran on a server with 420 cores. This setup leads to a running time of approximately 30
hours for the 250,000 iterations and 50 hours for the 500,000 iterations.

It can be noted that there are two areas where the results differ due to simulating time. The first
interval is obtained for $6^\circ<\alpha<10^\circ$ where, as shown in the first part of the paper, the way the air
detaches from the vehicle body changes. Considering that we already identified the change in the air
detachment form the vehicle’s body, this deviation in results was expected. The second area is
towards the bigger values of $\alpha$, where the projected area increases much and the drag becomes of
important sizes. As the significant differences due to simulation time are registered only for $\alpha>17^\circ$, it
is considered that the CFD results obtained for a simulation time of 250,000 iterations are valid,
considering the purpose of the present paper.

5. Conclusions
The paper’s goal is to highlight the possibility of vehicle CO₂ reduction by other means than
optimizing the engine, transmission or exhaust system – another mean can be the reduction of the total
force that opposes to the vehicle movement (aerodynamic resistance). Aerodynamic performance,
through CdA, is an important part of the vehicle homologation process. New real life homologation
methods, like RDE, are developed in order for the authorities to ensure that consumers receive only
true information. One important difference between the conditions in the current homologation
process and the real-life usage conditions is represented by the existence of side wind. This paper
shows through CFD simulations that, for small deviation angles, the vehicle’s performance may be
considered uniform until $\alpha<8^\circ$ and after $\alpha>10^\circ$ the performance is degrading in a linear manner. This
occurs due to the increased projected area and the change in the air detachment. For the studied
hatchback vehicle, the air detachment changes at $8^\circ<\alpha<10^\circ$. Also, it must be mentioned that the results
are significantly influenced by the direction of the side wind ($\pm\alpha$), due to the asymmetry of the
mechanical parts found under the vehicle’s body.

The second part of the article focuses on the CFD method and its importance for the development
of today’s vehicles. Although it has many advantages, due to its sensitivity for each application, the
used mathematical models must be wisely chosen. For the current study it was considered necessary to
validate the results from the CFD simulation time point of view. The number of iterations is a main
factor in capturing the full development of the drag behind the vehicle. Simulations done at 250,000
iterations and 500,000 iterations indicated that the results are slightly varying at the $8^\circ<\alpha<10^\circ$ and
towards big angle values ($\alpha>17^\circ$). Taking in consideration the small deviation and the current paper’s
focus on small side wind angles, the results are considered valid for the simulation time of 250,000
iterations. Nevertheless, a wind tunnel test is necessary to fully validate the presented CdA values.
The paper reveals the importance of vehicle’s aerodynamic performance in today’s context. It is
considered a priority to allow full development of aerodynamic elements to maximise CdA gain, so
future pollution norms could be respected. The CFD tools can bring great benefit for the development
process, but must be optimised for new methods like side wind behaviour. The present results are also
a strong argument for the necessity of integrating active elements that can adapt to vehicle speed and
even side wind, to allow the best possible performance. The research will continue with studies on
other body type vehicles in the same conditions, with focus on active aerodynamic elements.

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