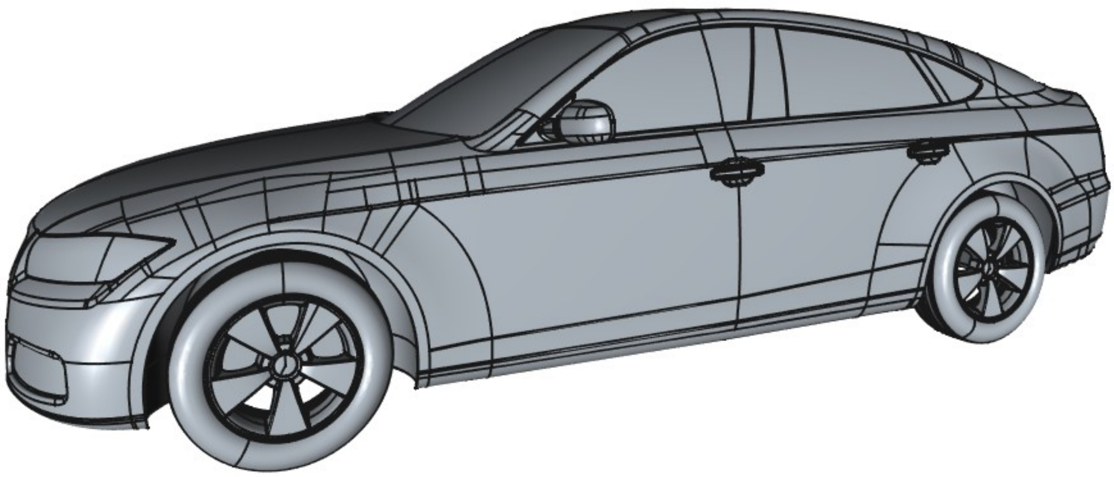
Parametric Investigation of Spoiler-Induced Flow Alterations Using the Drivaer Model as a Baseline



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Introduction

Aerodynamic refinement plays a crucial role in vehicle performance, influencing factors such as fuel efficiency, stability, and overall handling. Among the many aerodynamic components employed in automotive and aerospace design, spoilers stand out as effective flow-control devices capable of altering drag and lift characteristics to optimize performance. This study investigates the aerodynamic effects of varying spoiler angles using the Drivaer model as a reference.

A spoiler is an aerodynamic device designed to manipulate airflow around a vehicle, primarily by reducing unwanted lift and modifying wake characteristics to improve stability. Unlike wings, which generate lift, spoilers disrupt airflow to enhance traction and drag balance, making them integral to sports cars, high-speed vehicles, and even commercial automobiles where stability is a priority. An optimally designed spoiler can delay flow separation, reduce turbulence, and influence aerodynamic coefficients, leading to better stability and efficiency. Spoilers can be categorized based on their placement and functionality:

- Rear Spoilers: Common in sports cars and racing vehicles, they provide additional downforce at high speeds.
- Front Spoilers (Air Dams): Located near the front bumper, they help manage airflow beneath the vehicle to minimize front-end lift.
- Active Spoilers: Adaptive systems that adjust dynamically based on driving conditions to optimize aerodynamic efficiency.
- Roof Spoilers: Used in SUVs and hatchbacks, primarily to control wake turbulence behind the vehicle.

In high-performance applications, spoiler angles play a decisive role. Altering the angle of attack modifies pressure distribution and shear-layer detachment, influencing lift and drag forces. This parametric study explores angles ranging from -15° to 30°, systematically assessing their influence on aerodynamic behaviour using CFD simulations.

The Drivaer model [1] is a widely recognized benchmark for automotive aerodynamics. Developed to simulate realistic vehicle shapes while maintaining computational simplicity, the model serves as an excellent foundation for spoiler-based aerodynamic investigations. Although the original Drivaer model lacks a spoiler, it provides a consistent geometry for controlled parametric analysis, allowing precise evaluation of spoiler-induced flow alterations.

This study employs a resource-efficient 2D approach, acknowledging its limitations while extracting meaningful insights into spoiler aerodynamics. The findings aim to highlight aerodynamic trends and flow separation characteristics.

CAD Modelling

The CAD modelling was done with *FreeCAD*. The DrivAer model of the fastback configuration coded as F_S_wM_wW was considered as the baseline model in this project. A 2D surface from the symmetry plane was extracted from the 3D model. Various iterations of this surface were made, by appending it with a rear spoiler on the edge of the trunk at -15°, 0°, 5°, 12°, 20°, and 30° angles from a line that is tangent to the trunk, as shown in figure 1.

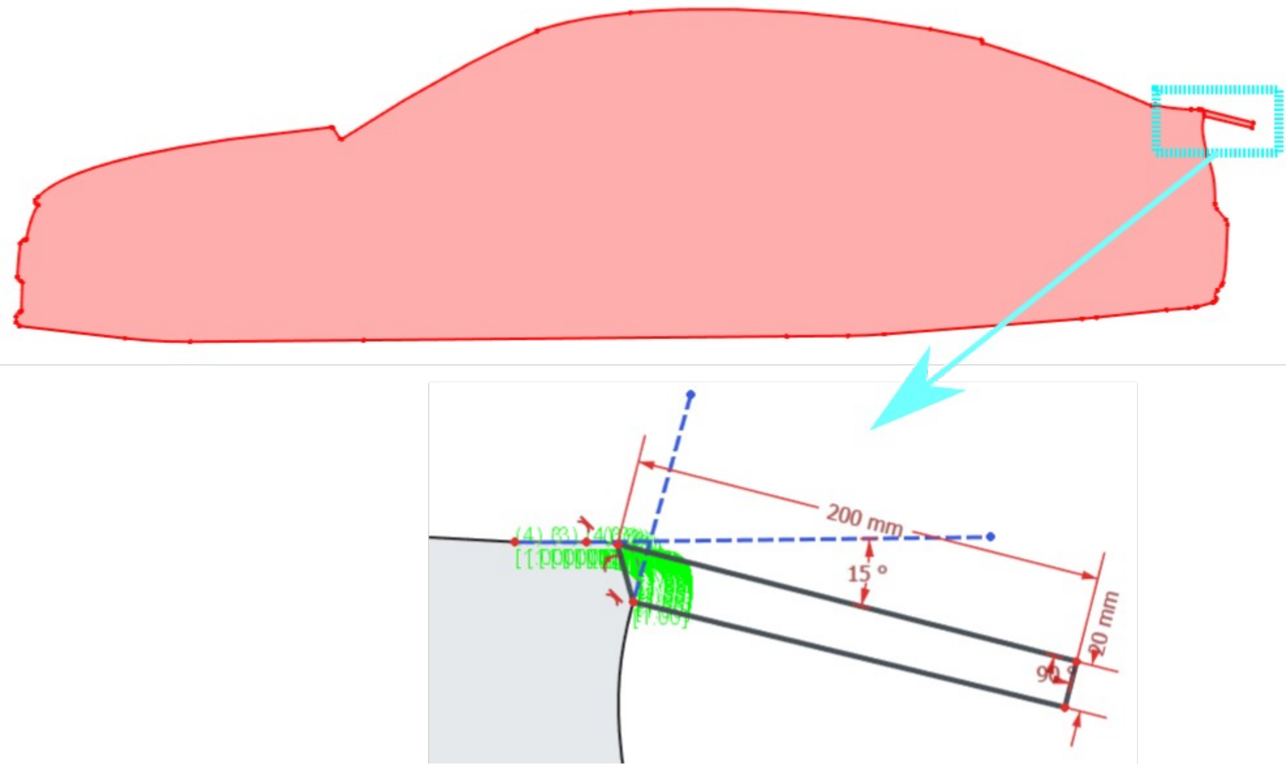

Figure 1: 2D plane geometry of the car and spoiler

For the sake of simplicity, the spoiler is modelled as a thin plate 20 mm thick and 200 mm long.

CFD Modelling and Simulation Setup

The CFD modelling and simulations were carried out on the *CfdOF* workbench of *FreeCAD*. Figure 2 shows the computational domain of the simulations. Different boundary conditions are labelled. The inlet is located at 2L from the model while the outlet at 8.5L, where L is length of the model. The total height of the domain is 8H, where H is the height of the model. The table below enlists all the parameters used for simulation setup. Inflation layers, keeping $y^{+}<1.5$, were added on the car surface.

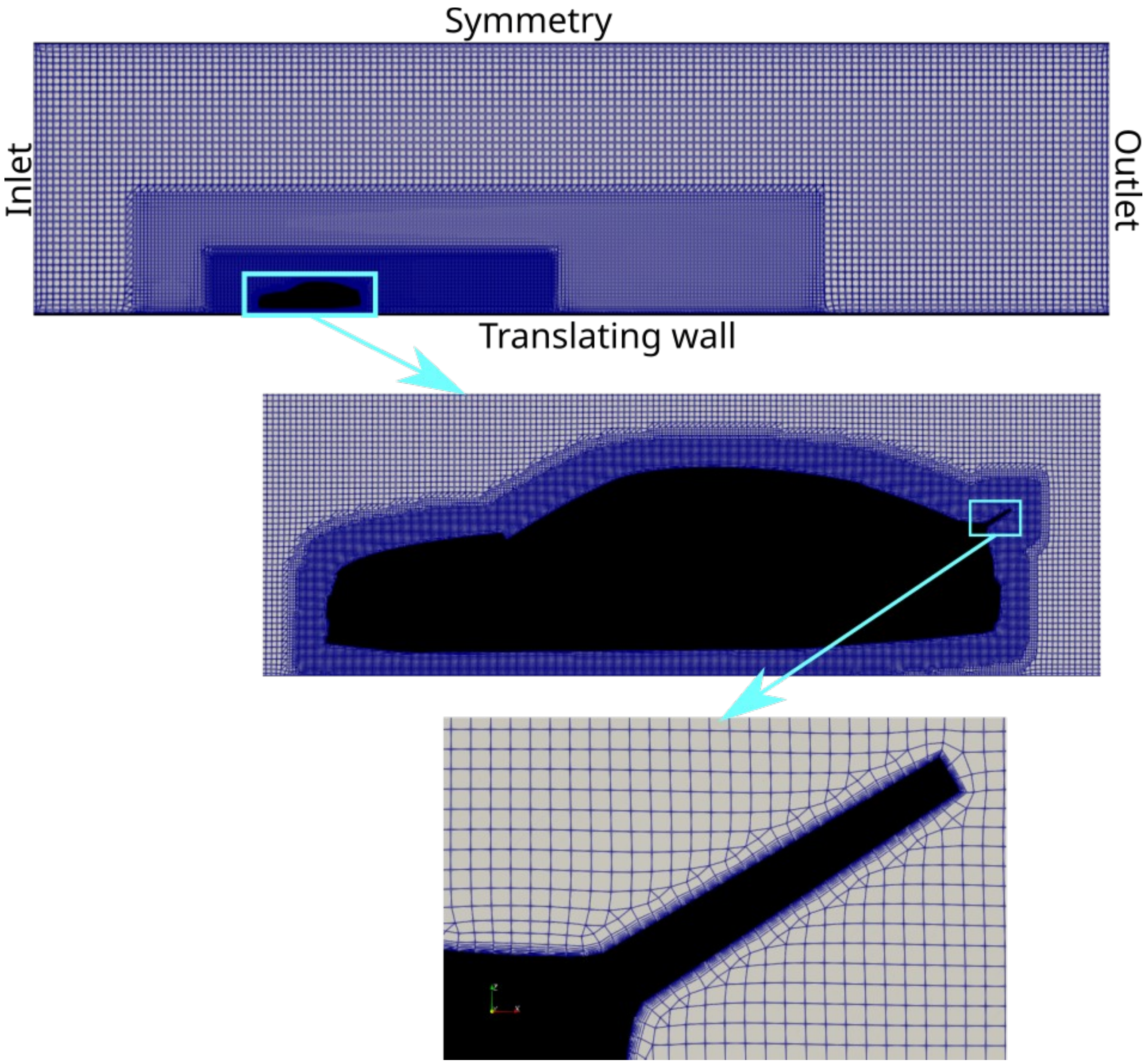

Figure 2: Meshed simulation domain

Inlet velocity [m/s]	16
Reynolds Number	4.87×10^6
Air kinematic viscosity [m^2/s]	0.000015
Air density [kg/m^3]	1.2
Time dependency	Steady-state
Turbulence model	kOmegaSST
No. of volume cells (different cases)	75k - 87k

Results and Discussion

Lift, Drag and Efficiency:

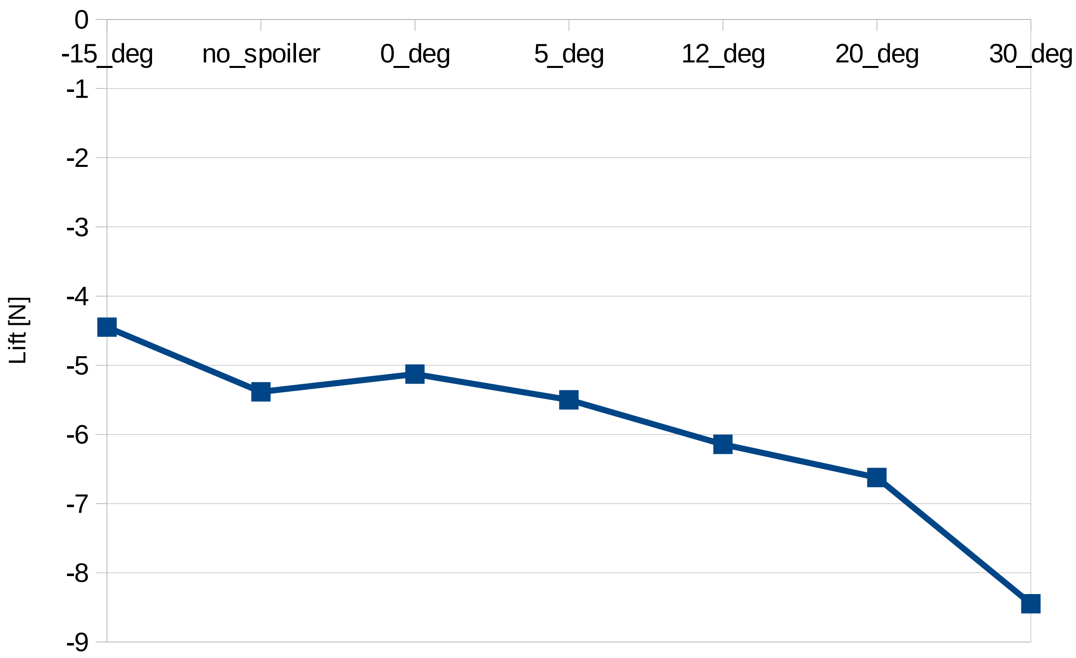

Figure 3: Lift force generated by the car vs spoiler angle

	Lift	Drag	L/D	Incremental Lift Change	Incremental Drag Change	Incremental L/D Change	Total Lift Change	Total Drag Change	Total L/D Change
-15°	-4.448	0.414	10.75	-17.39%	-11.63%	-6.52%	-17.39%	-11.63%	-6.52%
Baseline	-5.385	0.468	11.50	-	-	-	-	-	-
0°	-5.128	0.449	11.42	-4.77%	-4.09%	-0.71%	-4.77%	-4.09%	-0.71%
5°	-5.499	0.469	11.71	7.25%	4.55%	2.58%	2.14%	0.28%	1.85%
12°	-6.143	0.505	12.15	11.70%	7.62%	3.78%	14.09%	7.92%	5.71%
20°	-6.622	0.542	12.22	7.80%	7.26%	0.51%	22.98%	15.76%	6.24%
30°	-8.448	0.707	11.95	27.57%	30.49%	-2.24%	56.89%	51.05%	3.86%

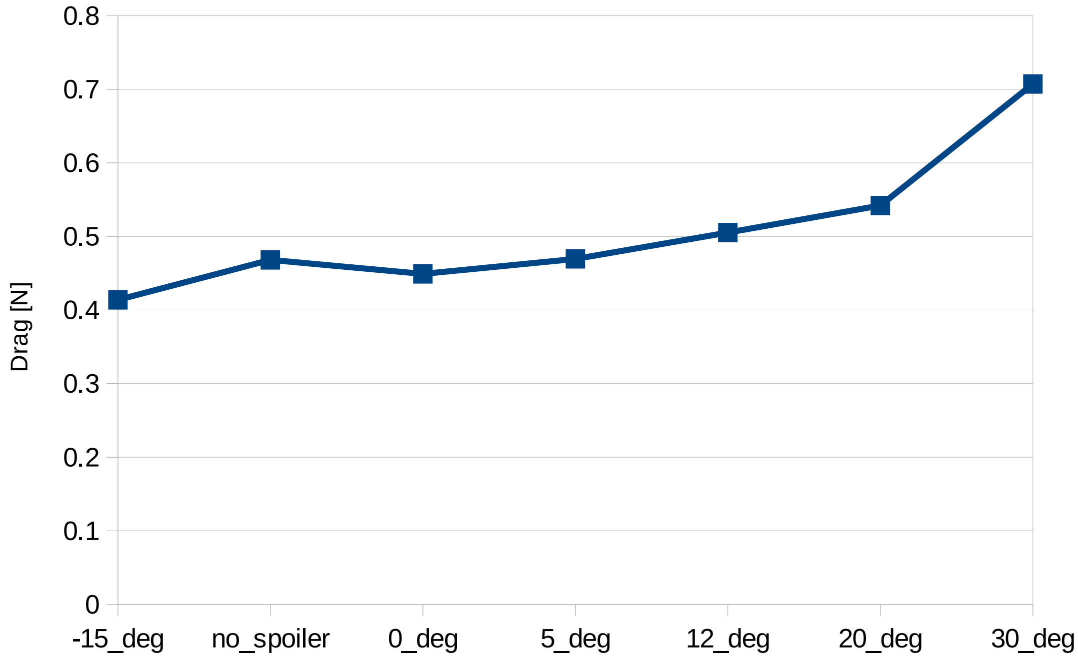

Figure 4: Total drag acting on the car vs spoiler angle

Figures 3, 4, and 5 show respectively the lift force (downforce), drag force, and L/D values for different spoiler angles. Both downforce and drag values show a direct proportionality relation with positive spoiler angles (upward spoiler). The spoiler at 0° (neutral spoiler) shows a slight reduction in both downforce and drag values. Negative spoiler angle (downward spoiler) also show decreasing trend in downforce and drag from the baseline of no-spoiler car. The L/D plot clearly shows diminishing returns for upward spoilers, hitting a maximum at 20°. While a huge downfall is observed in L/D for the downward spoiler.

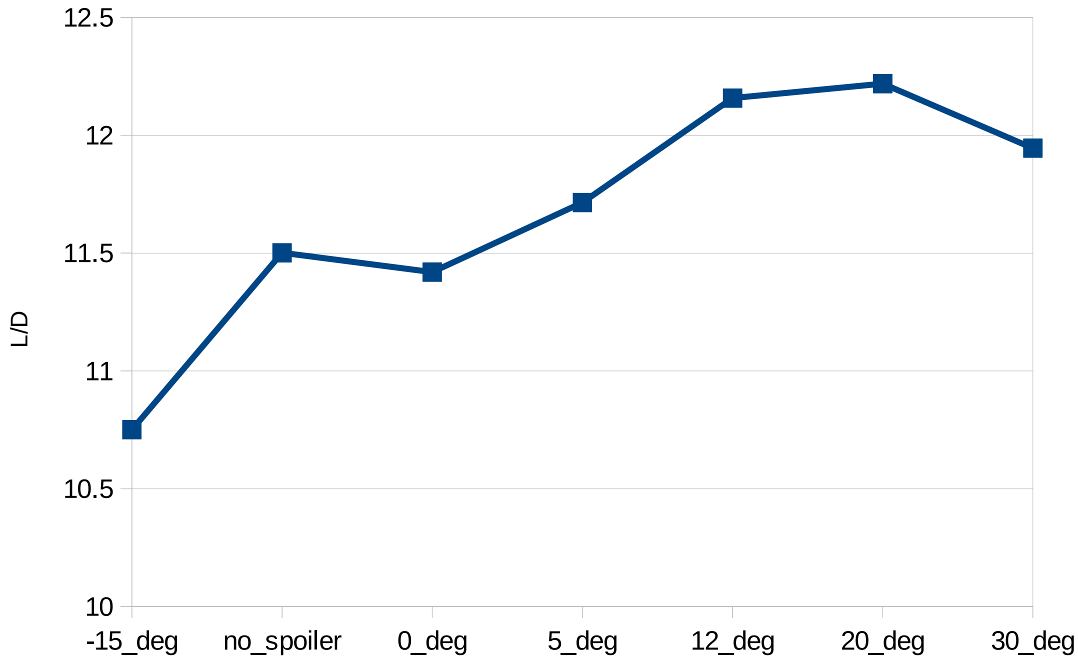

Figure 5: L/D values v/s spoiler angle

The table above presents the average of downforce and drag of the last 200 iterations, for each spoiler angle simulation. Both incremental percentage change and accumulated percentage change are calculated, as the angle is successively increased from -15° to 30°.

Results show that the downward spoiler decreases the total downforce of the car by more than 17%. But this reduction in downforce is amortised by a drag reduction of more than 11.6%. The neutral spoiler also shows a slight drag reduction of 4% with a very small penalty of 0.7% in L/D value i.e aerodynamic efficiency of the car. The upward spoiler at 5°, shows moderate improvement in both downforce and efficiency. Increasing the angle to 12° from here, shows the biggest improvement in both downforce and efficiency of 11.7% and 3.8% respectively. Further increasing the angle 20° shows a mere 0.5% increase in efficiency, indicating that the downforce gains are almost equal to drag penalty. Making the spoiler angle 30° from here, reveals that 20° was the inflection point and that the drag penalty outpaces downforce gain.

Depending on the objective, different spoilers can be chosen for different applications based on the result of this parametric study. Following are some use case:

- Hatchbacks/ EVs/ Station-wagon – since these vehicles are used in city and as daily drivers, high fuel efficiency is an important objective. Downward spoiler (-15° spoiler) is the most suitable candidate for these types of cars, since it gives the maximum drag reduction in this study.
- SUV/ MPV – these kind of cars are generally boxy and forms a large wake right behind them, causing a very abrupt, turbulent, and highly unstable vortices. This causes large pressure fluctuations on the rear surface of the vehicle which further leads to instability, especially during high-speeds. The neutral spoiler (0° spoiler) can be mounted on the roof of these vehicles, since it provides a smoother flow separation from the vehicle and a stable wake region. The results show that with a very small penalty in efficiency, it also gives a drag reduction.
- Racecar/ sportcar/ sedans/ hot-hatch – these high-performance cars need downforce for high-speed cornering and handling. The traction on the rear wheels is paramount since most of the them are RWD cars. Upward spoilers direct the airflow in the up direction causing a downward force on the spoiler. The spoiler also breaks the airflow and slows down the flow over the rear-windshield and the trunk, forming a high pressure region. The results suggest that the 20° angle spoiler is the best option for this purpose, since it results in an increase of 23% in the downforce as well as a 6.24% improvement in the efficiency compared to the baseline. For racetrack application where fuel efficiency and drag force isn’t a bigger issue, one could also chose 30° spoiler which gives the maximum downforce gain of ~57% from the baseline. But it might only be useful during cornering and could be disadvantageous on straight section of the track.

Static Pressure Coefficient Distribution:

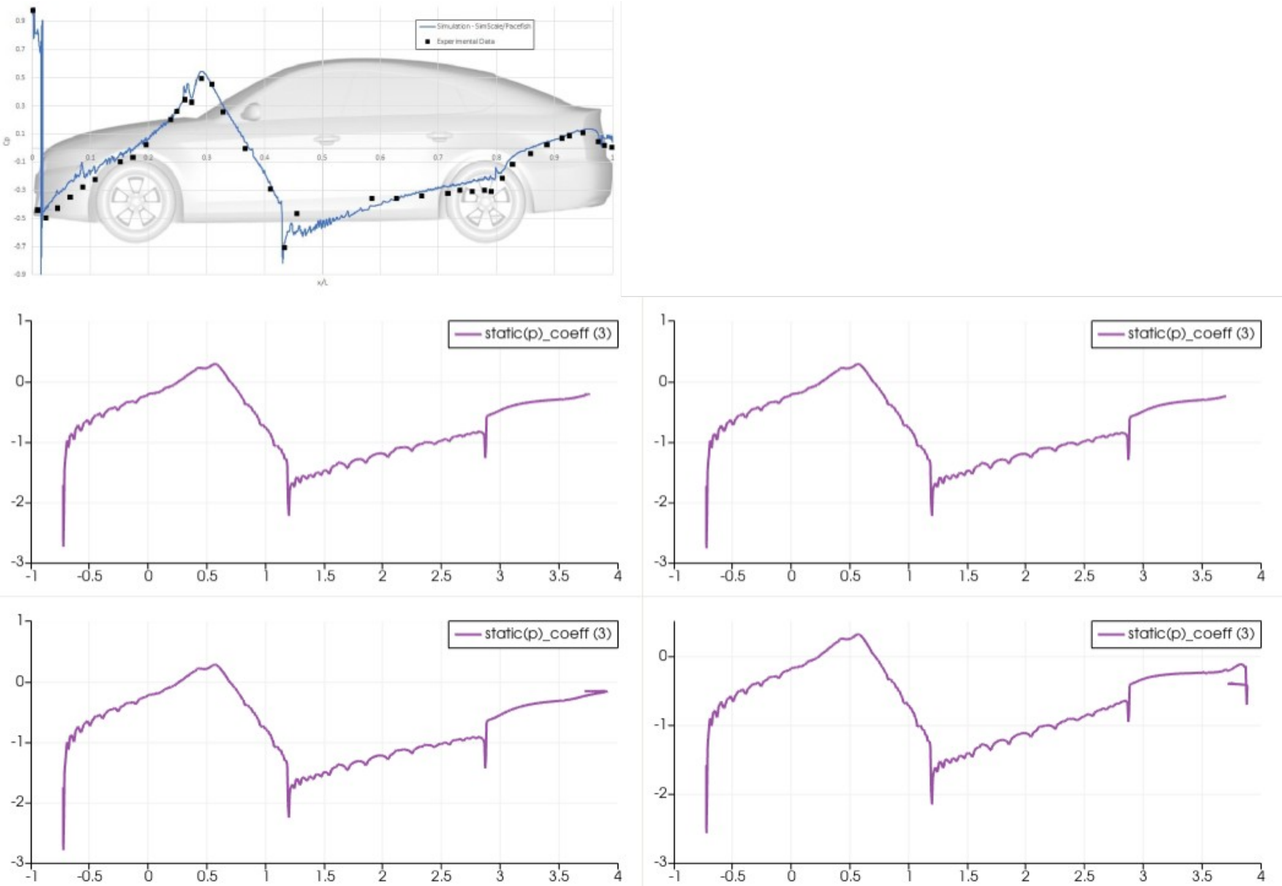

Figure 6: Static pressure coefficient distribution over the top surface of the car at symmetry plane. (Top-left) Wind-tunnel test result at black points [4] , (Middle-left) Baseline model, (Middle-right) 0° spoiler model, (Bottom-left) -15° spoiler model, (Bottom-right) 30° spoiler model

In the figure 6 above, are distribution plots of static-pressure coefficient over the top surface of the car. The wind tunnel test values marked as black boxes are shown in the top-most image. The plot in blue colour is the simulation result from the validation study done by *Simscale* [4], using LBM based CFD.

In the present work, 2D steady-state RANS method is used without mesh convergence study. So quantitive comparison is not possible with the experimental results. However, as can be seen in the middle-left plot, the overall distribution pattern of the pressure coefficient is very similar to that of the experimental data at the symmetry plane of the 3D model, with offset errors in the simulation result.

Having qualitatively validated the pressure coefficient plot for the baseline model, we can now analyse the changes in the distribution pattern when different types of spoilers are added to the drivaer model, viz. upward (30°), neutral(0°) and downward(-15°) spoilers. In figure 6, the distribution remains unchanged for the neutral spoiler model. The plot offsets down in the negative direction from the start of the roof, for the downward spoiler model indicating a reduction in downforce. The opposite trend is observed in the upward spoiler where the plot is offset upwards from the starting point of the roof, suggesting increased air pressure. The spoiler effect is therefore seen all the way up to the roof starting point.

Velocity Contour and Vector Visualization:

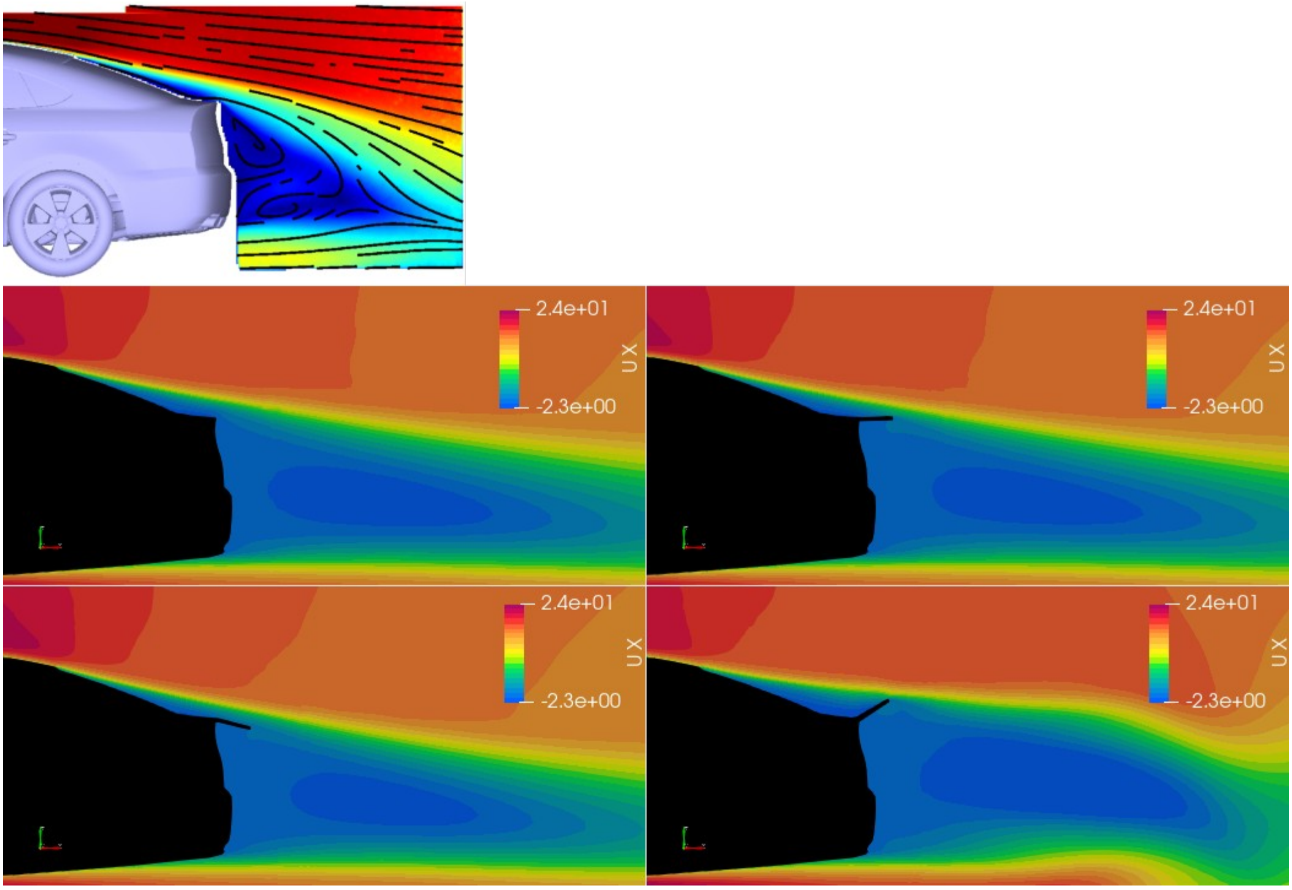

Figure 7: Velocity contours. (Top-left) PIV data at centreline from wind-tunnel test plotted as normalised velocity contour [3] , (Middle-left) Baseline model, (Middle-right) 0° spoiler model, (Bottom-left) -15° spoiler model, (Bottom-right) 30° spoiler model

Figure 7 shows velocity contours for different models. The topmost contour is that of the normalised velocity at the centreline plane of the 3D drivaer model determined from the PIV data from the wind tunnel tests. When compared to the contour of the x-component of velocity from the baseline model simulation result, there are some differences. The immediate visual difference that can be observed, is that the wake bubble looks smaller and deflected downward in the PIV data. This could indicate the influence of the counter-rotating vortex structures formed at the C-pillar, inducing a downwash in the wake.

In the present 2D simulation, these 3D flow effects aren't realised. There can also be effects of the rotating wheels in the wake, which again are missing from the current simplified simulations. However, the flow separation from the roof and also the wake over the rear windshield have some similarity. Having said that, we can consider the contour of the baseline model to be a simplified version of the PIV data contours of the drivaer model. The neutral spoiler doesn't affect the overall wake structure as seen in the figure above, but it does shifts the wake bubble downstream. The bubble is slightly smaller as well. This explains the small drag reduction as seen in the force data. The displaced wake bubble also leads to lesser turbulence and pressure fluctuations in the immediate vicinity of the car, thus improving stability at high-speeds.

The downward spoiler affects the rear wake as well as the wake over the rear windshield. The rear wake bubble is perceptibly smaller compared to that of the baseline model and is also shifted downstream away from the car. The overall wake size itself is reduced. The spoiler also seems to pull the shear-layers downward, causing a delayed separation over the rear windshield. All of these together result in a significant drag reduction as seen in the force data. However, the flow is attached over the spoiler and causes the flow to deflect downwards, leading to increased circulation and therefore, lift generation. This explains the big reduction in downforce.

The upward spoiler, on the other hand, increases the wake size. Additionally, a bigger separation bubble is formed over the rear windshield. In figure 7 the spoiler angle of 30° is shown, which is very large and leads to very high unsteadiness in the wake. Large vortex structures are formed and shed, which is visible even when the flow is simulated using RANS method. For smaller angles, the unsteadiness is less and the wake size is also smaller. The reduced velocity over the rear windshield and the trunk leads to a pressure rise in that area, ultimately contributing to the increased downforce. A horizontal component of this additional pressure force also acts on the rear windshield, which counters the drag force.

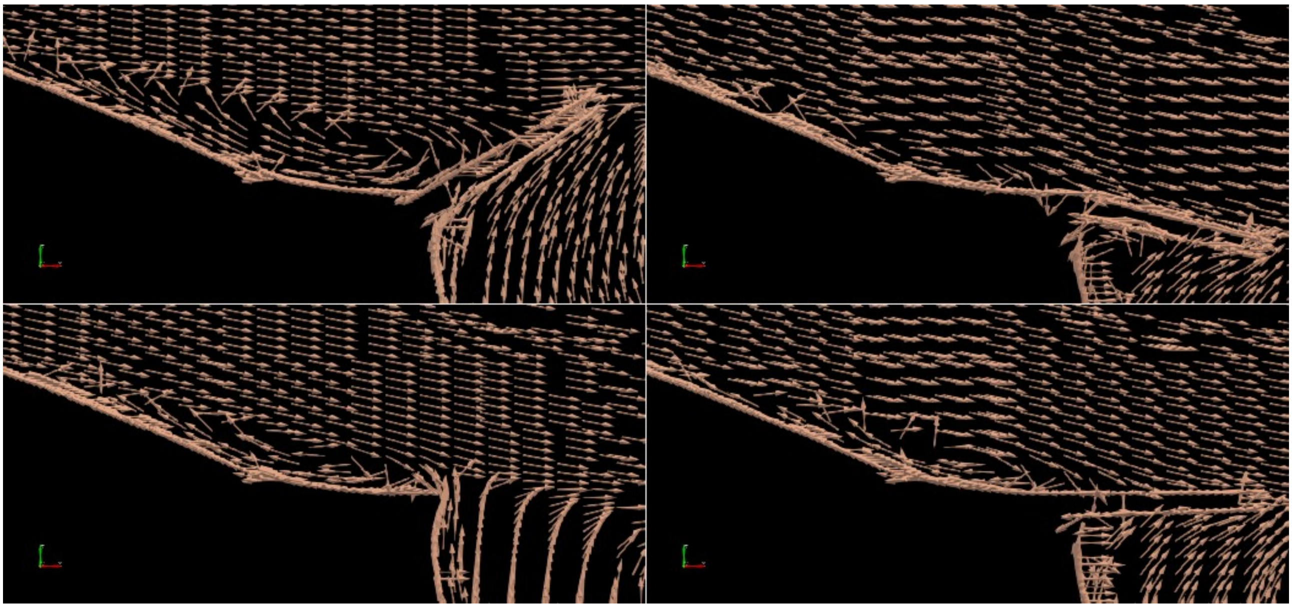

Figure 8: Velocity vector field visualization for all models.

Figure 8 shows the velocity vectors for all the models. The vector fields corroborate the above discussion on separation bubbles over the rear windshield. The bubble is biggest for the upward spoiler, while it is smallest for the downward spoiler due to delayed flow separation. In the case of the neutral spoiler model, the bubble size is almost the same when compared to the baseline model. However, the presence of the spoiler isolates the bubble over the rear windshield from the rear wake. Since the interaction between the two wakes is mitigated, the bubble structure is more stable. In the absence of the spoiler, the separation bubble is unstable and is shed as vortices into the rear wake causing pressure fluctuations.

Static Pressure Contour Plots:

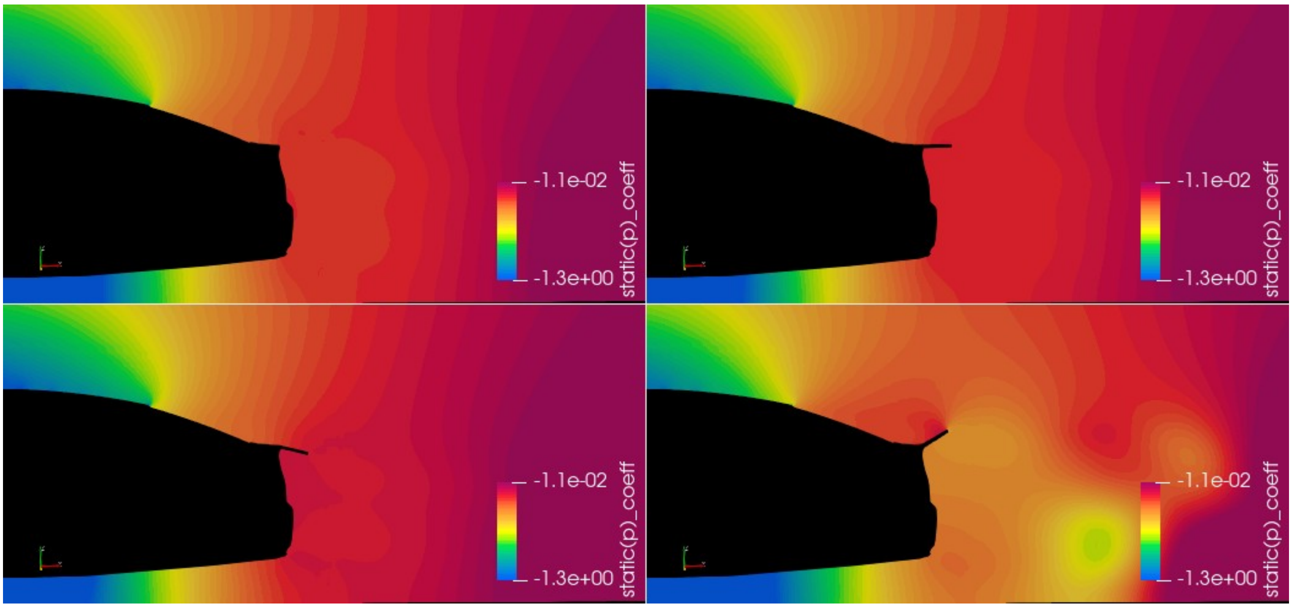

Figure 9: Static pressure coefficient contour plots for various models.

The contour plots shown in figure 9, depicts the effect of different spoilers on the static pressure distribution around the drivaer model. The neutral spoiler doesn't have any significant effect on the distribution over the car surface. However, a slight increase in the pressure in the wake region can be seen. For the downward spoiler model, there is a pressure decrease over the rear windshield and the trunk. While a significant pressure rise is visible in the wake when contrasted to the baseline. The upward spoiler clearly increases the pressure not only over the rear windshield and the trunk, but also on the roof. But a large low pressure wake is also formed in this case.

Vorticity Contour Plots:

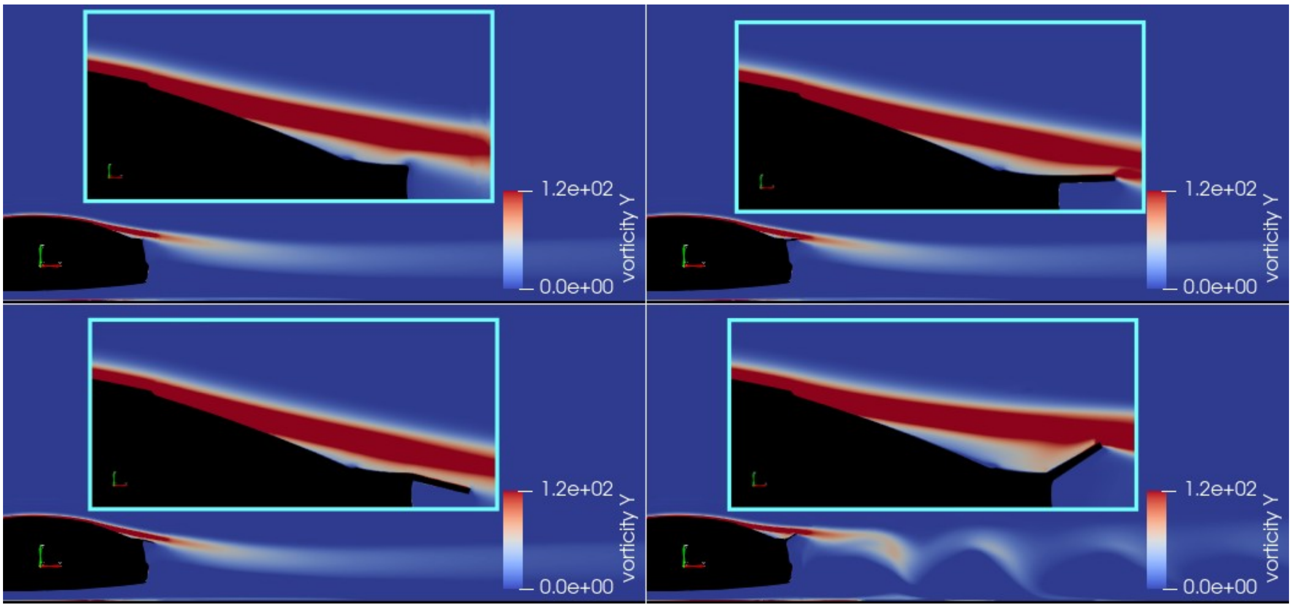

Figure 10: Vorticity contour plots for various models.

Figure 10 shows the vorticity contours for different models. The red bands are the shear layers that form near the surface. Positive vorticity in these plots show a clockwise rotation. Close to zero and negative values of vorticity over the top surface of the car suggests separation and recirculation in the flow. Again the neutral spoiler doesn't cause much alterations in the flow pattern over the rear section of the car. The downward spoiler model shows attached flow over the rear windshield for slightly longer extent causing the separated flow region to shrink. The upward spoiler causes early separation over the rear windshield and forms a larger recirculation zone. The vortex structures are also visible in the wake of this model. For the neutral and upward spoiler, the flow is attached over the spoiler surface till the trailing edge. However for the downward spoiler, the flow seems to be slightly detached at the trailing edge.

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