Paper ID: 503

Numerical Analysis of the Aerodynamic Impact of Front Splitters on Lift and Drag Forces in BMW 5 Series E60

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Abstract

This study presents a numerical analysis of the aerodynamic effects of adding a flat plate splitter to the front bumper of a BMW 5 Series E60 model. The effect of various splitter lengths (4mm, 6mm, 8mm, and 10mm) on lift and drag forces, were analyzed with the help of ANSYS Fluent student version. The results show that the use of a splitter reduces the lift force considerably, up to 26.7%, for the 10mm splitter at an air velocity of 10 m/s. On the other hand, the drag force increases by up to 8% for the smallest splitter. Longer splitters ensure a higher value of downforce, thus increasing the stability of the vehicle at high speed, but at the cost of increased drag. The findings contribute valuable insights into the design of aerodynamic add-ons for performance vehicles.

Keywords: Lift force, Drag force, Flat Plate Splitter, Aerodynamics, CFD Simulation.

1. Introduction

A car traveling at high speeds experiences a substantial amount of lift force, which is proportional to the square of its velocity [1]. This lift force causes loss of control due to poor tire grip on the road. To overcome the problem, engineers have concentrated on increasing the downforce of the car. One way to increase downforce is to add some weight to the car body. Although increasing the weight of a car can enhance downforce, it can also raise the inertia of the car and fuel consumption [2]. Another way to counteract lift force is to use various flow control devices to improve aerodynamic performance and increase downforce. These aerodynamics devices to improve aerodynamics performance are known as aerodynamic add-on devices [3]. Those aerodynamic add-on devices are usually mounted at different locations of the car to maintain a balanced downforce and prevent understeer or oversteer [4]. Some examples of such flow control devices are a side skirt, under tray, rear diffuser, spoiler, airfoil, vortex generator, air dam, splitter, dive plate, hood vent, front diffuser, and wheel well vent. Among them, a splitter is one of many aerodynamic add-on devices that generate downforce at the front of the car. When air strikes the car at the front bumper at high velocity, the pressure at that region increases. So, there is high pressure on the upper surface of the splitter. Again, as the splitter is added near the road surface, the space between the splitter and the road surface is small. As a result, pressure decreases under the splitter when air passes through that narrow space. Due to this pressure difference between the upper and lower surfaces of the splitter, it is pushed downward, reducing lift force. Although these splitters can be seen on many road vehicles, they are merely a fashion. Because on the road, the car moves much slower than on the racing track. So, on a road vehicle, its weight is enough to have a grip for a safe journey. An aerodynamic add-on device's effectiveness can be seen in cars that move very fast, which can be seen in racing competitions.

This paper aims to study the effect of a splitter on a car in terms of variable splitter length. That means the impact of adding a splitter on drag and lift forces will be investigated for various lengths of the splitter.

In this paper, a few associated terminologies have been described. Then, the steps for simulation are illustrated. After that, to understand the effect of a splitter on a car model, the results collected from the simulation have been analyzed. Splitter's effect on lift force in this current study is compared qualitatively with the work of Bhattacharjee et al [5]. where they worked on a full-scale NASCAR 2019 car prototype using an asymmetrical airfoil as a splitter. Likewise, change in drag force after adding a splitter is also compared with the work of Ruia and Dixit [6] where they studied on the combined effect of a few aerodynamic add-ons on drag force.

2. Theory

Lift force is the upward-acting force which is measured using the projected area of the top surface. Equation 1 defines lift force in a non-dimensional form which is called coefficient of lift. This force is useful for airplanes but not for a car traveling on a road. So, it is required to increase the downforce acting on a car by mounting different aerodynamic add-ons. But the problem is that some of those aerodynamic add-on devices can actually increase drag force. For instance, due to the presence of aerodynamic add-on devices, racing cars have a higher coefficient of drag compared to road vehicles which is around 0.7 to 1.1 [7]. Drag force is the force acting in the opposite direction to the vehicle's motion. It results from the combined effect of the pressure difference between two ends of a car and wall shear forces towards the fluid flow. The drag force can be expressed in a non-dimensional form called the drag coefficient shown in Equation 2.

$$C_l = \frac{Lift\ force}{\rho v^2 A_t/2} \tag{1}$$

$$C_d = \frac{Drag\ Force}{\rho v^2 A_d/\ 2} \tag{2}$$

To study the effects of those add-on devices on a car model, Computational Fluid Dynamics or CFD is an economical and powerful tool. It is a branch of fluid mechanics that solves fluid flow problems using numerical methods and algorithms. During calculation, a set of governing equations is solved by numerical iteration in a computer to get pressure, forces, coefficients, etc.

3. Methodology

For the present study, a SolidWorks-designed car model has been imported into ANSYS to discretize into small volumes in such a way that they get a mathematical identity. Skewness has been checked within the standard range to ensure good meshing size. The computational result has then been analyzed and compared with the results obtained by Bhattacharjee et al. [5] and Ruia and Dixit [6].

Design of car model in SolidWorks

In SolidWorks, a 3D concept model of the BMW 5 series E60 following a blueprint shown in Fig. 1 has been created [8]. Figure 2 and Fig. 3 demonstrate the 2D drawing of the car model and the 3D model of the car respectively, created using the blueprint. It is approximately 26 times smaller than the car shown in the blueprint. Figure 4 shows a drawing of a car model with a splitter of 8 mm in length. Figure 5, Fig. 6, Fig. 7, and Fig. 8 represent wooden 3D car models with splitters of 4 mm, 6 mm, 8 mm, and 10mm in length respectively. Usually, splitter length is limited between 100 mm to 300 mm in racing competitions like NASA ST5, NASA ST1-ST4, Champcar. Our splitter lengths have been taken considering this limitation and the scale factor.

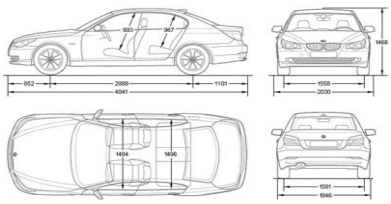


Fig. 1. Blueprint of BMW 5 series E60

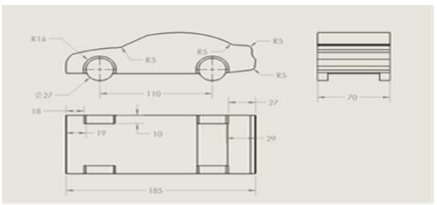


Fig. 2. Drawing of car model without splitter



Fig. 3. Car model without splitter

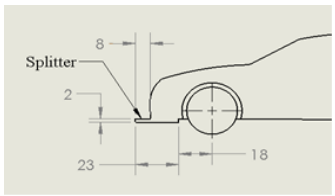


Fig. 4. Drawing of car model with splitter of 8mm in length



Fig. 5. Car model with splitter of 4mm in length



Fig. 6. Car model with splitter of 6mm in



Fig. 7. Car model with splitter of 8mm in length



Fig. 8. Car model with splitter of 10 mm in length

Simulation in ANSYS Fluent

ANSYS Fluent student version has been used to solve fluid flow problems. After designing the 3D model part in SolidWorks, it has been imported into ANSYS Fluent. The workflow during simulation in ANSYS Fluent can be divided into three steps. They are pre-processing, the solver, and post-processing. In pre-processing, the enclosure has been generated around the car model, and then the Boolean tool has been used to subtract the car model from the enclosure. Hence, a computational domain has been generated. Then, meshing has been done to discretize the computational domain into small volumes. Those small volumes are known as cells. The meshing quality has been checked by tracking the skewness of the mesh. A mesh is acceptable if its skewness lies below 0.95 [9]. In this paper, the skewness of any computational domain is below 0.95. For meshing, relevance is kept at 30 for any simulation. Relevance center and smoothing are kept as fine and high for all simulations in this paper. In Assembly Messing, the Tetrahedrons Method has been selected. Figure 9 shows mesh for the car model without a splitter.

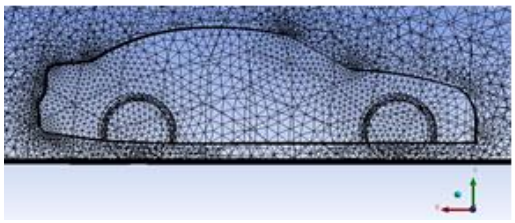


Fig. 9. Mesh for car model without splitter.

In solver, three governing equations from RANS (continuity equation, momentum equation, and energy equation) and two from the k-ε model (kinetic energy and dissipation) have been solved numerically using the selected tools described in Table 1. Boundary conditions and flow parameters are shown in Table 2 and Table 3 respectively.

Table 1. Some of the selected tools

Descriptions	**Selected options**
Solver type	Pressure-Based
Velocity Formulation	Absolute
Time	Steady
Model	k-epsilon
k-epsilon model	Realizable
Near-Wall Treatment	Non-Equilibrium Wall Function
Solution Initialization	Hybrid Initialization

Table 2. Boundary conditions

Description	Conditions
Velocity inlet	10 m/s
Pressure outlet	0 Pa
Wall	No-slip condition
Car surface	No-slip condition

Table 3. Flow parameters

Parameter	Value
Viscosity	7894e-05 kg/m-s
Density	1.225 kg/m^3
Temperature	288 K
Ratio of Specific Heats	1.4
Enthalpy	0 kJ/kg

The last part of the simulation is the post-processing which deals with extracting results and various images.

4. Result and discussion

In ANSYS Fluent, numerical analysis for both with and without a splitter car model has been done, by keeping stationary on the ground at an air velocity of 10 m/s. Table 4 details the dimensions of the enclosure for the model without a splitter. To consider splitter length, only the Cushion -X value needs to be adjusted by subtracting the splitter length from 207.5 mm. Here, the cushion refers to the enclosure. Table 5 presents the lift and drag forces for both configurations.

Table 4. Dimension of enclosure

Axis	Dimension
Cushion +X value	207.50 mm
Cushion +Y value	242.00 mm
Cushion +Z value	114.75 mm
Cushion -X value	207.50 mm
Cushion -Y value	0.0010 mm
Cushion -Z value	114.75 mm

Table 5. Drag force and lift force

Description	Drag force (N)	Lift force (N)
Car model without splitter	0.12084139	0.11835160
Car model with splitter of 4mm in length	0.13056898	0.107268540
Car model with splitter of 6mm in length	0.12718174	0.096346843
Car model with splitter of 8mm in length	0.12934969	0.091193868
Car model with splitter of 10mm in length	0.12616394	0.086700943

Figure 10 shows in a car model without a splitter, velocity is lower near the front bumper as the air gets deflected when it strikes the front bumper. That increases the pressure in that area, marked by the reddish zone in Fig. 11.

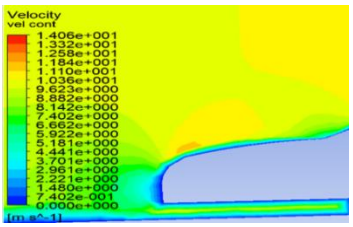


Fig. 10. Velocity contour of car model without splitter

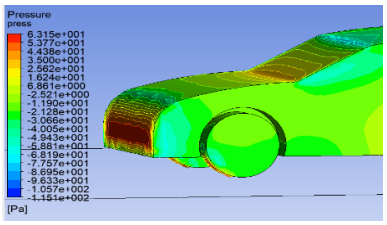


Fig. 11. Pressure contour of car model without splitter

Figure 12 shows the velocity contours for a car model with a 4 mm splitter length. The blue zones on the car's surface indicate stagnation points which can be attributed to the no-slip conditions on the surface of the car. In Fig. 13, low velocity can be observed near the front bumper, leading to increased pressure in that area abiding by Bernoulli's Law. This figure also shows that pressure above the splitter is higher than below, resulting in a downward force that reduces lift. Similar trends appear in Fig. 12, Fig. 14, Fig. 16, and Fig. 18 for velocity, and Fig. 13, Fig. 15, Fig. 17, and Fig. 19 for pressure, showing that as splitter length is increased from 4 mm to 10 mm, the pressure region expands, further decreasing lift.

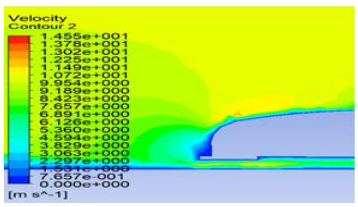


Fig. 12. Velocity contour of car model with splitter of 4mm in length

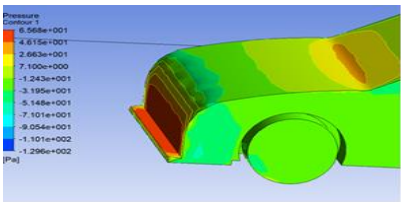


Fig. 13. Pressure contour of car model with splitter of 4mm in length

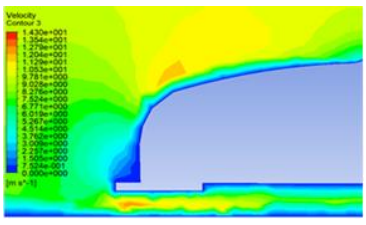


Fig. 14. Velocity contour of car model with splitter of 6mm in length

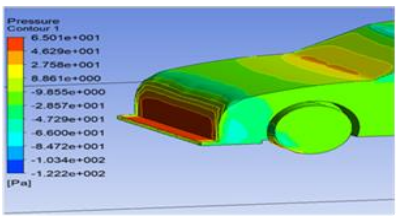


Fig. 15. Pressure contour of car model with splitter of 6mm in length

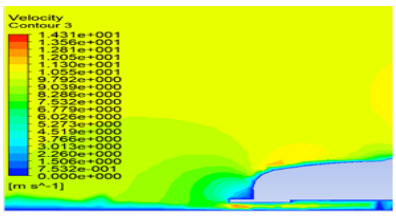


Fig. 16. Velocity contour of car model with splitter of 8mm in length

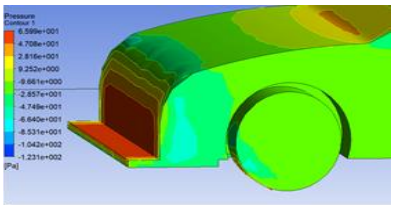


Fig. 17. Pressure contour of car model with splitter of 8mm in length

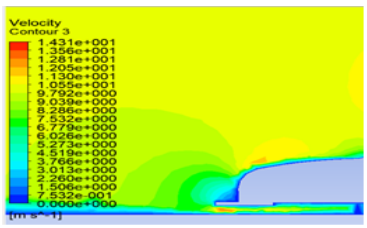


Fig. 18. Velocity contour of car model with splitter of 10 mm in length

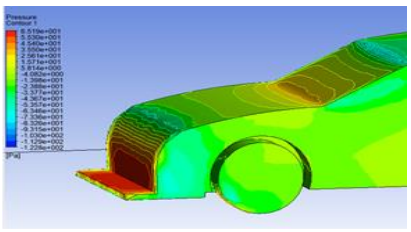


Fig. 19. Pressure contour of car model with splitter of 10 mm in length

Figure 20 illustrates the effect of splitter length on lift force. It can be seen from the figure that the lift force of the car model decreases when a splitter is added. This occurs because as the splitter is added to the car model, high-pressure air above the splitter pushes it downward, reducing lift. Additionally, as splitter length increases, lift force decreases even further. This happens because a high-pressure region near the front bumper also increases as the splitter length increases. This increase in length or in other words, an increase in the area, will produce more downforce. Thus, the lift force decreases further as the splitter length is increased. This finding is congruent with the work of Bhattacharjee et al. [5]. They had also found decrease in lift force as they increased the length of the splitter added to the NASCAR 2019 car model.

Figure 21 demonstrates that, any drag force for a car model with a splitter is higher than those for the car model without a splitter. This happens because the width of the splitter adds to the frontal area of the base model. Since drag force is proportional to the frontal area, drag force increases thereby [4]. The figure also indicates that as the length of the splitter increases, the changes are within a small range. A similar result of increased drag force had been found by Ruia and Dixit [6] in case 4 where they studied the effect of the air dam, splitter, and rear wing on drag coefficient or, in other words, drag force.

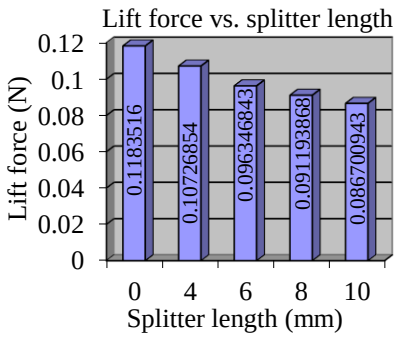


Fig. 20. Bar chart of lift force vs. splitter length

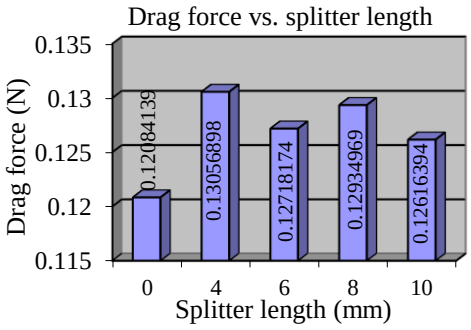


Fig. 21. Bar chart of drag force vs. splitter length

Table 6 represents the impact of splitter length on drag force and lift force compared to the car model without a splitter. Adding a spitter and increasing the length decreases lift force gradually at the cost of increased drag force. It can be observed that, as splitter length is incrementally increased by 2 mm from 4 mm to 10 mm, the percentage of decrease in lift force for two successive splitters becomes smaller. For instance, we see a 4.3% decrease in lift force if we switch a 6 mm splitter with an 8 mm splitter. This is because pressure intensity is not the same between the point at the front bumper and the point at the tip of the splitter. Thus, as the length of the splitter is increased, the lift force doesn't decrease linearly. It can also be observed that as the splitter length increases, the drag force change fluctuates within a narrow range.

Table 6. Change in drag force and lift force due to adding a splitter

Splitter length	Change in lift force relative to car models without a splitter	Change in drag force relative to car models without a splitter	Change in lift force between two successive splitter lengths
4 mm	9.4% decrease	8% increase	
6 mm	18.6% decrease	5.2 % increase	9.2% decrease
8 mm	22.9% decrease	7% increase	4.3% decrease
10 mm	26.7% decrease	4.4% increase	3.8% decrease

5. Conclusion

This research has shown that adding a splitter reduces lift force, but it increases the drag force. The study has further investigated the effect of splitter lengths on lift force. It has been found that increasing the splitter length further reduces the lift force, but the rate of this reduction is not uniform; it diminishes with longer splitters. In this research, splitters of 4 mm, 6 mm, 8mm, and 10 mm have been analyzed, and the 10 mm long splitter decreased the maximum amount of lift force. It has also been observed that the drag force for a car model with a splitter is consistently higher than that for a car model without a splitter. The distance between the splitter and the ground is an important factor for drag and lift force. In the future, that factor can be studied.

7. Acknowledgement

This project is partially funded by the Department of Mechanical Engineering, Chittagong University of Engineering and Technology.

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12. Nomenclature

Symbol	Meaning	Unit (SI)
ρ	Density of Air	Kg/m^3
υ	Velocity of Air	m/s
A_f	Projected Area on the Front Surface	m^2
A_t	Projected Area on the Top Surface	m^2
C_d	Coefficient of Drag	
C_l	Coefficient of Lift	