 https://doi.org/10.3311/PPtr.40035

Periodica Polytechnica Transportation Engineering, 54(1), pp. 34–40, 2026

Examination of the Effect of Wind on Vehicle Drag Coefficient from Aerodynamics Point of View

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Received: 30 January 2025, Accepted: 06 August 2025, Published online: 24 September 2025

Abstract

The aim of the paper is to investigate the wind effect on vehicle aerodynamic properties. Two-dimensional Ahmed body is examined with Computational Fluid Dynamics (CFD) method. During the analysis, two different studies were carried out. First, the simplified vehicle shape was examined in standing position, only the force from the wind velocity affected the body. The drag coefficient change was examined in case of different wind velocities and angles of attack. After that, the effect of wind while driving was investigated. The body was defined as a moving object and at another inlet the wind was defined. Different travelling and wind velocities with different angles of attack were studied. Based on the results of the simulations, a comprehensive impact of the wind can be measured on the drag coefficient. This proves that the wind has a measurable effect on vehicle aerodynamic properties and must be taken into account when investigating the effect of weather conditions on vehicle aerodynamic properties.

Keywords

vehicle aerodynamics, electric mobility, weather conditions, energy efficiency, sustainable mobility

1 Introduction

Within the automotive industry, energy efficiency is one of the most important research field. With the spread of electric vehicles, energy efficiency became one of the key parameters of a vehicle. It depends on several factors such as battery type, vehicle mass, suspension system or the aerodynamic behaviour.

The energy efficiency of a vehicle depends on several parameters and is widely examined. Lots of papers have been created on the topic of battery type (Xu et al., 2023), regenerative braking (Pan et al., 2023) or environment temperature effect (Yang et al., 2023) on energy efficiency. Yang et al. (2023) proved with data-based analysis the connection between battery temperature and energy efficiency. Moisture has also a significant effect on energy consumption (Zhou et al., 2023). The research, which was carried out in −1 °C, used segmented test method for different energy levels. Applying regenerative braking to electric and hybrid vehicles could affect beneficially the energy consumption (Lee et al., 2023). It is also proven that tools for passenger comfort e.g., heating, air-conditioning or just circulating the air uses measurable energy (Lesage et al., 2024). Artificial intelligence (AI) also plays a key role in this field. With the help of AI data collection, process and evaluation can be enhanced using path-finding algorithms (Qin et al., 2022), simulation methods (Adedeji, 2023b) or neural networks (Adedeji, 2023a). Over these factors, vehicle shape has also a significant effect on energy consumption. It has been proven for a long time, since 1995, that the flow of air around a vehicle significantly affects its drag and lift coefficients, which are proportional to energy efficiency and driving stability (Fukuda et al., 1995). The impact of aerodynamic forces and moments on energy consumption is less studied than the pre-discussed parameters but there are some important literatures in this field.

Focusing on how weather conditions can affect a vehicle's aerodynamic properties several types can be defined. Strong crosswind effect on vehicles was examined by Winkler et al. (2016) using detached eddy simulations. Moreover, strong wind and rain can affect the slip factor, the visibility conditions or the drag coefficient. Gao et al. (2020) analysed how the fog modifies the safety factors of the

Cite this article as: Péter, B., Kardos, P., Lakatos, I. (2026) "Examination of the Effect of Wind on Vehicle Drag Coefficient from Aerodynamics Point of View", Periodica Polytechnica Transportation Engineering, 54(1), pp. 34–40. https://doi.org/10.3311/PPtr.40035

mobility (e.g. following distances). Several other papers examined the weather conditions' effects from aerodynamic point of view. A paper written by Cui et al. (2025) studied the differences between electric (EV) and internal combustion (IC) vehicles in terms of their dependence on weather conditions. The results shows that EVs are more sensitive to weather conditions than IC vehicles (Cui et al., 2025). The wind has a massive effect on bridges, where no object impedes the flow. A vehicle-bridge system was examined with CFD tools to obtain the effect of this weather condition. A different tool was applied and examined in order to improve the vehicle's aerodynamic property and decrease the exposure to wind (Wang et al., 2023) and define the connection of the wind profile, wind speed and angle of attack (Zhang et al., 2022). Several papers study the weather conditions' effect on heavy-duty vehicles (McTavish and McAuliffe, 2021) and trains (Yu et al., 2022) both of which confirm that this topic has relevance on the current traffic issues.

The appearance of electric vehicles has changed the structure of the automotive industry. 20 years ago, long travel range (600–800 km) and comfortability were the key parameters of a vehicle. Nowadays, it has changed to low drag coefficient (increased energy efficiency) and medium travel range (300–500 km). This has enabled electric vehicles to become widespread. However, using electric vehicles for long trips has several limitations. The average range of electric vehicles does not exceed 500 km, and not all the charging points are able to fast charge the vehicle. Therefore, examining the parameters that affects the energy efficiency of a vehicle is justified.

The low drag coefficient and energy efficiency depend on many parameters such as vehicle shape, travelling velocity or current weather conditions (Hucho, 1987). The main weather conditions, which could affect the vehicle aerodynamic parameters are the temperature difference, the precipitation and wind.

In case of windy weather condition, forces from the wind are acting on the vehicle. This causes increased drag coefficient, which decreasing energy efficiency (Suda, 2022). The behaviour of the wind depends on several parameters. The most important information about it is the wind speed, wind direction and wind type (constant, changing or pulsating). One more important factor is the climate change, which strongly affects the behaviour of the wind.

Climate change affects the weather conditions in different ways. Temperature, precipitation and wind are also affected by the climate change and global warming. Because of the climate change the wind behaviour changes a lot (Gahlot, 2024). Wind patterns not only affect the mobility directly as a force but also have a huge impact on season circulation and precipitation trend. Therefore, if wind patterns change drastically, which is highly likely based on current climate change, critical weather events could occur.

Focusing on wind trends and their direct effects on vehicles necessitates to examine the wind patterns more precisely. Lots of investigations are carried out in Hungary in this field. For example, increasing numbers of windstorms can be detected nowadays (Vigh, 2023). Extreme windstorms usually occur in winter, 1–2 thousand times in the northern part of Transdanubia and hundred times in the Great Plain. Regarding the current state of global warming, this trend will increase at a rate of 8 days/year. If global warming decreases, this trend will slow down to 1–2 days/year. It is also proven that increasing amount of greenhouse gases contribute the creation of windstorms connected to cyclone activity. Global warming also affects storm tracks and wind direction.

2 Drag coefficient

Different forces act on a road vehicle during its operation. The source of these forces is extensive. The relevant force for this investigation is the aerodynamic force. In order to calculate the force acting on a vehicle, it is necessary to determine how the force can be calculated on a unit surface.

A force acts on a body placed in a flow if the friction is not neglected (Lajos, 2019). This force is called aerodynamic force. The aerodynamic force consists of two parts: the force from pressure difference and the force from shear stress. These come from the viscosity and rate of deformation speed. Fig. 1 shows the aerodynamic force acting on a unit surface.

The force resulting from pressure difference is perpendicular to the unit surface, the shear stress-based force is parallel to it. Based on these, the aerodynamic force can be obtained as given in Eq. (1):

$$F_{\text{aero}} = -\oint \left(p - p_\infty \right) d\boldsymbol{A} + \oint \tau_0 \cdot \boldsymbol{e} \cdot \left| d\boldsymbol{A} \right| \quad (1)$$

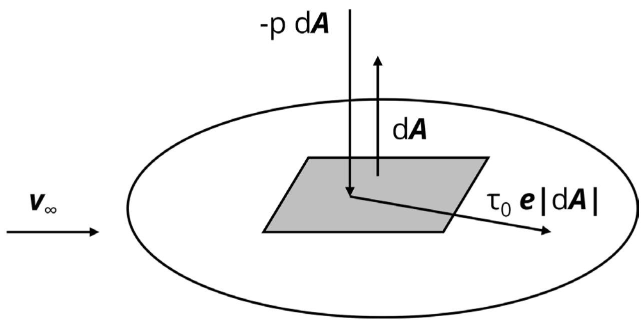

Fig. 1 Aerodynamic force acting on a unit surface

where p [Pa] is the local pressure, p_∞ [Pa] is the pressure in the free stream zone, τ_0 [MPa] is the shear stress, $\boldsymbol{A}$ [m^2] is the projection area, and $\boldsymbol{e}$ is the unit vector, which gives the direction of the shear stress-based force.

In case of vehicle aerodynamics, the aerodynamic force is usually divided into three components as depicted in Fig. 2.

As it can be seen, the drag force is parallel with the direction of travel and has an opposite direction. Drag force is the force which impedes the body in the flow. With the help of the drag force, drag coefficient can be calculated as detailed in Eq. (2):

$$c_D = \left(2 \cdot F_D\right) / \left(\rho \cdot A_{proj} \cdot \boldsymbol{v}^2\right) \tag{2}$$

where F_D [N] is the drag force, ρ [kg/m^3] is the density of the flow, A_{proj} [m^2] is the projected area and $\boldsymbol{v}^2$ [m^2/s^2] is the velocity of the free stream zone. This parameter helps and allows to compare different models or simulation results.

3 Simulation environment

Two-dimensional simulations were carried out to investigate the wind effects on vehicle aerodynamic properties (drag force and – coefficient). The investigated body was the Ahmed body from top view. Its dimensions are shown in Fig. 3 (Lienhart et al., 2000).

In this study two different simulation structures were investigated. In the first case, the Ahmed body was modelled as stationary body, its travelling velocity set as 0 m/s. The body was affected by only the wind. The computational volume was built up as presented in Fig. 4. The Fig. 4 contains all the dimensions of the computational volume and its boundary conditions.

In the second case, two inlets were defined. The body was modelled as a moving object, while the wind had a lateral effect. The dimensions of the computational volume and the boundary conditions are depicted in Fig. 5. The $\boldsymbol{e}$ unit vector indicates the resulting component of the wind velocity (α also defined for easier understanding in Figs. 4 and 5).

The Ahmed body was meshed in the same method for both cases. The general element size for the volume was set as 25 mm. The vehicle outline was refined as edge sizing 2.3 mm. The inflation layer was defined by the first layer height (1.37 mm) and the maximum layer number (10). The criteria parameters of the mesh were appropriate for the investigation.

The simulation was carried out using the k–ε turbulence model with high Reynolds wall treatment method. Based

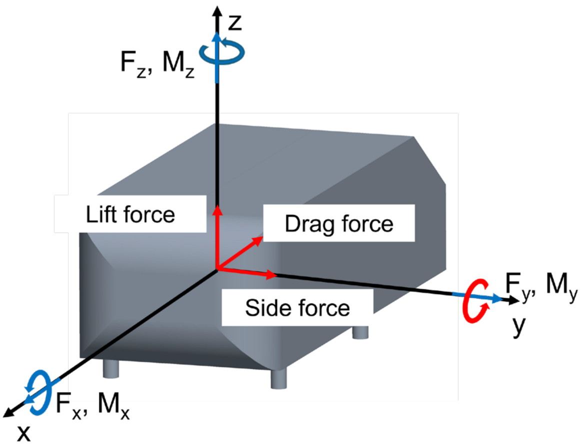

Fig. 2 Components of aerodynamic force

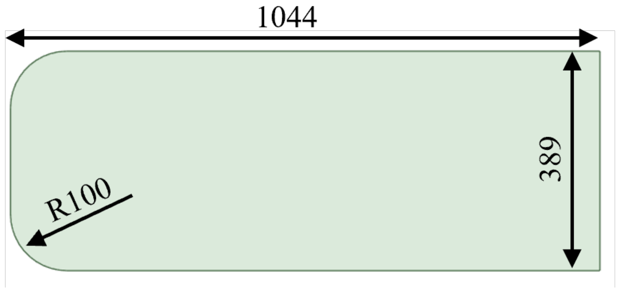

Fig. 3 Dimensions (in mm) of the applied 2D Ahmed body

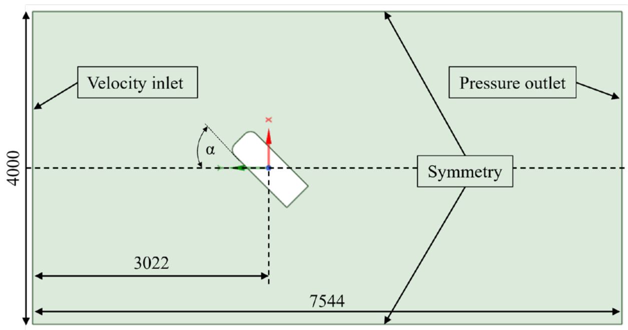

Fig. 4 Dimensions (in mm) of computational volume and its boundary conditions in the 1st case

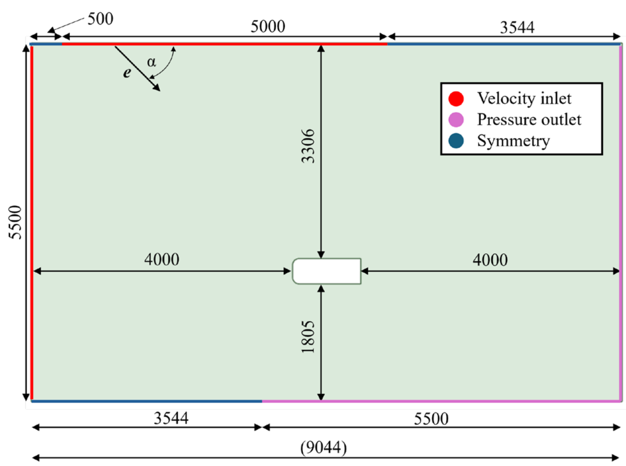

Fig. 5 Dimensions (in mm) of computational volume and its boundary conditions in the 2nd case

on this setting, the y^+ distribution was between 30 and 300 (Gergely, 2019). The inlet was set as a velocity inlet, the outlet as a pressure outlet. The side wall of the computational volume was set as symmetry and the vehicle as wall. These settings are depicted also in Figs. 4 and 5. The simulations converged appropriately, and their residuals were in the correct range.

4 Numerical results

The aim of this article is to examine the effect of wind on vehicle drag coefficient. The results were created by two-dimensional CFD simulations. During the investigation several traveling velocity, wind – and angle of attack values were studied. This section presents the numerical results for different cases. With the help of these values, further investigations can be carried out in more detailed and complicated simulations and wind tunnel tests to develop and study further the wind effect on the drag coefficient.

4.1 Ahmed body as a stationary object (1st case)

First, the Ahmed body was put in a stationary volume, only the wind affected the body. Different wind velocity and angle of attack parameter values were examined. Table 1 contains all the parameters that were studied. The wind velocities were defined based on the most common speed ranges in the case of road vehicles. All the velocities were examined at all angles of attack so overall 60 simulations were carried out.

The numerical results of a wind velocity equal to 5 m/s is depicted in Fig. 6. The drag coefficient distribution in cases of 0, 5, 10 and 15 m/s are similar in nature. Between 0 and 10 degrees the drag coefficient increases slowly as the angle of attack increases. At 10 degrees, there is a jump in the function of drag coefficient. The drag coefficient will be 2.5 times larger in case of an angle of attack of 15 degrees than at 10. After that, between 15 and 45 degrees the slope of the function grows steadily, almost linearly.

From wind velocity 20 m/s the nature of the drag coefficient distribution is similar, but the jump in the function is shifted to wind velocity 15 m/s. The case of a wind velocity of 20 m/s is depicted in Fig. 7. The rate of the jump is equal to the other cases.

Fig. 8 shows the numerical results from all cases. It is clear that the nature of the drag coefficient function is the same in all cases (except the above-mentioned difference). As the wind velocity increases the drag coefficient increases too, which was the assumed behaviour and strengthens the correctness of the model.

Based on the investigation the drag coefficient is sensitive to the angle of attack. The jump in the function should be investigated in 3D simulation also. The numerical results show that the side wind affects the drag coefficient measurably. It means that the wind effect should be taken into account when the examination is created for weather condition effects on vehicle aerodynamic properties. However, this case assumed that the vehicle is stationary and only the wind affects it. To get precise results of the wind effect on drag coefficients, the body should be set as a moving object.

Table 1 Examined parameters in the 1st case

Angle of attack, deg.	0, 5, 10, 15, 20, 25, 30, 35, 40, 45
Wind inlet velocity, m/s	5, 10, 15, 20, 25, 30

4.2 Ahmed body as a moving object (2nd case)

The first case investigated the wind effect on a stationary object. However, the flow around a vehicle is very complex. Flows from different directions have a massive

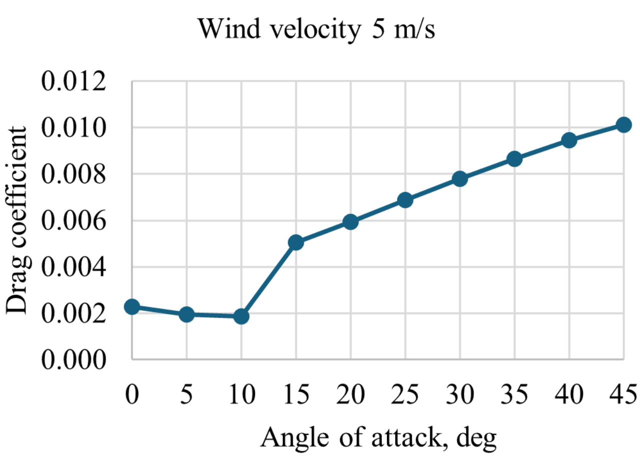

Fig. 6 Drag coefficient distribution in case of wind velocity 5 m/s

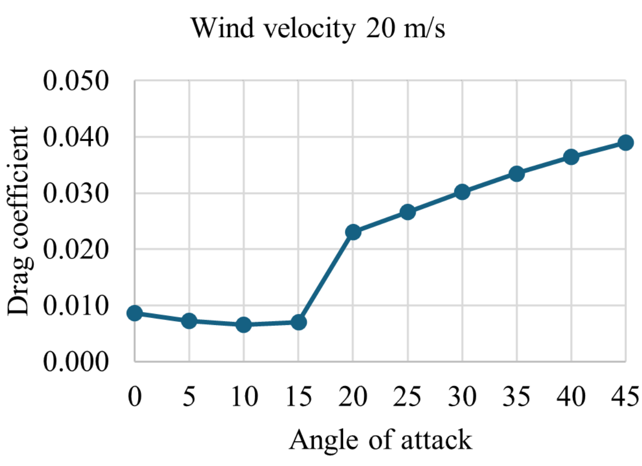

Fig. 7 Drag coefficient distribution in case of wind velocity 20 m/s

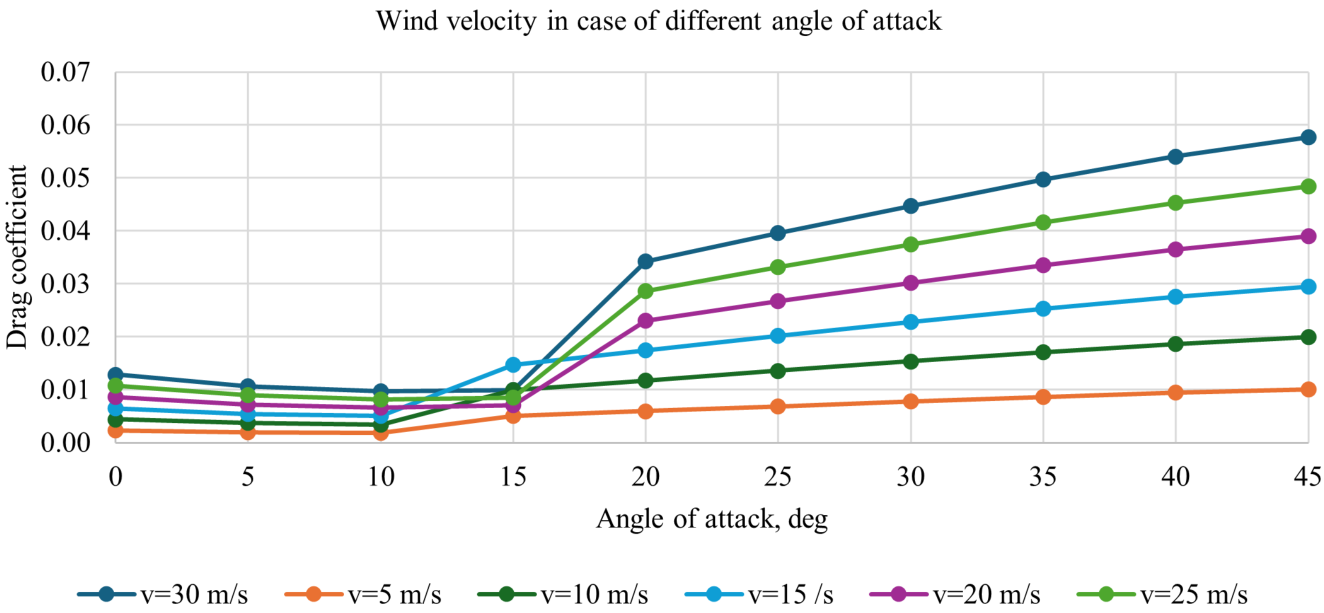

Fig. 8 Drag coefficient distribution in case of different wind velocities and angles of attack

impact on each other. Therefore, to get more precise data of the wind effect, two different inlet velocities should be involved in the simulation. Table 2 contains the moving and wind velocities and the examined angles of attack.

In this case the drag force calculation is not as simple as in the single inlet case. In order to calculate appropriately the resulting velocity vector, the following equation was applied.

$$v_{res} = \sqrt{v_{trav}^2 + v_{\text{wind}}^2 - 2 \cdot v_{trav} \cdot v_{\text{wind}} \cdot \cos(\alpha)} \tag{3}$$

Then the direction of the resulting velocity vector can be defined as,

$$\beta = \sin^{-1}\left(\left(v_{\text{wind}} / v_{res}\right) \cdot \sin(\alpha)\right). \tag{4}$$

The projection area was calculated regarding the resulting force vector (projection area is equal with the area perpendicular to the resulting force vector (Fig. 9).

Using this data, the drag force calculated as,

$$c_D = \left(2 \cdot F_D\right) / \left(\rho \cdot A_{proj,res} \cdot v_{res}^2\right) \tag{5}$$

where F_D [N] is the drag force, ρ [kg/m^3] is the density of the stream, $A_{proj,res}$ [m^2] is the projection area of the body and v_{res} [m/s] is the resulting velocity. The calculated results are depicted in Fig. 10.

Table 2 Examined parameters in the 2nd case

Angle of attack, deg.	22.5, 45, 67.5, 90
Wind inlet velocity, m/s	25, 30, 35
Moving inlet, m/s	15, 25, 30, 35

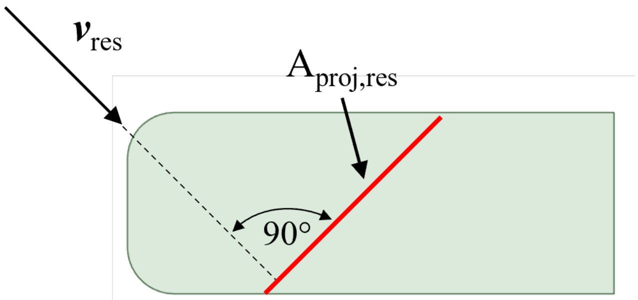

Fig. 9 Calculation method for the resulting projection area

It can be clearly stated that the results are much less stable than in the first case, there are some outstanding values (e.g., $c_D = 11$). The function of the drag coefficient does not have a steady growth slope. In some cases, data points are missing from the function. The reason is that some simulations were not stable enough to provide a usable result. At 22.5 degree, the drag coefficient is not zero but much smaller than in another cases. Here the results are in 0.1 order of magnitude. It can be also seen that the simulation was unstable where the travelling and wind velocities were equal. If there was a dominant inlet, the result was stable.

Beyond the sensitivity of the simulations, the drag coefficient increases as the angle of attack grows, especially, when the wind velocity is higher. In case of v_{trav} = 15, v_{wind} = 35 m/s and v_{trav} = 25, v_{wind} = 35 m/s the drag coefficient is outstanding. In the further investigations, it is important to analyse it more precisely and with three-dimensional investigations also to verify the large discrepancy.

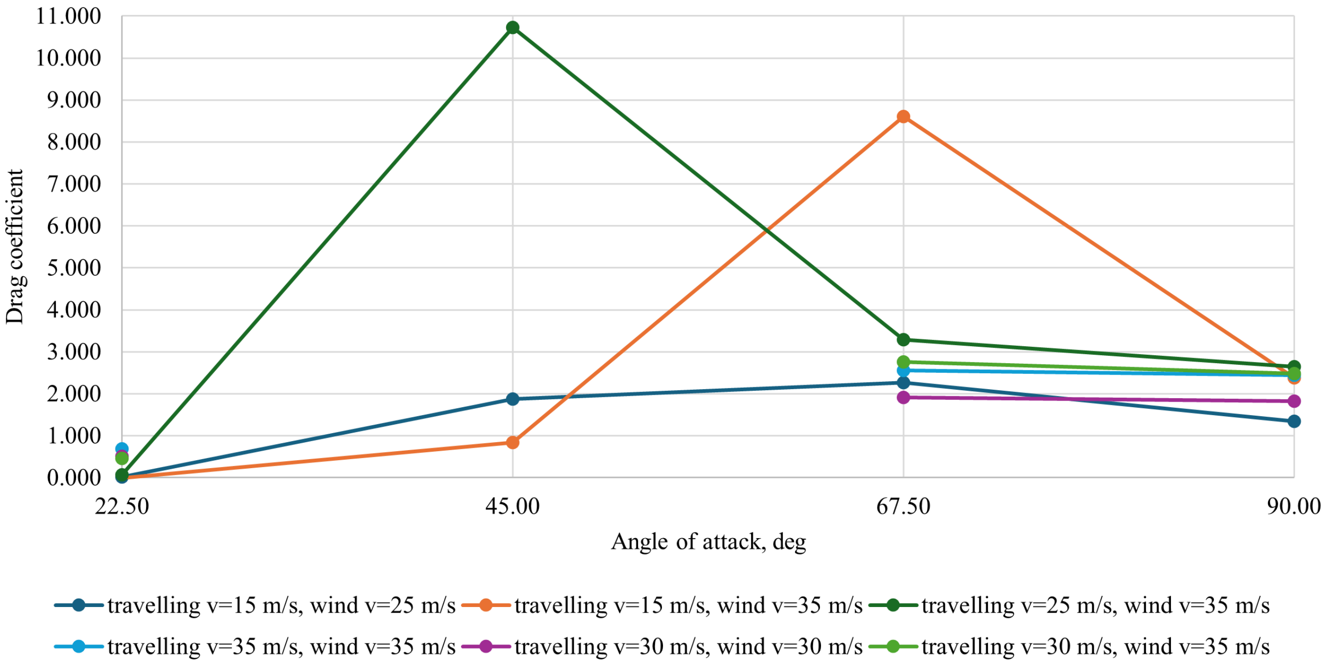

Fig. 10 Drag coefficient distribution in case of different travelling and wind velocities and angles of attack

Based on the multi-inlet simulation, the wind could have a massive impact on the drag coefficient. This investigation strengthens the first case that more detailed, three-dimensional and wind tunnel measurements are justified in order to investigate all the effects of weather conditions which impact a vehicle aerodynamic property.

5 Conclusion

Analysing the effect of wind on vehicle aerodynamic properties was carried out successfully. Two kinds of simulations with different structures were created. The simulation results are acceptable, usable and contain important information of the connection between drag coefficient, wind inlet velocity and travelling velocity.

In the two-dimensional simulations several travelling, wind inlet velocities and angles of attack were studied. The article contains results from more than 80 simulations. This allowed to examine extensively the topic and firm decision can be taken on the need of further investigations.

The results show that the wind has massive impact on the drag coefficient. Different angles of attack could cause 2–3 times growth in the drag coefficient. It is also obtained that there is a strong connection between the travelling and wind velocities, which highly affects the flow behaviour.

Overall, the study was carried out successfully, the results show that the wind has massive impact on the aerodynamic properties, so further investigations are needed.

Acknowledgement

The research presented in this paper was supported by the University Research Scholarship Pro-gram (EKÖP) project. The completion of this project is funded by the Ministry of Culture and Innovation and the National Research, Development and Innovation Fund.

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