# Evaluating the aerodynamics of different passenger vehicle configurations

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## Abstract

Aerodynamics, especially for passenger vehicles, have an enormous impact on the design and performance. Consequently, the design of the vehicle influences the drag and lift forces acting on it. When the drag force on the vehicle increases, or when the drag coefficient increases, the energy required to move the body in space increases. For a car, increased drag causes decreased speed and increased load on the engine and powertrain. Aerodynamic efficiency is especially critical to reducing fuel consumption and, thus, the vehicle's carbon footprint. Aerodynamic efficiency is typically defined using the ratio of a body's lift to drag, or the L/D ratio; thus, an efficient design maximises feasible lift while minimising drag. Increased lift often is produced from conditions like elevated speeds that also increase drag; trades must be considered for added features. Another consideration is minimising the wake of a vehicle, as it is heavily responsible for stability and drivability. It is therefore critical to determine which aerodynamic modification would best satisfy these criteria for each vehicle configuration. In this study, different vehicle modifications are explored, including the addition of spoilers, diffusers and curved front bumper profiles. Calculations and CFD analysis generally reserved for high-performance vehicles will be applied to passenger vehicles like SUVs and sedans in this study. The results show that on average a 16% reduction in drag coefficient and 232% reduction in lift coefficient across the board. The highest improvements in drag coefficient is seen in hatchbacks whereas the highest improvement in lift coefficient is seen in sedan and SUV cases.

# Evaluating the aerodynamics of different passenger vehicle configurations

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**Abstract:** Aerodynamics, especially for passenger vehicles, have an enormous impact on the design and performance. Consequently, the design of the vehicle influences the drag and lift forces acting on it. When the drag force on the vehicle increases, or when the drag coefficient increases, the energy required to move the body in space increases. For a car, increased drag causes decreased speed and increased load on the engine and powertrain. Aerodynamic efficiency is especially critical to reducing fuel consumption and, thus, the vehicle's carbon footprint. Aerodynamic efficiency is typically defined using the ratio of a body's lift to drag, or the L/D ratio; thus, an efficient design maximises feasible lift while minimising drag. Increased lift often is produced from conditions like elevated speeds that also increase drag; trades must be considered for added features. Another consideration is minimising the wake of a vehicle, as it is heavily responsible for stability and drivability. It is therefore critical to determine which aerodynamic modification would best satisfy these criteria for each vehicle configuration. In this study, different vehicle modifications are explored, including the addition of spoilers, diffusers and curved front bumper profiles. Calculations and CFD analysis generally reserved for high-performance vehicles will be applied to passenger vehicles like SUVs and sedans in this study. The results show that on average a 16% reduction in drag coefficient and 232% reduction in lift coefficient across the board. The highest improvements in drag coefficient is seen in hatchbacks whereas the highest improvement in lift coefficient is seen in sedan and SUV cases.

## 1 Introduction

Aerodynamics is the study of the motion of air and how it interacts with solid objects such as aircraft, cars, and other vehicles. The goal of vehicle aerodynamics is to reduce air resistance, or drag, and improve the vehicle's efficiency, stability, and handling. Improving the aerodynamic performance of vehicles is crucial to reducing fuel consumption, increasing speed, improving handling, and making them safer, more efficient, and more environmentally friendly.

The study of aerodynamics dates to the late 15th and early 16th centuries, with Leonardo da Vinci being one of the first to observe and document the principles of airflow over bodies in motion. Since then, the field has evolved rapidly, and aerodynamics has become an essential aspect of many fields, including automotive, aerospace, and marine engineering. In the early 19th century, Sir George Cayley was one of the first to understand the principles of aerodynamics and apply them to the design of gliders and other flying machines. His work laid the foundation for modern aerodynamics, and since then, the field has seen significant advancements in technology and design **[1]**.

In the automotive industry specifically, aerodynamics plays a significant role. With the growing impacts of climate change, the need to improve fuel efficiency and reduce emissions has only become more important. Improved aerodynamics can help reduce drag and increase vehicle efficiency, resulting in better fuel economy and lower emissions. The other reason is that it is important for vehicle performance, especially high-performance vehicles like sports cars or race cars. Aerodynamics can enhance a vehicle's handling, stability, and overall performance by reducing drag, improving downforce, and managing airflow. Today, several modifications can be made to improve the aerodynamic performance of vehicles. This paper will focus on spoilers, diffusers, and front bumper profiles specifically. These modifications were chosen as they are some of the most common components considered in vehicle development by car manufacturers **[2]**.

A spoiler is an aerodynamic device that is typically mounted on the rear of a vehicle. Its primary function is to reduce drag and increase downforce on the rear wheels, which can improve the vehicle's overall handling and stability **[3]**. Spoilers work by disrupting the airflow over the rear of the vehicle, which in turn maximises the L/D ratio. Afianto et al. **[4]** has shown that spoilers can increase the lift coefficient by 6% and decrease drag by 5% while decreasing the wake of one specific car shape.

**Figure 1 Modern spoilers**

**Source: *Modern Spoilers*. (n.d.). Retrieved July 26, 2023, from https://tiimg.tistatic.com/fp/1/007/881/automobile-easy-to-use-longer-life-fine-finishing-plastic-sedan-car-universal-spoiler-135.jpg.**

Diffusers, on the other hand, are used to increase downforce and reduce drag. They work by accelerating the airflow underneath the car, which creates a low-pressure area that helps reduce drag and improve the car's handling **[5]**. Huminic & Huminic **[6]** and Senthilkumar et al. **[7]** and have shown that the optimum diffuser angle for hatchbacks and sedans lies somewhere between 5° and 8°.

**Figure 2 Modern diffusers**

**Source: *Modern Diffuser*. (n.d.). Retrieved July 26, 2023, from https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRYKA_25aNTZEoHFN8nELlla9iIgRZ_JzI0xA.**

Front bumper profiles are designed to alter the airflow around the front of the vehicle. They work by reducing the amount of air that hits the front of the car, which reduces drag. Another way that the front bumper profile impacts aerodynamics is in the wake characteristics of the vehicle itself. By designing a front bumper that directs the airflow to the sides of the car instead of into the wake, the size of the wake can be reduced. This can aid in high-speed stability. Front bumper profiles are often used on race cars, where even small reductions in drag can lead to significant improvements in performance. As suggested in Wu et al. **[8]**, optimisation of the front bumper can amount up to a 32-count reduction in drag.

This paper explores these modifications and applies them to the most common passenger car bodies: hatchbacks, sedans, and SUVs. This methodology shows how effective each modification is for each car body and, unlike previous research, does not restrict the sample size to any one specific car body shape.

In recent years, there has been a growing interest in aerodynamics to solve the growing emissions problem. It is looked at as one of the more efficient ways to cut down on energy requirements, reduce fuel consumption, and decrease pollutants **[9]**. Moreover, aerodynamics is one of the most effective ways to reduce the carbon footprint of the vehicle itself. Even though there is a rise in sales of battery electric vehicles (BEVs) and hydrogen electric vehicles (HEVs), there is still a major need for vehicles in the transition, which are ICEVs, and for these vehicles, aerodynamics is one of the ways to reduce emissions. Balaa et al. **[10]** showed that a 2.5% improvement in fuel economy can be seen just through a diffuser in sedans, and Browand **[11]** has shown that a 7% fuel economy saving can be made depending on the configuration and aerodynamic gains, in addition to a monetary gain due to the corresponding fuel efficiency gains as well.

To evaluate the impact of these modifications on different vehicle segments, computational fluid dynamics (CFD) simulations are employed. CFD simulations are powerful, fast tools that can be used to analyse the complex airflow patterns around vehicles and predict their performance. By simulating different aerodynamic modifications on hatchbacks, SUVs, and sedans, a better understanding of how each modification impacts the aerodynamic performance of each vehicle segment is achieved.

In this work, optimal aerodynamic points for passenger vehicles are sought. An optimal aerodynamic point is defined as the point where a vehicle experiences the least amount of drag and the most amount of lift. As drag and lift are highly nonlinear functions, multiple optimal aerodynamic points can exist. This point is crucial for maintaining the vehicle's stability and minimising the wake generated as it moves through the air. Achieving the optimal aerodynamic point is dependent on several factors, including the vehicle's design, speed, and environmental conditions. In general, a vehicle with a lower drag coefficient and a lower lift coefficient will have a more efficient aerodynamic performance. In some cases negative lift coefficient values can also be seen. A negative lift coefficient is a situation in which the lift force acting on a vehicle is directed downwards, rather than upwards. This is nothing but downforce. Downforce is generally seen in race cars, but in road vehicles it can increase stability and in certain cases also help with drag. Therefore, engineers strive to optimise vehicle design and aerodynamic modifications to achieve the optimal aerodynamic point for each vehicle configuration.

One of the primary ways to achieve optimal aerodynamic performance is with aerodynamic modifications. In this study, with the help of the CFD software SimFlow, a GUI of the OpenFoam software, the effects of different aerodynamic modifications on the aerodynamic efficiency and coefficients of various segments of passenger vehicles, including sedans, SUVs, and hatchbacks, are investigated. How these modifications affect the optimal aerodynamic point for each vehicle configuration is also examined. In doing so, a better understanding of how these modifications can be used to improve the overall performance of passenger vehicles and ultimately reduce their impact on the environment is elucidated.

## 2 Methodology

### 2.1 CFD Software

The choice of CFD software for the simulations is SimFlow. SimFlow is software that is based on the popular open-source software and solver OpenFoam, using the same numerics **[12]**. SimFlow employs the Finite Volume Method (FVM) as its numerical discretization scheme, specifically utilising a cell-centred approach. In FVM, the computational domain is divided into a grid composed of control volumes, or cells, which are typically hexahedral or structured. SimFlow assigns the flow variables, such as pressure and velocity, to the cell centres, ensuring that the conservation equations are solved on these control volumes. This cell-centred approach provides accurate and stable results by capturing the flow behaviour within each control volume.

Following are the CFD details:

**Table 1 Solver Settings**

| | |
|---|---|
| Solver Name | SIMPLE |
| Solver Type | Pressure Base |
| Governing Equations | Navier-Stokes equations |
| Discretization Method | Finite Volume Method |
| Pressure-Velocity Coupling | Segregated Approach |
| Pressure Solver | Pressure Correction |
| Velocity Predictor | Implicit |
| Momentum Equation Solver | Implicit |
| Time Integration Scheme | Steady State |
| Flow Type | Incompressible |
| Turbulence Model | RANS (k-ω SST) |
| Transport Model | Newtonian |
| Base Mesh Type | Box |
| Cell Size | 0.9m x 0.6m x 0.31125m |
| Inlet Velocity | 20m/s |
| Absolute Tolerance | 1e-06 |
| Relative Tolerance | 0.1 |

## 2.2 Formulas and Equations

SimFlow uses the following formula to calculate the drag ($C_D$) and lift coefficients ($C_L$), respectively:

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A}$$

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 A}$$

where $C_D$ is the aerodynamic drag coefficient, $C_L$ is the aerodynamic lift coefficient, D is the aerodynamic drag force (N), A is the reference area or the frontal area of the vehicle ($m^2$), V is the free stream velocity (m/s), and ρ is the free stream or ambient air density ($kg/m^3$).

## 2.3 Model and Test Matrix

Three major configurations were tested: hatchbacks, sedans, and SUVs. For the hatchback, a simplified CAD model based on the Volkswagen Polo (**Figure 3**) was designed; for the sedan, a simplified CAD model based on the Honda Accord (**Figure 4**) was designed; and for the SUV, a simplified CAD model based on the Range Rover Evoque (**Figure 5**) was designed.

**Figure 3 Volkswagen Polo Simplified Model**

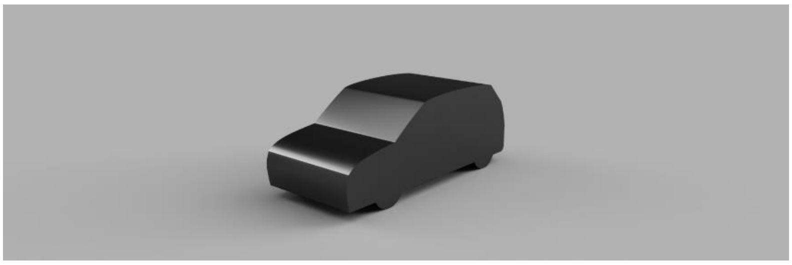


**Figure 4 Honda Accord Simplified Model**

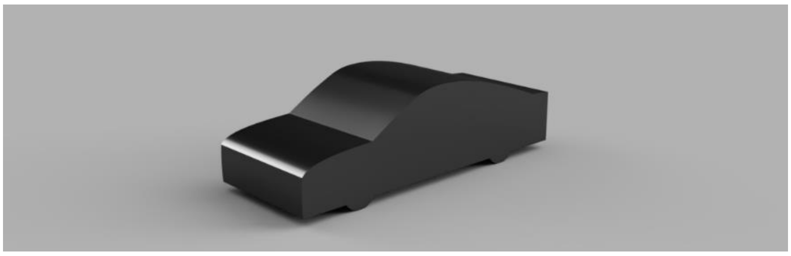
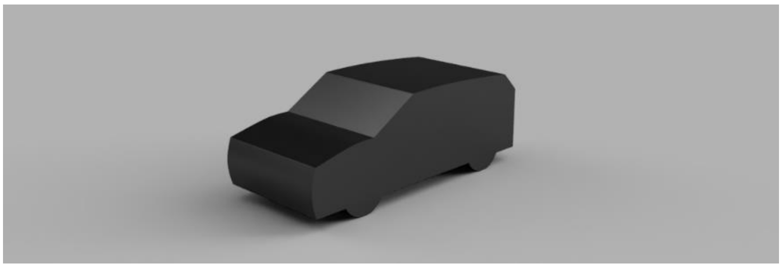


**Figure 5 Range Rover Evoque Simplified Model**



The CAD models are based on 2D blueprints and the general shape of the vehicle. They were made in Autodesk Fusion 360. The CAD models are made to scale relative to the actual vehicles they were based on. The test matrix below was tested for each base vehicle.

**Table 2 Configuration Text Matrix Table**

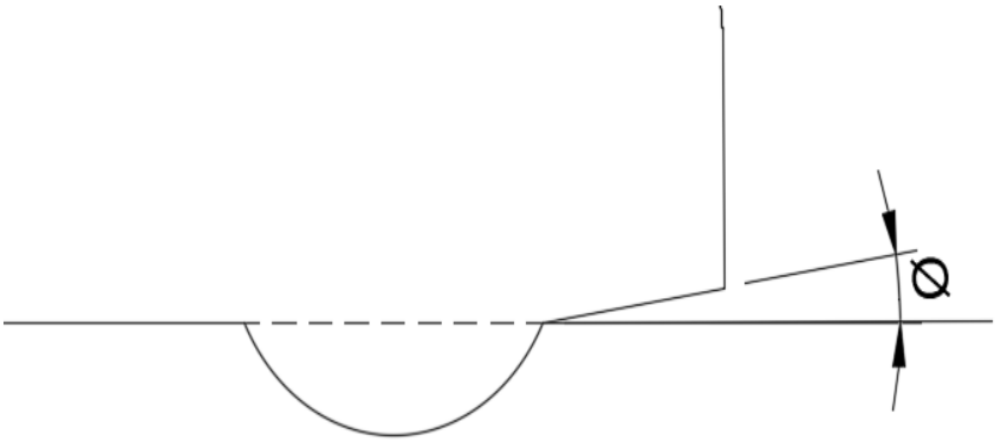
| Sno | Diffuser Angle (in degrees, Φ) | Front bumper curvature (%) | Spoiler length (in mm) | Spoiler Angle (in degrees, Φ) |
|---|---|---|---|---|
| **1.** | - | - | - | - |
| **2.** | 3 | - | - | - |
| **3.** | 5 | - | - | - |
| **4.** | 7 | - | - | - |
| **5.** | 9 | - | - | - |
| **6.** | 11 | - | - | - |
| **7.** | 13 | - | - | - |
| **8.** | - | 33 | - | - |
| **9.** | - | 66 | - | - |
| **10.** | - | 100 | - | - |
| **11.** | - | - | 150 | 6 |
| **12.** | - | - | 150 | 9 |

| | | | | |
|---|---|---|---|---|
| **13.** | - | - | 150 | 12 |
| **14.** | - | - | 200 | 6 |
| **15.** | - | - | 200 | 9 |
| **16.** | - | - | 200 | 12 |

The 33%, 66%, and 100% correspond to percentile figures of the curvature possible for the front bumper.

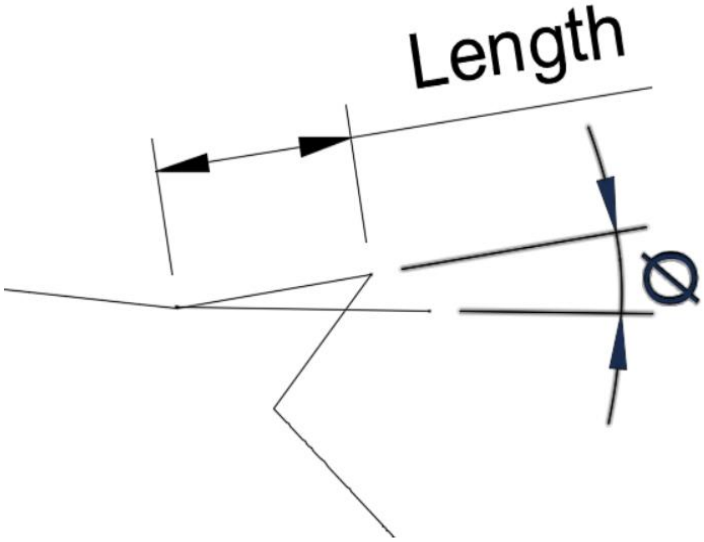
The diffuser design is laid out as such:

**Figure 6 Diffuser design, where Φ is the angle (in °) between the horizontal and diffuser**



The spoiler design is as follows:

**Figure 7 Spoiler design, where *Φ* is the angle (degrees) between the horizontal and spoiler**



All vehicles have some sort of diffuser or spoiler integrated in their design, the difference being the ranges these different aerodynamic modifications are being run at.

# 3 Results

## 3.1 Diffuser Analysis

In total, five different angles were tested for each vehicle.

3.1.1 Hatchback:

**Table 3 Hatchback diffuser data**

| Configuration | **Drag Coefficient** | **Lift Coefficient** |
|---|---|---|
| Base | 0.266 | 0.172 |
| 5° | 0.256 | 0.119 |
| 7° | 0.253 | 0.098 |
| 9° | 0.252 | 0.085 |
| 11° | 0.252 | 0.085 |
| 13° | 0.253 | 0.091 |

From the table above, the optimal diffuser angle range lies somewhere between 7° and 9°. At these diffuser angles, a 5.4% reduction in drag coefficient is observed, as well as almost a 50.85% reduction in the lift coefficient, or a 50.85% increase in the downforce of the vehicle. Even the addition of a basic diffuser at an angle of 5° can result in a reduction in the drag coefficient of 3.64% and a 30.81% reduction in the lift coefficient.

Following is the velocity plot comparing the wake of the vehicle between the base and 9° cases. Note that for all velocity plots, red infers higher velocity (around 20-22m/s), whereas blue infers lower velocities approaching zero. Both colours are in a gradient accordingly. The data for all velocity plots are in units of m/s.

**Figure 8 Velocity plot of base hatchback**

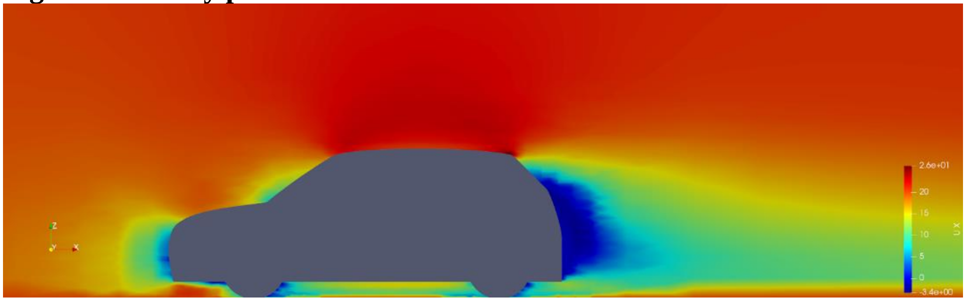


**Figure 9 Velocity plot of hatchback with 7° diffuser angle**

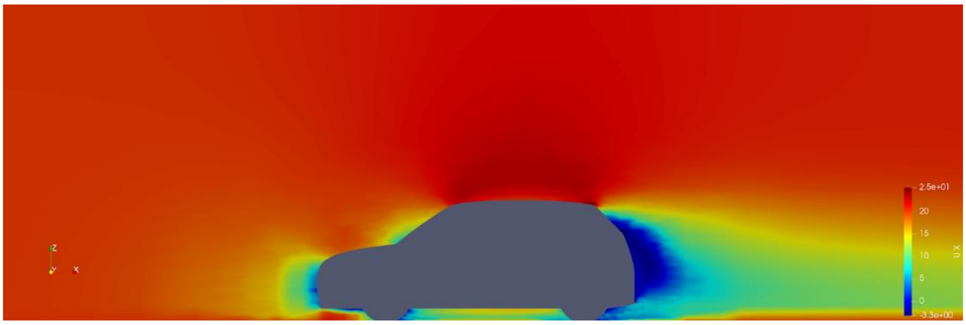
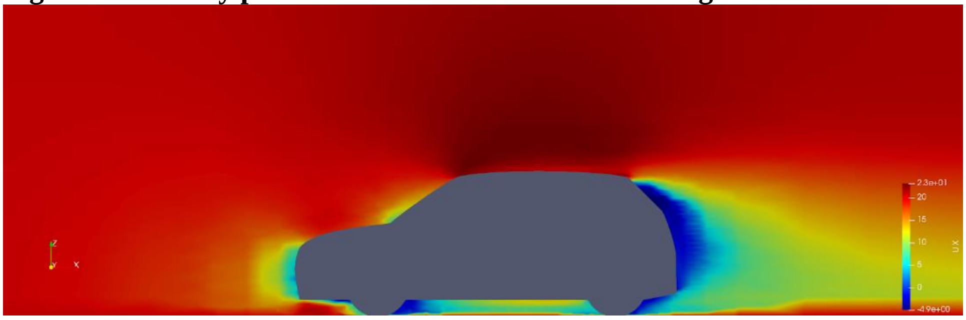


**Figure 10 Velocity plot of hatchback with 9° diffuser angle**



As can be seen from the velocity plots, in addition to the drag and lift improvements that result from the reduction in wake in the lower blow region compared to the base which lies near the diffuser region. This reduction in wake adds to the  stability to the vehicle as well. The difference between the wake of the 7° and 9° cases is quite considerable; therefore, for road vehicles, the advantage of reduced wake might outweigh the minor difference in drag and lift values.

3.1.2 Sedan:

**Table 4 Sedan diffuser data**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.158 | 0.052 |
| 5° | 0.151 | -0.033 |
| 7° | 0.154 | -0.033 |
| 9° | 0.155 | -0.044 |
| 11° | 0.155 | -0.051 |
| 13° | 0.156 | -0.055 |

For sedans, the optimal diffuser angle is about 5°, which amounts to a 4.35% reduction in the drag coefficient, and a 162.77% reduction in the lift coefficient, which implies the addition of downforce. Unlike the hatchback, for sedans the optimal diffuser angle is quite low in the range of diffuser angles, meaning that even a very low-angle diffuser for road vehicles would make a huge impact on its performance.

**Figure 11 Velocity plot of base sedan**

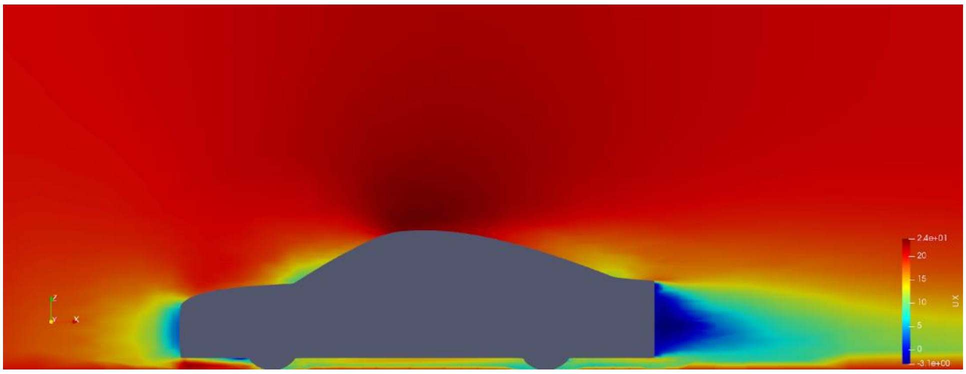
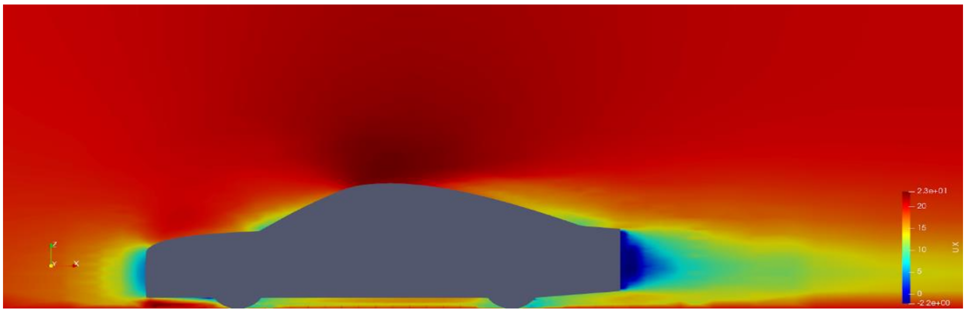


**Figure 12 Velocity plot of sedan with 5° diffuser angle**



In the velocity plots seen above, we can see that the velocity of airflow has increased relative to the base case, this concurs with the lift coefficient improvements or the additions in downforce seen in the CFD data. This also can be contributed to the reduction of wake in the region behind the vehicle due to the addition of the diffusers.

3.1.3 SUV:

**Table 5 SUV diffuser data**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.259 | 0.097 |
| 5° | 0.253 | 0.043 |
| 7° | 0.252 | 0.024 |
| 9° | 0.256 | 0.025 |
| 11° | 0.251 | -0.007 |
| 13° | 0.251 | -0.021 |

The optimal diffuser angle for the SUV case lies between 11° and 13°. This results in a reduction in drag coefficient of 3.15%, and a reduction in lift coefficient of 106.86%. Similar to the hatchback case, the addition of a basic diffuser at about 5° is also really helpful, as it reduces the drag coefficient by 2.49% but, more importantly, reduces the lift coefficient by 55.71%.

**Figure 13 Velocity plot of base SUV**

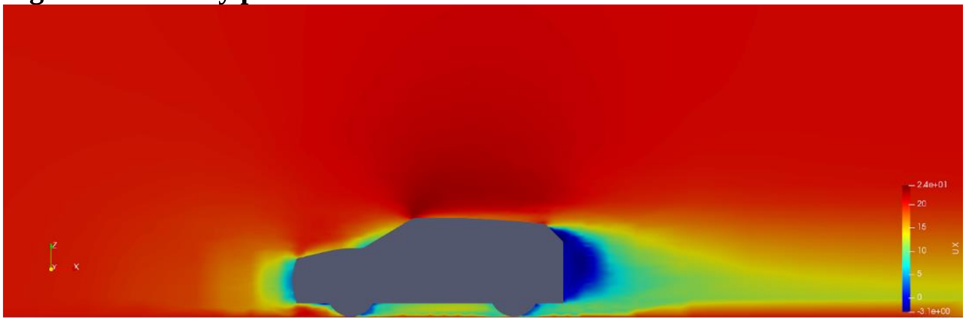


**Figure 14 Velocity plot of SUV with 5° diffuser**

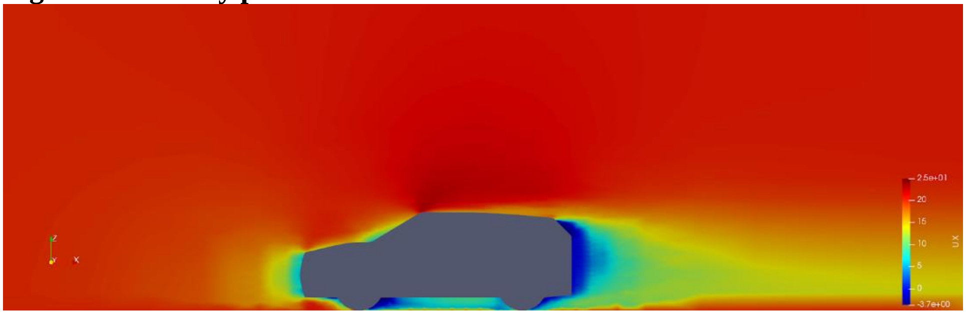
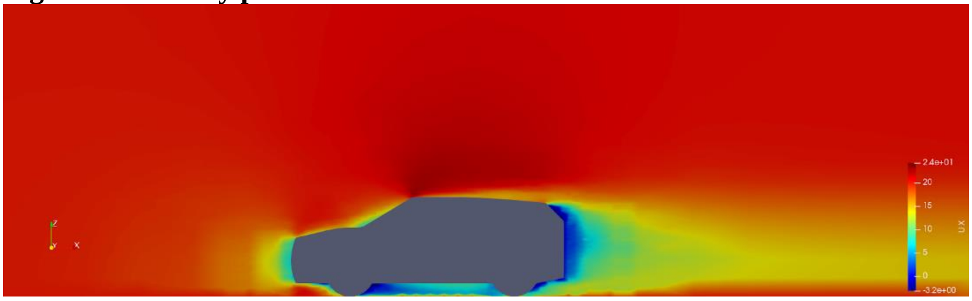


**Figure 15 Velocity plot of SUV with 11° diffuser**



Similar to the Hatchback and Sedans, in the optimal diffuser angle range we can see increased velocity in the rear of the vehicle. In addition to that we can also see a reduction in wake. A thing to note is that the optimal diffuser angle is higher for the SUV case compared to the other two cases, this can be attributed to the general high ride height/ higher ground clearance of SUVs which requires a steeper angle for a similar effect seen in hatchbacks and sedans.

## 3.2 Front Bumper Analysis

A total of three different cases were tested for each vehicle.

### 3.2.1 Hatchbacks:

**Table 6 Hatchback front bumper data**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.266 | 0.172 |
| Minor | 0.246 | 0.181 |
| Medium | 0.234 | 0.177 |
| Max | 0.224 | 0.167 |

For the minor and medium cases, there is a drop in the drag coefficient but a slight increase in the lift coefficient. The most optimal design is the max configuration, which amounts to a 15.65% reduction in drag coefficient and a 2.68% reduction in lift coefficient.

**Figure 16 Velocity plot of minor configuration of hatchback**

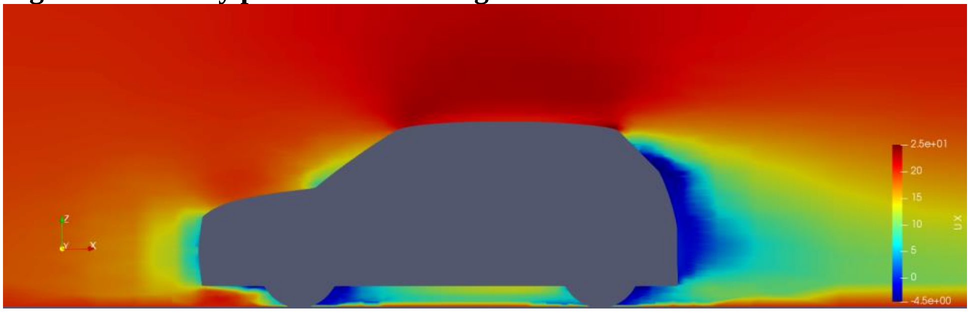
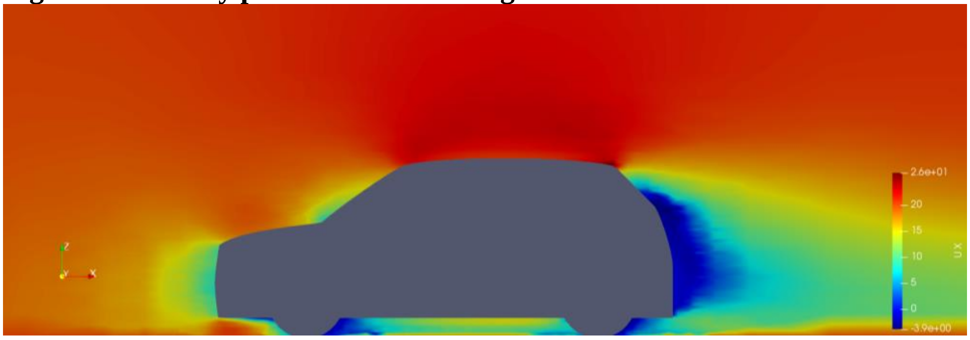
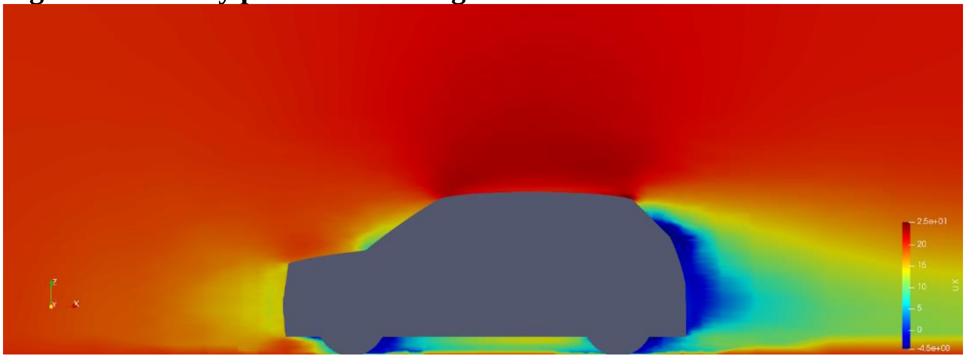


**Figure 17 Velocity plot of medium configuration of hatchback**



From the velocity plots it can be observed that at the front of the vehicle near the modifications, a similar or slight reduction in velocities. This leads to the variation observed in the lift coefficient values.

**Figure 18 Velocity plot of max configuration of hatchback**



In the max configuration, unlike the minor and medium configurations, a clear increase in velocities is observed at the front of the vehicle leading to the corresponding lift and drag gains.

### 3.2.2 Sedan:

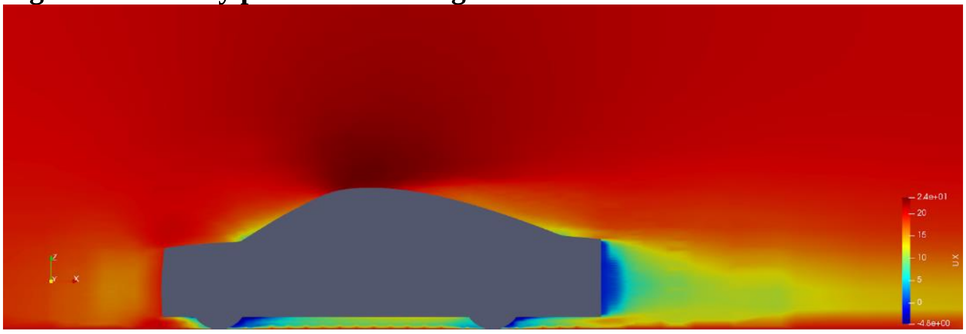
**Table 7 Sedan front bumper data**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.158 | 0.052 |

| | | |
|---|---|---|
| Minor | 0.144 | 0.051 |
| Medium | 0.141 | 0.050 |
| Max | 0.137 | 0.045 |

Similar to the hatchback case, the most optimal design is the max configuration. This can be attributed to the same general sizing of the front end of the vehicle, which has led to the same configuration being the optimal for both vehicles. It sees a reduction of 13.18% in drag and 13.93% in lift.

**Figure 19 Velocity plot of max configuration of sedan**



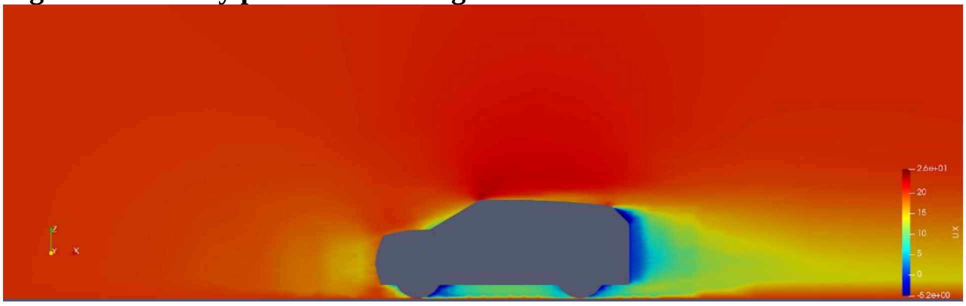
3.2.3 SUV:

**Table 8 SUV front bumper data**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.259 | 0.097 |
| Minor | 0.248 | 0.093 |
| Medium | 0.239 | 0.109 |
| Max | 0.233 | 0.099 |

For the SUV case, it is concluded that the max configuration is again the optimal design. However, unlike the previous two cases, there is no reduction in the lift coefficient observed; on the contrary, an increase in the lift coefficient of 2.01% is observed. However, a 10% reduction in the lift is also observed. This is one of the few modifications that predominantly affects the drag while keeping the lift coefficient at a similar level.

**Figure 20 Velocity plot of max configuration of SUV**



### 3.3 Spoiler Analysis

A total of six different spoiler configurations per vehicle were tested.

3.3.1 Hatchbacks:

**Table 9 Hatchback spoiler data**

| Configuration (Length - Angle) | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.266 | 0.172 |
| 150mm-6° | 0.237 | -0.001 |
| 150mm-9° | 0.239 | -0.008 |
| 150mm-12° | 0.241 | -0.017 |
| 200mm-6° | 0.236 | -0.013 |
| 200mm-9° | 0.237 | -0.023 |
| 200mm-12° | 0.240 | -0.034 |

The first conclusion is that any spoiler in the ranges looked at here is immediately better than the base case. Also, there is a consistent major decrease in the lift coefficients throughout. The optimal configuration is 6° and can be either 150mm or 200mm long. There is an 11.23% reduction in drag and a 107.6% reduction in lift under these conditions.

**Figure 21 Velocity plot of hatchback with 150mm and 6° spoiler**

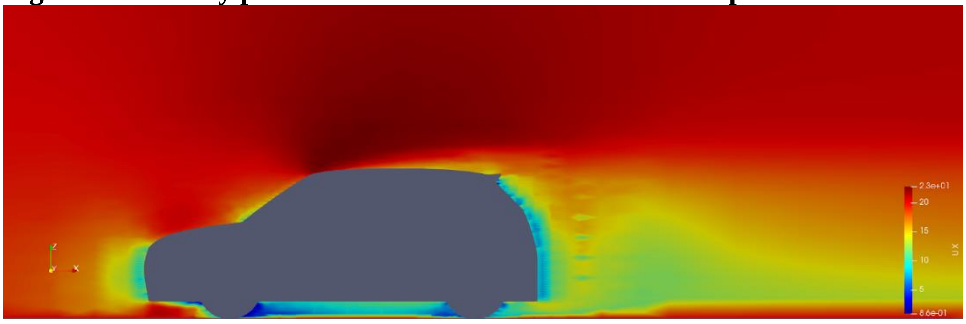
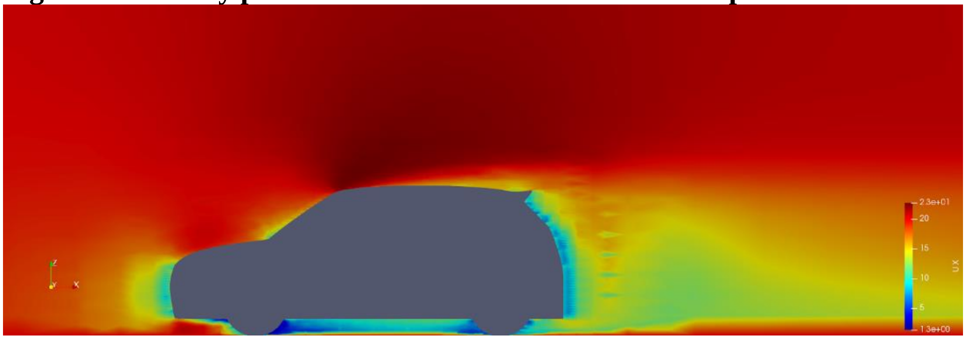


**Figure 22 Velocity plot of hatchback with 200mm and 6° spoiler**



From the velocity plots it can be inferred that the spoiler is redirecting airflow above the vehicle surface, unlike the base case. This leads to a drastic decrease in the lift coefficients. It can also be observed that the lift coefficients are in negative, inferring the production of downforce on the vehicle due to the air. This can aid in stability. Negative lift coefficient values would be observed in most spoiler modification test cases.

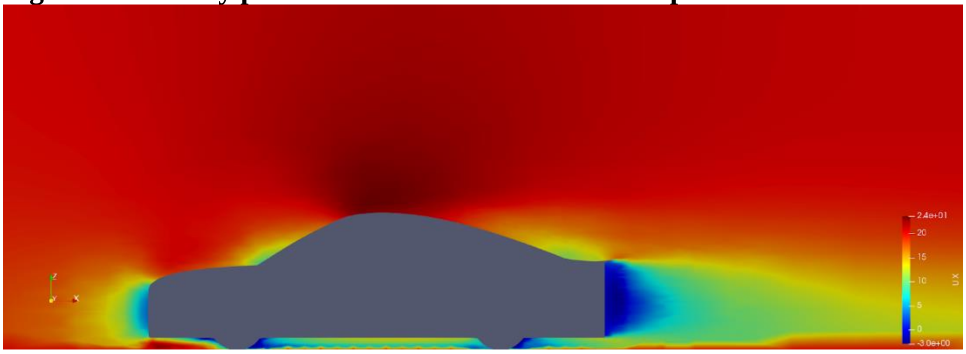
### 3.3.2 Sedan:

**Table 10 Sedan spoiler data**

| Configuration (Length-Angle) | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.1579 | 0.0522 |
| 150mm-6° | 0.1548 | 0.0284 |
| 150mm-9° | 0.1557 | 0.0234 |
| 150mm-12° | 0.1567 | 0.0186 |
| 200mm-6° | 0.1547 | 0.0210 |
| 200mm-9° | 0.1556 | 0.0158 |
| 200mm-12° | 0.1569 | 0.0089 |

Unlike the hatchback case, there is not much reduction in drag relative to the hatchback, but lift reduction is still large. This can be attributed due to general design characteristics of a sedan. As the sedan's spoiler location is much lower relative to the hatchback, the spoiler's effect is less. Unlike the hatchback case the lift coefficient is still in positive suggesting less lift coefficient improvements relative to the hatchback. For the optimal configuration, the spoiler is 200mm long and at 6°. It results in a 2.04% reduction in drag and a 59.69% reduction in lift.

**Figure 23 Velocity plot of sedan with 200mm and 6° spoiler**



### 3.3.3 SUV:

**Table 11 SUV spoiler data**

| Configuration (Length-Angle) | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Base | 0.259 | 0.097 |
| 150mm-6° | 0.246 | -0.016 |
| 150mm-9° | 0.248 | -0.027 |
| 150mm-12° | 0.249 | -0.033 |
| 200mm-6° | 0.244 | -0.025 |
| 200mm-9° | 0.247 | -0.036 |
| 200mm-12° | 0.249 | -0.043 |

Similar to the hatchback case, all configurations provide a considerable improvement to the lift and drag coefficients. In terms of the most optimal configuration, it is again either 150mm or 200mm length and a 6° angle. A 5.85% reduction in drag is observed, in addition to a 125.54% reduction in lift.

**Figure 24 Velocity plot of SUV with 150mm and 6° spoiler**

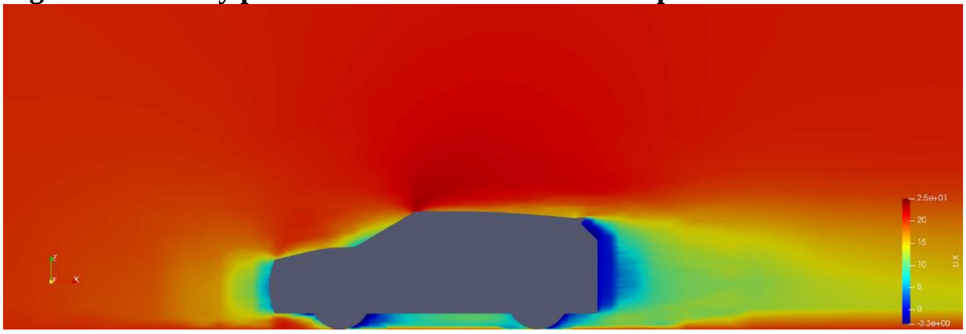
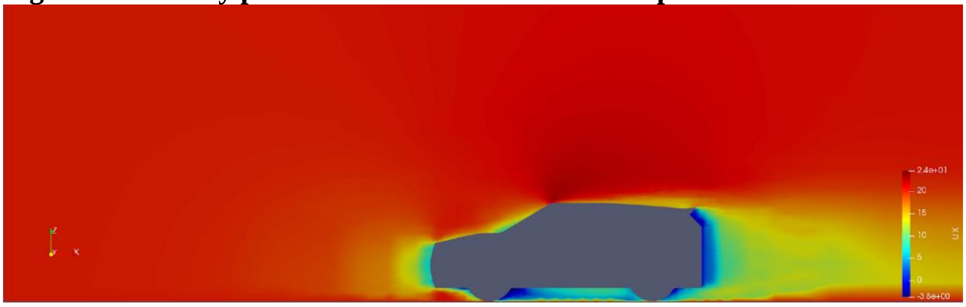


**Figure 25 Velocity plot of SUV with 200mm and 6° spoiler**



## 4 Conclusion

Considering all the observations from CFD analysis, the following are the optimal configurations for the vehicles in consideration:

**Table 12 Optimal vehicle configurations for each vehicle type**

| Car Name | Diffuser Angle (degree) | Front Bumper Profile | Spoiler (Length-Angle) |
|---|---|---|---|
| **Polo** | 9° | Max | 200mm - 6° |
| **Accord** | 5° | Max | 200mm - 6° |
| **Range Rover** | 11° | Max | 200mm - 6° |

One thing to note is that the spoiler configuration is the same for all three vehicles, but making the step size smaller would enable precise (e.g. 3 significant figure) optimization for L/D and likely reveal small differences in optimal configuration.

**Figure 26 Comparing base (left) and final (right) configurations for Hatchback**

**Figure 27 Comparing base (left) and final (right) configurations for Sedan**

**Figure 28 Comparing base (left) and final (right) configurations for SUV**

**Table 13 Performance results for optimal vehicle configurations**

| Configuration | Drag Coefficient | Lift Coefficient |
|---|---|---|
| Hatchback Optimal | 0.205 | -0.103 |
| Sedan Optimal | 0.137 | -0.077 |
| SUV Optimal | 0.224 | -0.183 |

The drag coefficient of the final configuration of the hatchback is 23% less than the base, and the lift coefficient is 160% less than the base. For the sedan, the final configuration has a 13% lower drag coefficient and a 248% lower lift coefficient. Finally, for the SUV case, the drag coefficient is reduced by 14% and the lift coefficient is reduced by 288%. In the results section, across most modifications a reduction in lift coefficient is observed. A major reduction was seen in the spoiler test cases. All these reductions add up to to a net negative value for the lift coefficient which when compared to the base configurations is stark. The negative lift coefficient implies a net downforce acting on the vehicle rather than lift due to the air.

**Figure 29 Velocity plot of final configuration of hatchback**

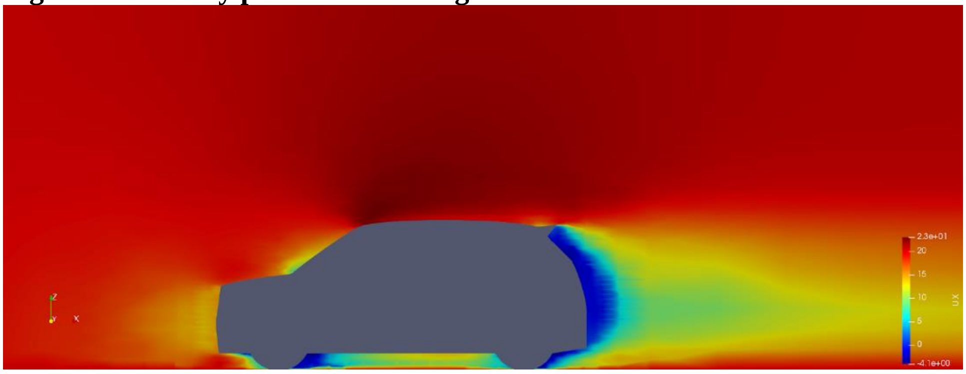


**Figure 30 Velocity plot of the final configuration of sedan**

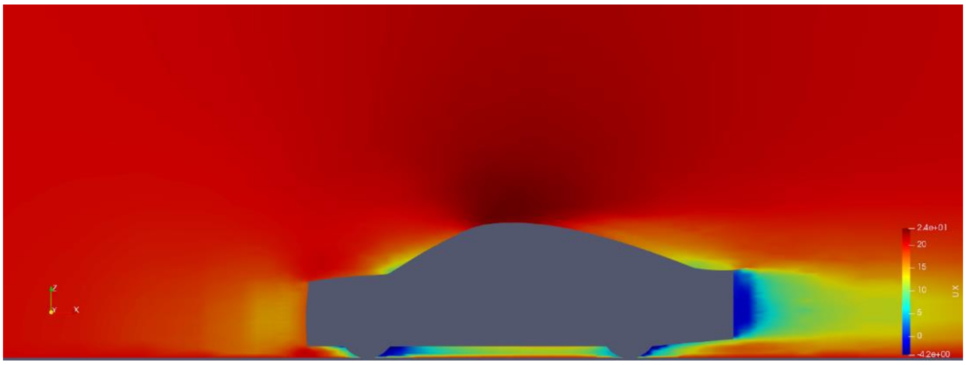
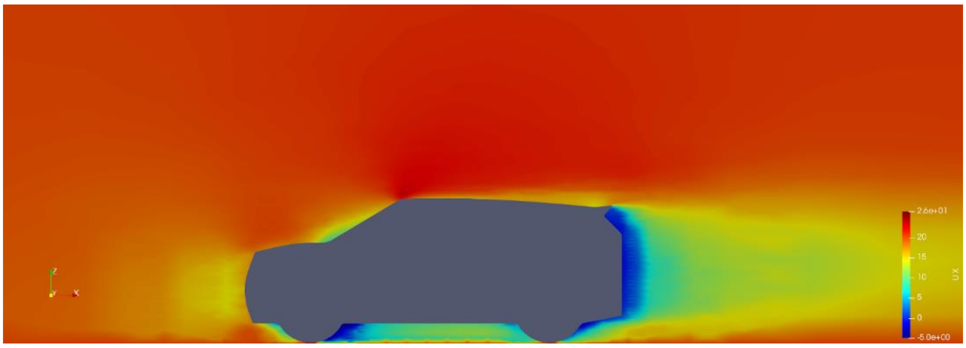


**Figure 31 Velocity plot of the final configuration of SUV**



In conclusion, the application of computational fluid dynamics (CFD) simulations in the study of aerodynamics has provided valuable insights into improving vehicle performance and efficiency. By analysing the CFD results obtained for various vehicle components, including the diffuser, front bumper profile, and spoiler, deeper understanding of their impact on aerodynamic characteristics is uncovered.

The research conducted in this study supports the significance of aerodynamics in the automotive industry. By leveraging CFD simulations and analysis, engineers and designers can make informed decisions to enhance vehicle aerodynamic performance, leading to improved fuel efficiency through enhanced downforce and, as a result, reduced emissions. This research contributes to the ongoing efforts to develop more eco-friendly and efficient vehicles, ultimately promoting sustainability in the transportation sector. For example, the 23% reduction in drag seen in hatchback case, can amount to an 11.5% improvement in fuel economy **[13]**. To quantify this impact, an average hatchback has a fuel economy of about 25 miles per gallon or about 10.63 kmpL **[14]**. With the added aerodynamics, the fuel economy could go up to 11.85 kmpL, or 27.87 mpg. If the car travels roughly 15000 km a year, then a total of 141.38 L of fuel can be saved. Now the combustion of 1 L gasoline leads to the production of 2.3kg CO2 **[15]**, hence a 141.38L reduction in fuel usage would lead to a CO2 emission reduction of 325.17 kg. The cost of 1L gasoline varies from time to time but has recently averaged $ 3.5 per L, amounting to a saving of about $495 per year. Thus, in addition to an environmental advantage, there is a cost-benefit.

In summary, the use of CFD simulations in aerodynamics research has proven to be a valuable tool for studying and optimising vehicle design. The insights gained from these simulations offer opportunities to enhance vehicle performance, reduce drag, and ultimately contribute to the development of more sustainable and efficient vehicles.

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