Aerodynamic Optimization of a Rear Spoiler of a Rally Car

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***Abstract*—Aerodynamics plays an important role in improving stability, control and fuel efficiency of high-speed automobiles. Rear spoilers are widely used in various vehicles to enhance the vehicle aerodynamic behaviour by increasing downforce and reducing lift which is generated at the rear end of the vehicle. The following research work focuses on the aerodynamic optimization of a rear spoiler with the purpose of keeping the aerodynamic drag as low as possible.**

In this study, a rear spoiler model is designed and evaluated using Computational Fluid Dynamics (CFD) analysis to examine the aerodynamic characteristics under different design parameters such as spoiler angle, height and profile geometry. Various spoiler design configurations are simulated to study their influence on downforce production and drag coefficient values. Based on the simulation results, an optimized spoiler configuration is identified and selected by comparing its aerodynamic performance with the original baseline configuration.

The results indicate that suitable changes in spoiler geometry can considerably improve aerodynamic efficiency, resulting in enhanced vehicle stability and overall driving performance. This study offers valuable understanding for effective design and aerodynamic optimization of rear spoilers in automotive engineering applications.

I. LITERATURE REVIEW

1) Title: Review of Effects the Rear Spoiler Aerodynamic Analysis on Ground Vehicle Performance
Authors: Zhaowen Deng, Sijia Yu, Wei Gao, Qiang Yi, Wei Yu
Published In: Journal of Physics: Conference Series, 2020
This study presents a comprehensive review of the aerodynamic effects of rear spoilers on ground vehicle performance. The paper discusses how aerodynamic devices such as rear spoilers influence vehicle stability, fuel efficiency and overall aerodynamic characteristics. It explains that the installation of a rear spoiler modifies the airflow pattern at the rear end of the vehicle, which helps reduce turbulence and minimize lift acting on the vehicle body. As a result, improved downforce is generated, enhancing vehicle stability and road handling at high speeds. The study also reviews various aerodynamic analysis techniques such as Computational Fluid Dynamics (CFD), wind tunnel testing and numerical simulations used to evaluate spoiler performance. Additionally, both passive and active spoiler control methods are discussed for improving aerodynamic efficiency. The review concludes that proper aerodynamic design and optimization of rear spoilers can reduce drag, improve vehicle stability and contribute to better fuel efficiency in ground vehicles.

2) Title: Numerical Investigation of Drag Reduction Techniques in a Car Model Using CFD
Authors: Z.M. Saleh and A.H. Ali
Published In: IOP Conference Series: Materials Science and Engineering. 2020
This study investigates different aerodynamic techniques used to reduce drag in passenger vehicles through Computational Fluid Dynamics (CFD) analysis. The research focuses on analysing the aerodynamic performance of a car model by introducing aerodynamic devices such as vortex generators, rear underbody diffuser slices and rear wing spoilers. The simulation was carried out using CFD tools to observe parameters such as velocity distribution, pressure contours, drag coefficient and airflow behaviour around the vehicle body. The results indicated that the addition of aerodynamic

devices, particularly a rear wing spoiler, significantly affects the airflow at the rear region of the vehicle and reduces flow separation in the wake region. This modification leads to a noticeable reduction in the drag coefficient and improves the aerodynamic efficiency of the vehicle. The study concludes that proper aerodynamic modifications at the rear end of the vehicle can effectively enhance vehicle stability and reduce energy losses caused by aerodynamic drag.

3) Title: The Effect of Spoiler Shape and Setting Angle on Racing Cars Aerodynamic Performance
Authors: Hesam Eftekhari, Abdulkareem Sh. Mahdi Al-Obaidi, Shahrooz Eftekhari
Published In: Indonesian Journal of Science and Technology, Volume 5, Issue 1, 2020
This study investigates the influence of spoiler shape and setting angle on the aerodynamic performance of racing cars using both numerical and experimental analysis. Different spoiler airfoil profiles such as NACA 0012, NACA 4412 and S1223 were analysed to evaluate their effects on drag coefficient and lift coefficient. The analysis was performed on an ERC vehicle model inspired by the Porsche 911 with a constant Reynolds number of $2x10^5$. Several cases were considered including vehicles without spoilers and vehicles equipped with spoilers at different setting angles. The results showed that the installation of a rear spoiler significantly affects the pressure distribution at the rear end of the vehicle, leading to changes in lift and drag forces. Among the tested configurations, the S1223 airfoil produced the highest downforce and better aerodynamic stability compared to NACA 0012 and NACA 4412 airfoils. It was also observed that setting the spoiler at a negative angle improves stability and handling of the racing car by generating negative lift. The study concludes that spoiler geometry and angle of attack play an important role in improving aerodynamic efficiency and vehicle stability.

4) Title: CFD Analysis of Car Using NACA 4412 Spoiler
Authors: M.H.R. Sakih and M.S. Mahmud
Published In: SCSE Journal, 2025
This study focuses on analysing the aerodynamic performance of a passenger vehicle using a NACA 4412 airfoil rear spoiler through Computational Fluid Dynamics (CFD). A three-dimensional car model was developed and simulated to investigate the influence of spoiler inclination on aerodynamic forces. The analysis was carried out at different Reynolds numbers using the Reynolds-Averaged Navier Stokes (RANS) equations with the k-epsilon turbulence model to study the airflow behaviour around the vehicle. Several cases were considered including a vehicle without a spoiler and a vehicle equipped with a NACA 4412 spoiler at different angles of attack. The results indicated that the installation of a rear spoiler significantly reduced the lift acting on the vehicle and improved aerodynamic stability. It was observed that increasing the spoiler angle increased the negative lift (downforce) acting on the vehicle; however, a slight increase in drag was also noted. The study concluded that the use of a properly designed rear spoiler can effectively control turbulence at the rear region of the vehicle and enhance overall aerodynamic performance and vehicle stability at higher speeds.

5) Title: CFD Analysis of Rear Spoiler Effects on Vehicles Aerodynamic Performance
Authors: Prakash Badu, Rahul Panjiyar, Kushal Guragain, Pankaj Yadav
Published In: OODBODHAN, Vol.07, 2024
This study investigates the aerodynamic behaviour of a sports car model with and without a rear spoiler using Computational Fluid Dynamics (CFD) analysis. Two models were analysed at different velocities to evaluate the effects on drag force, lift force and overall performance. The results indicate that the inclusion of a rear spoiler significantly improves vehicle stability by increasing downforce and reducing lift, particularly at higher speeds. However, the increase in downforce is accompanied by a rise in drag force, highlighting a trade-off between aerodynamic efficiency and stability. The study also examines pressure and velocity distributions, showing that the spoiler modifies airflow patterns and reduces turbulence in the wake region. The use of the NACA 2412 airfoil profile is found to provide a balanced performance by enhancing downforce while limiting excessive drag at moderate speeds. The findings emphasize that careful aerodynamic design of spoilers can optimize vehicle handling and high-speed performance.

6) Title: Aerodynamic Analysis of Car Rear Spoiler with Computational Fluid Dynamics for Different Angles and Profiles
Authors: Muhammed Ali Oztemel, Fatih Aktas, Nuri Yucel
Published In: International Journal of Energy Studies, 2023
This study focuses on the aerodynamic analysis of car rear spoilers using Computational Fluid Dynamics (CFD) by considering different airfoil profiles, angles of attack and velocities. The investigation compares drag coefficient, lift coefficient and downforce generated by two different airfoil geometries under varying operating conditions. The results show that downforce increases with increase in camber, angle of attack and vehicle speed, improving vehicle stability at high speeds. However, it is observed that an increase in downforce is accompanied by a significant rise in drag coefficient, indicating a trade-off between performance and efficiency. The study also highlights that selection of appropriate airfoil profile and angle of attack plays a crucial role in optimizing aerodynamic performance. Furthermore, CFD analysis demonstrates that pressure distribution and velocity contours vary significantly with spoiler geometry, directly affecting flow behaviour and wake formation. The findings conclude that proper spoiler design enhances road grip, cornering ability and overall aerodynamic efficiency of vehicles.

II. METHODOLOGY

1) Problem Definition: The objective of this study is to improve the aerodynamic behaviour of a hatchback rear spoiler by reducing drag and improving downforce, maintaining structural integrity using carbon fibre material (Young's Modulus=230 GPa).

2) Literature Review: The research began with a literature review to create a research platform, followed by designing two car models in Solid Works: a baseline model without spoiler and a model with a NACA 6412 air foil rear spoiler. The NACA 6412 air foil is preferred over other designs due to its moderate camber, which generates the down force needed for stability while minimizing drag at moderate speeds.
A review of previous research papers on spoiler aerodynamics was conducted to identify:

- Spoiler geometries
- Airflow behaviour over hatchback rear spoiler
- Improving downforce and drag reduction techniques

3) CAD Modelling: The geometrical design involves creating digital representations of car models. This process focusses on capturing the key elements affecting aerodynamic efficiency to explore the impact of forces. A 3D model of the spoiler was created using Cad software (SolidWorks). Various spoiler geometries were designed by varying;

- Angle of Attack
- Curvature or Profile

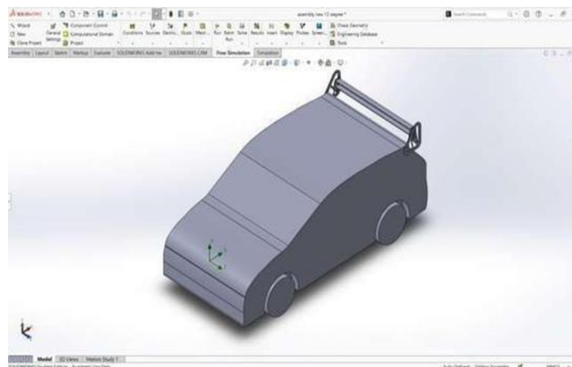


Fig. 1: SolidWorks model of a car with rear spoiler (12° angle of attack)

4) Aerodynamic Analysis (CFD): Aerodynamic evaluation of air flow over an object can be performed using analytical method or CFD approach. On one hand, analytical method of solving air flow over an object can be done only for simple flows over simple geometries like laminar flow over a flat plate. If air flow gets complex as in flows over a bluff body, the flow becomes turbulent and it is impossible to solve Navier-Stokes and continuity equations analytically. On the other hand, obtaining direct numerical solution of Navier-Stokes equation is not yet possible even with modern day computers. In order to come up with reasonable solution, a time averaged Navier-Stokes equation is being used (Reynolds Averaged Navier-Stokes Equations – RANS equations) together with turbulent models to resolve the issue involving Reynolds Stress resulting from the time averaging process. In present work the k-e turbulence model with non-equilibrium wall function is selected to analyse the flow over the

generic passenger car model. This k-e turbulence model is very robust, having reasonable computational turnaround time, and widely used by the auto industry.

- A computational domain (wind tunnel) was created around the vehicle to initiate the simulation workflow.
- Following boundary conditions were applied:
  - Inlet velocity (11.1 – 55.5 m/s)
  - No-slip condition on vehicle surfaces

I. Mesh Generation were carried out to capture the boundary layer effects

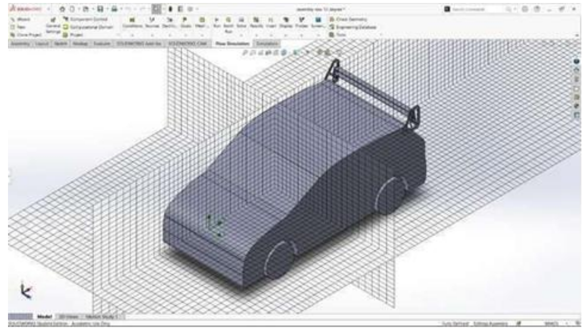


Fig. 2: Meshed Model of Base Car

II. Simulations were run for different spoiler configurations to get the coefficient of drag (C_D), coefficient of lift (C_L) and lift to drag ratio

- Simulation of Rear Spoiler with 7° angle of attack to calculate C_D:

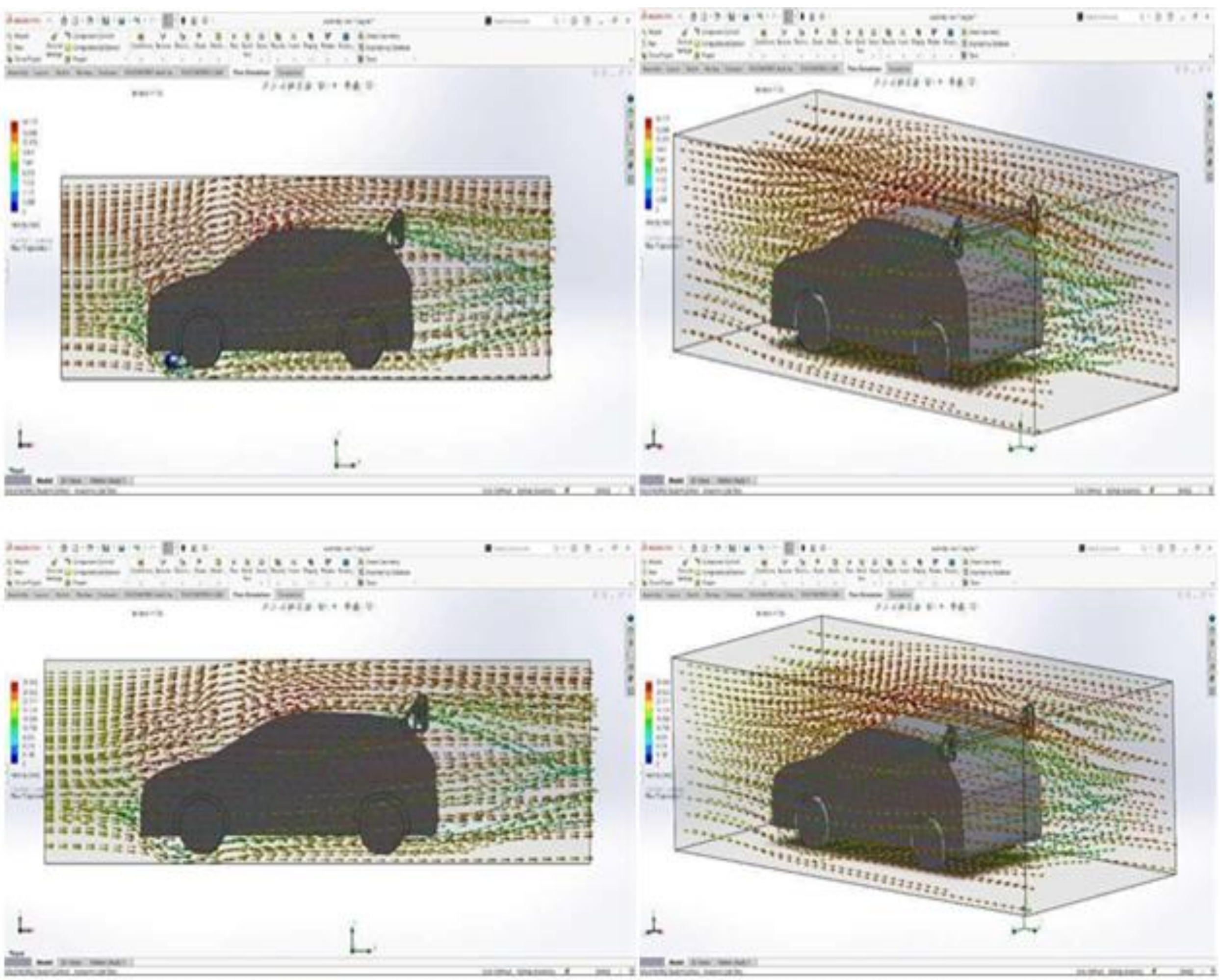


Fig.3: Simulation with speed 11.1 m/s (40 km/hr) detecting low speed downforce behaviour

Fig.4: Simulation with speed 22.2 m/s (80km/hr)

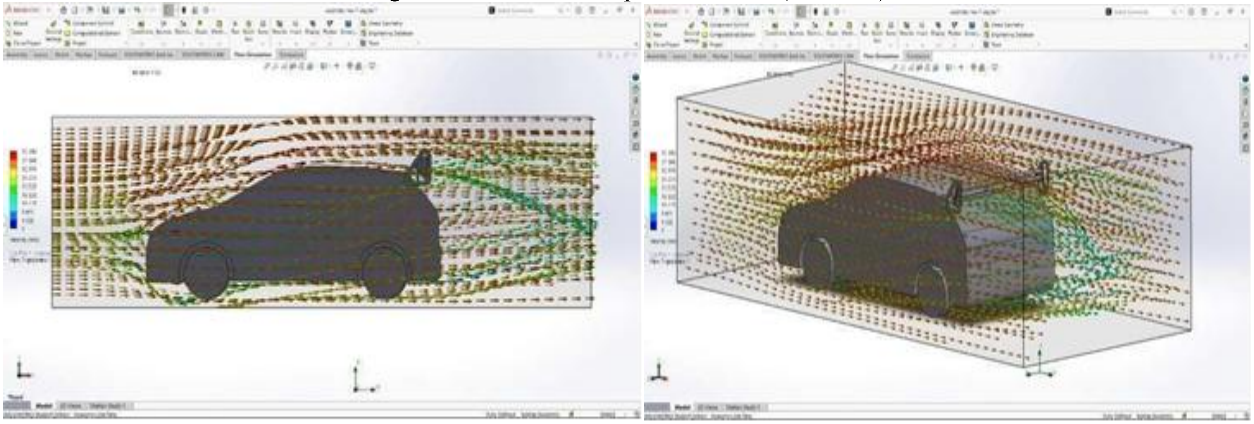


Fig.5: Simulation with speed 33.3 m/s (120 km/hr)

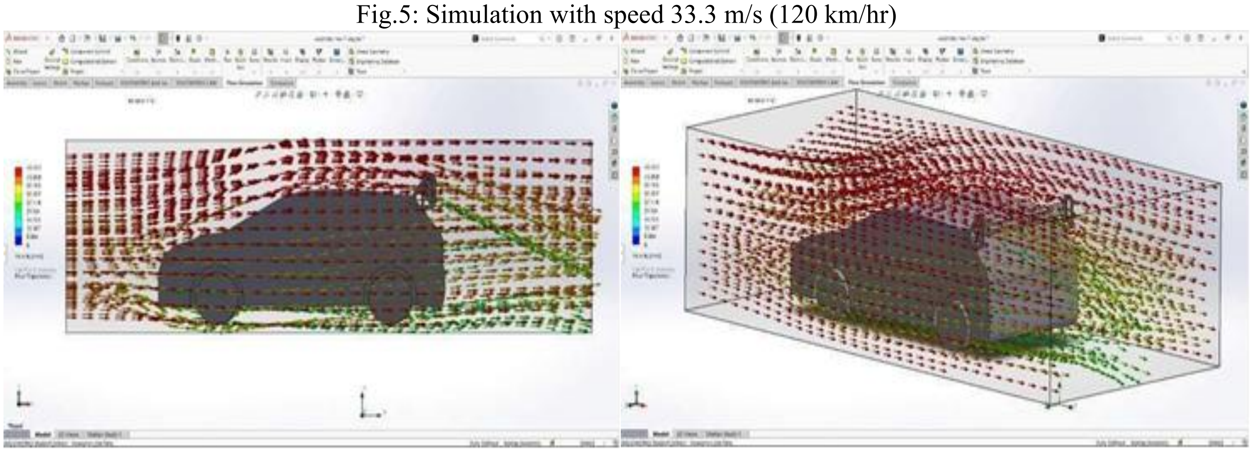


Fig 44.4

Fig.6: Simulation with speed 44.4 m/s (160 km/hr)

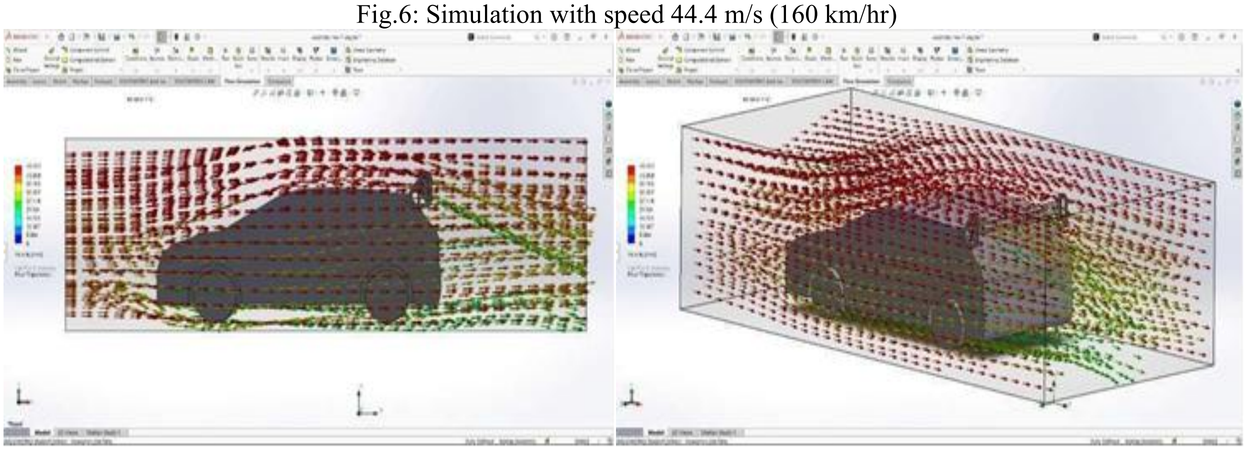


Fig.7: Simulation with speed 55.5 m/s (200 km/hr)

- Simulation of Rear Spoiler with 12° angle of attack to calculate C_D:

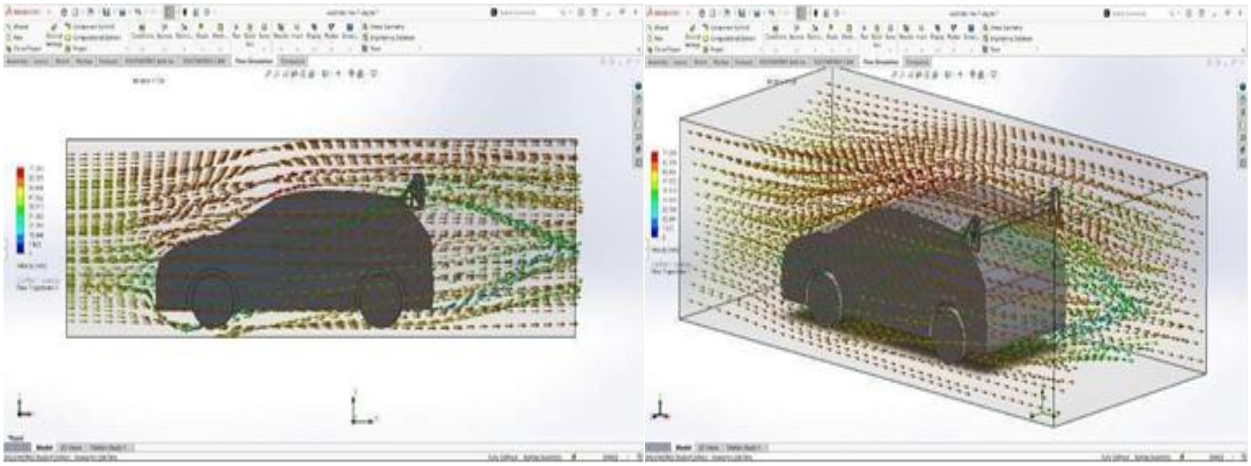


Fig 11.1

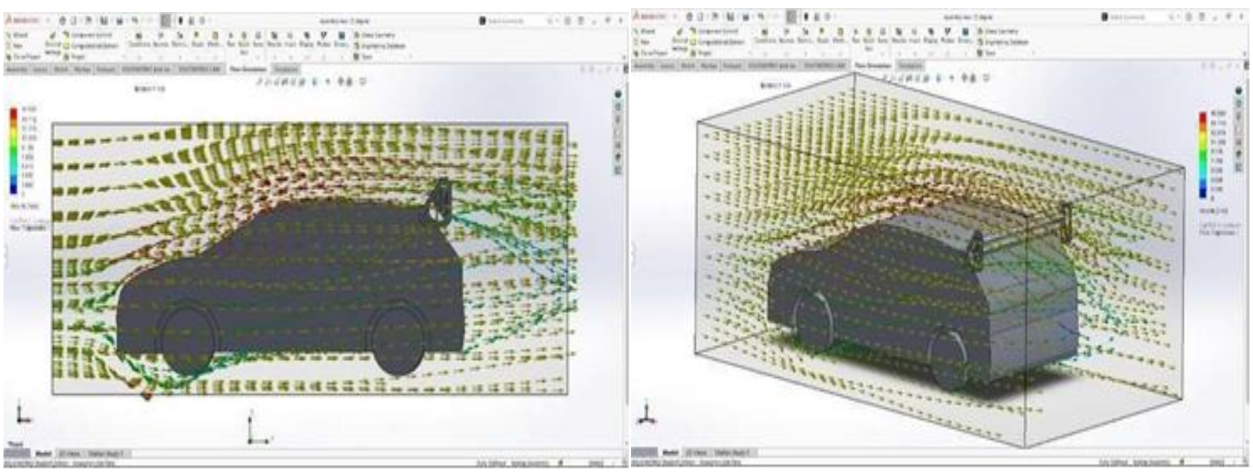


Fig 11.1

Fig.8: Simulation with speed 11.1 m/s (40 km/hr) detecting low speed downforce behaviour

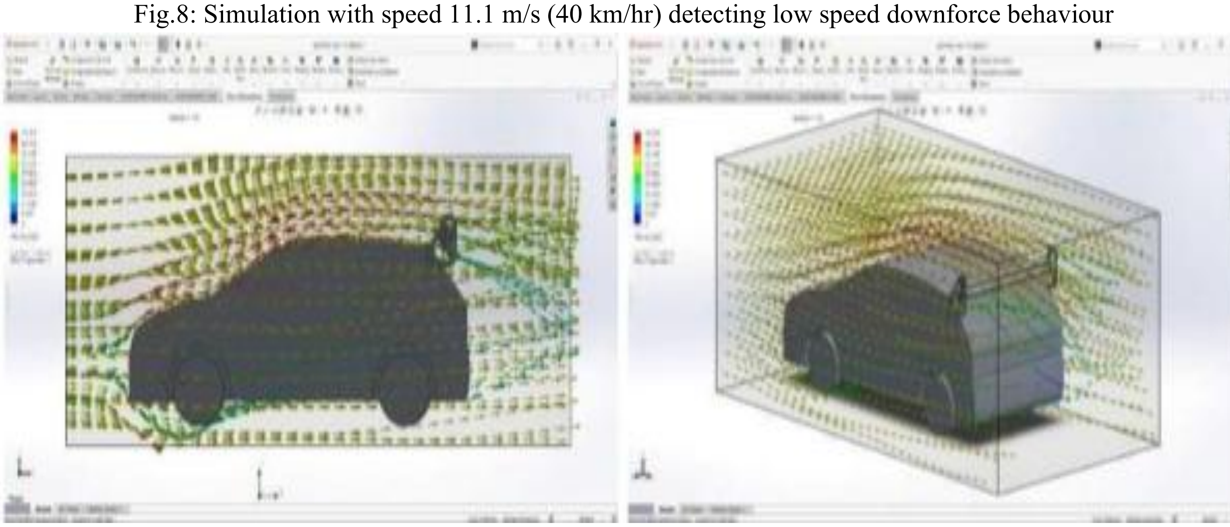


Fig.9: Simulation with speed 22.2 m/s (80 km/hr)

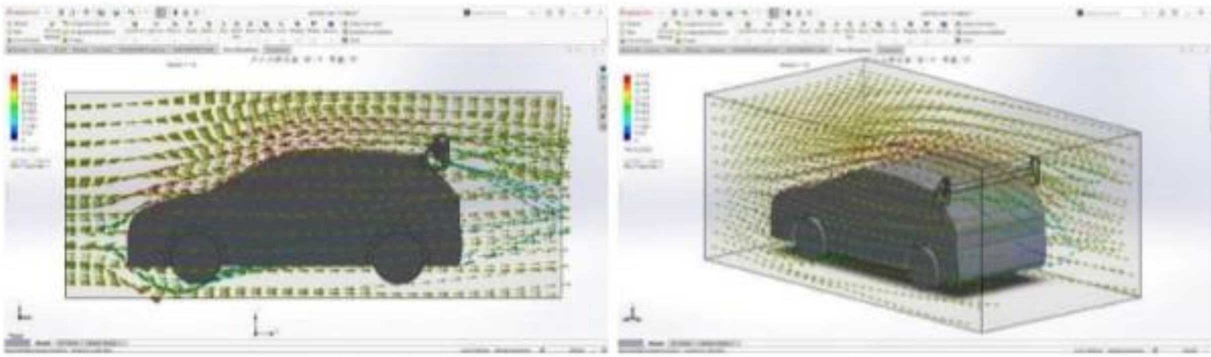


Fig.10: Simulation with speed 33.3 m/s (120 km/hr)

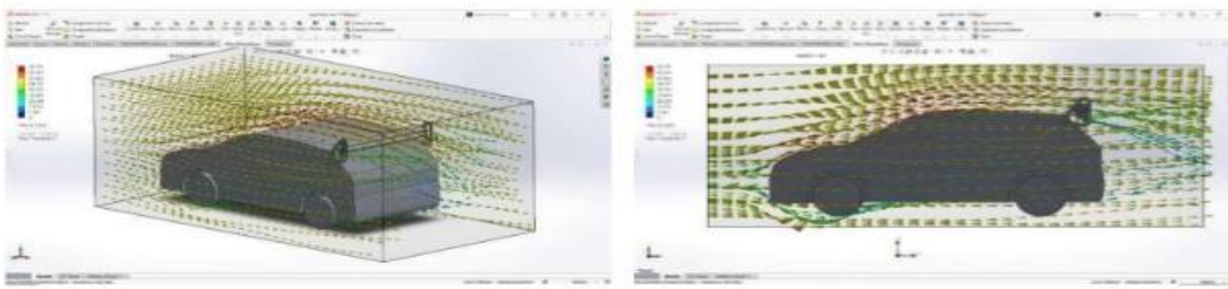


Fig.11: Simulation with speed 44.4 m/s (160 km/hr)

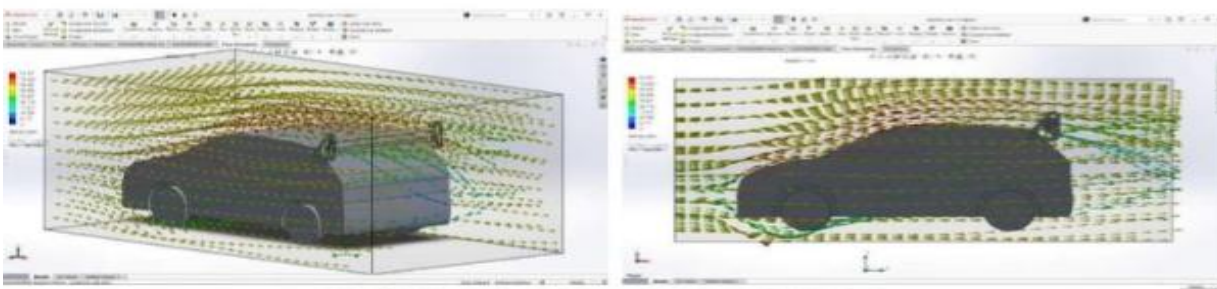


Fig.12: Simulation with speed 55.5 m/s (200 km/hr)

- Simulation of Rear Spoiler 7° angle of attack to calculate C_L:

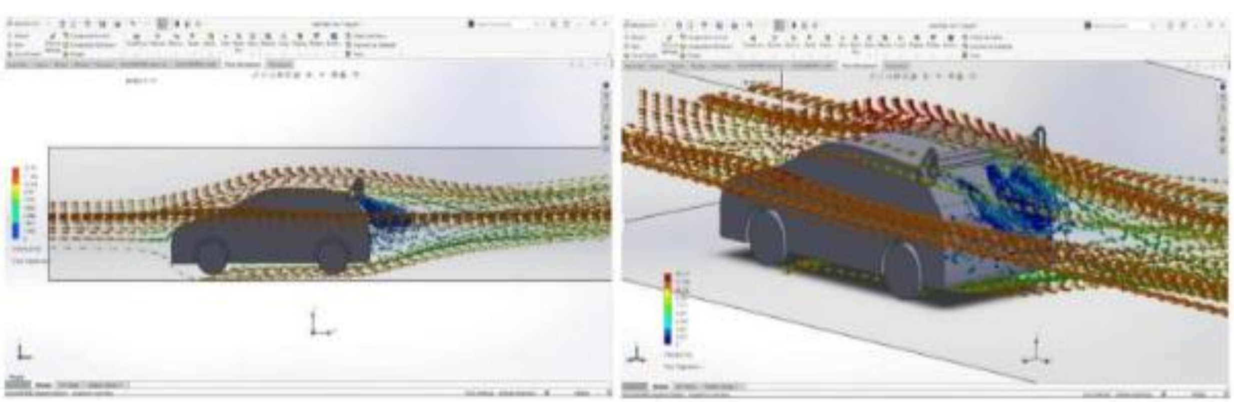


Fig 11.1

Fig.13: Simulation with speed 11.1 m/s (40 km/hr)

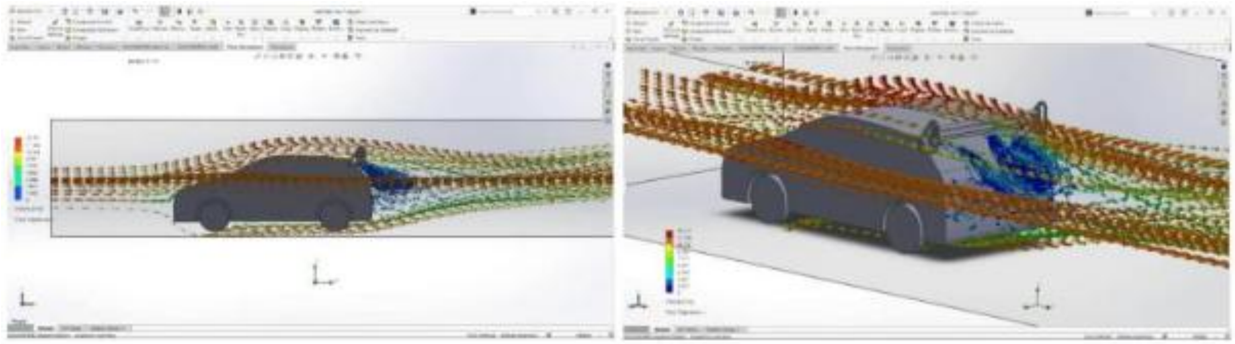


Fig.14: Simulation with speed 22.2 m/s (80 km/hr)

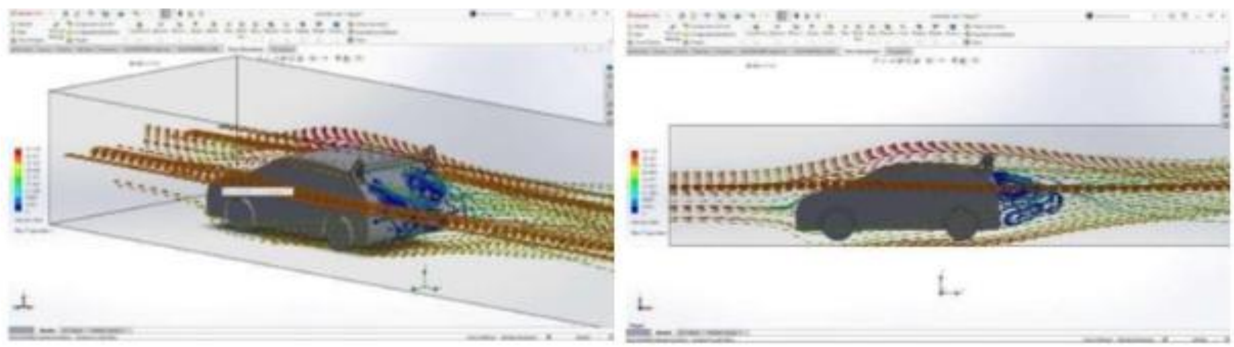


Fig 33.3

Fig.15: Simulation with speed 33.3 m/s (120 km/hr)

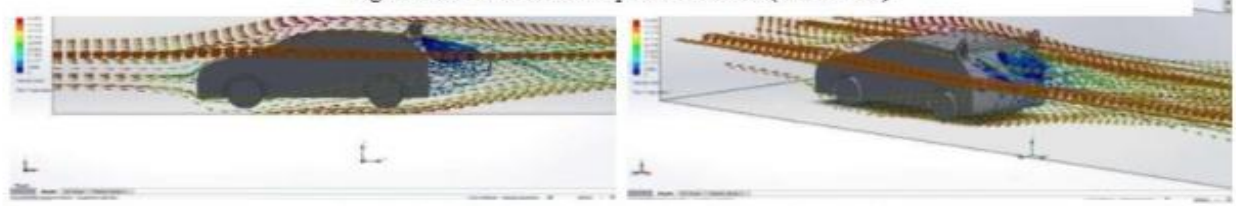


Fig.16: Simulation with speed 44.4 m/s (160 km/hr)

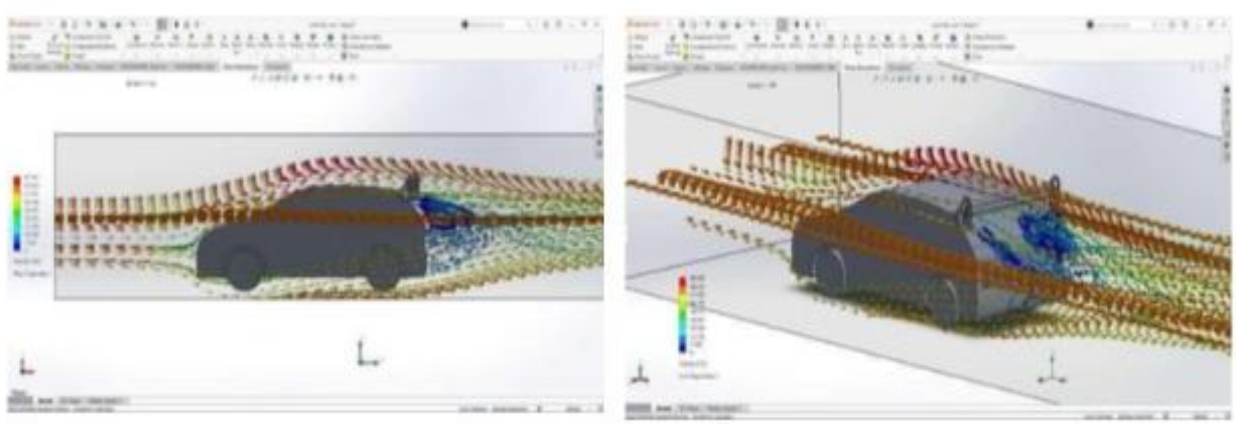


Fig 55.5

- Simulation of Rear Spoiler 12° Angle of Attack to calculate C_L:

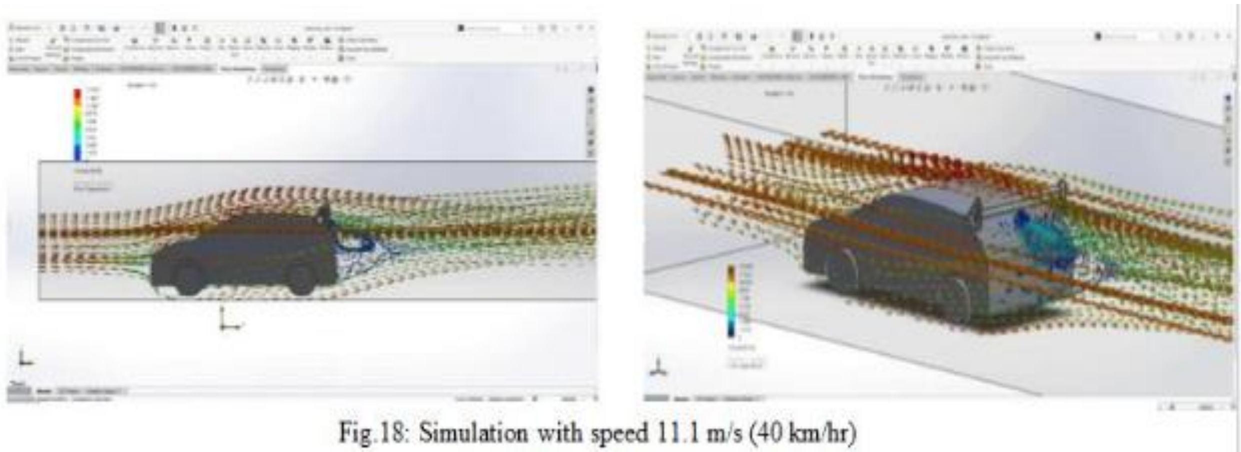


Fig.18: Simulation with speed 11.1 m/s (40 km/hr)

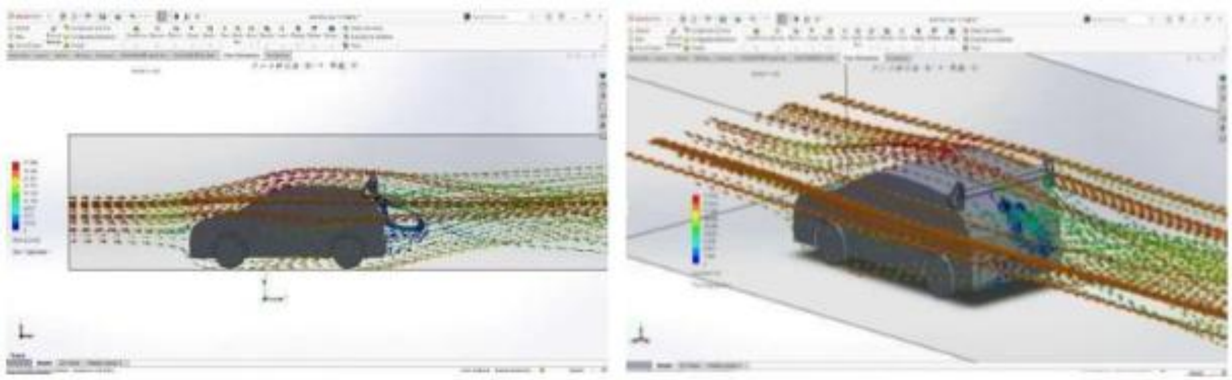


Fig.19: Simulation with speed 22.2 m/s (80 km/hr)

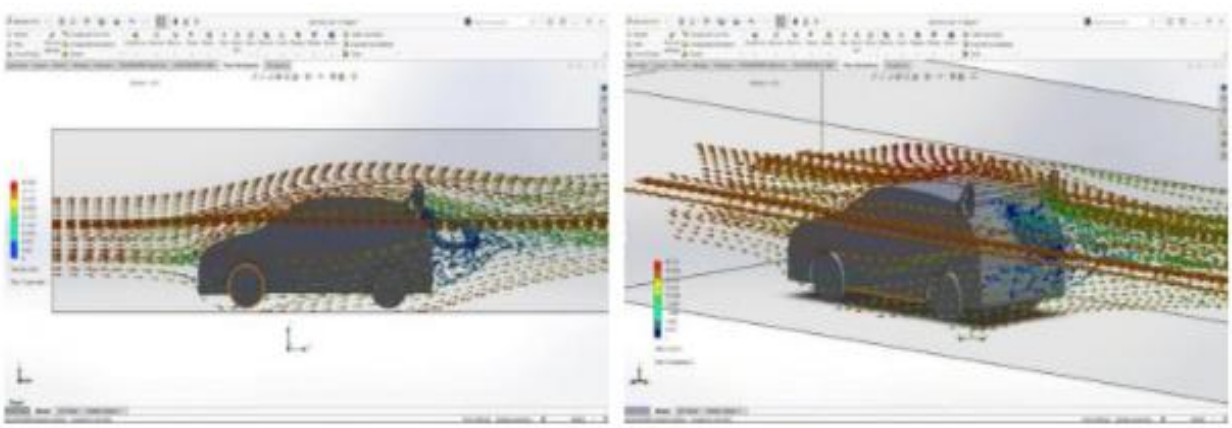


Fig.20: Simulation with speed 33.3 m/s (120 km/hr)

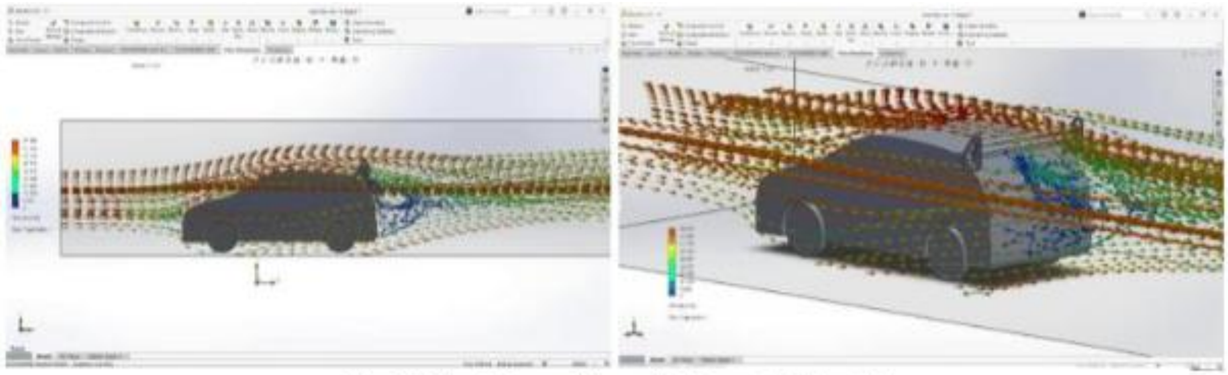


Fig.21: Simulation with speed 44.4 m/s (160 km/hr)

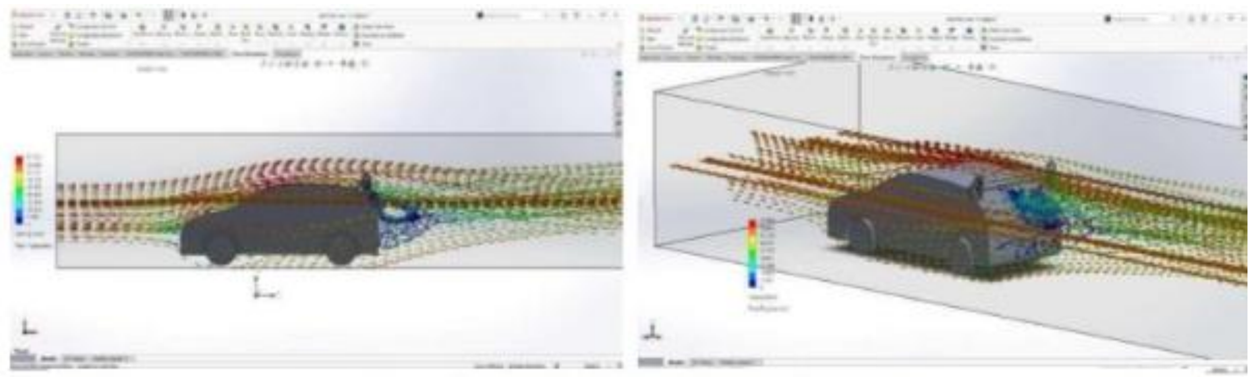


Fig.22: Simulation with speed 55.5 m/s (200 km/hr)

5) Material Selection: Carbon fibre is an ideal material for the rear spoiler because it provides an excellent combination of high structural strength and extremely low weight. This lightweight property is crucial to improve vehicle aerodynamics and fuel efficiency without adding unnecessary bulk to the rear end. After reviewing the various research paper, it is concluded that Carbon fibre has high strength to weight ratio, high stiffness and also it is corrosion resistance. So, carbon fibre is selected as the material to be used for the spoiler.

6) Structural Analysis (FEA): The optimized spoiler geometry was integrated into the FEA software (SolidWorks) to prepare the model for meshing and structural analysis. High stress regions, such as mounting brackets and sharp aerodynamic curvature, were isolated for localized mesh refinement.

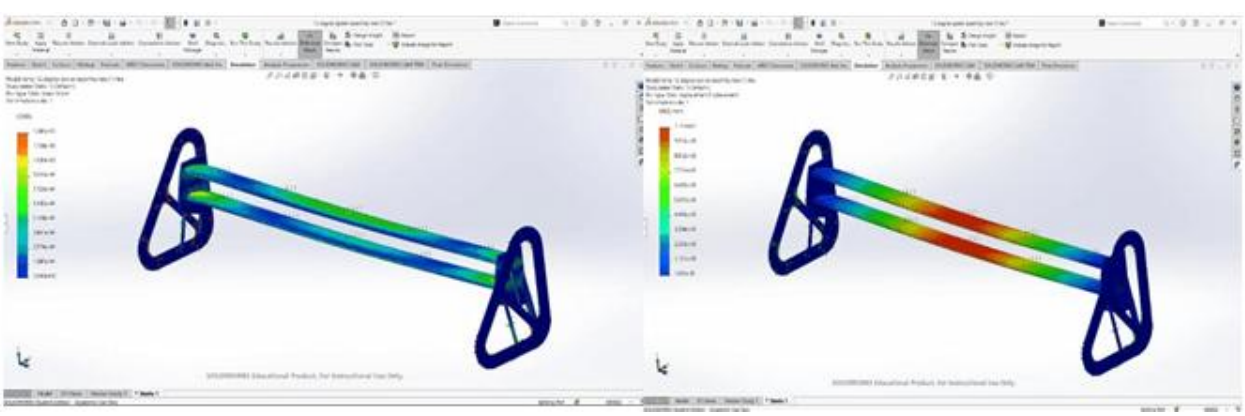


Fig.23: Structural Analysis of Spoiler Assembly

7) Results and Validation: The results obtained from the aerodynamic analysis of the rear spoiler were validated by comparing different spoiler configurations and available reference data. The comparison was carried out;

- Between the vehicle model with and without spoiler
- With published literature and empirical aerodynamic data
- Between single element spoiler and double element spoiler configuration

8) Conclusion and Optimization Outcome: The final spoiler design was selected after performing detailed aerodynamic analysis and comparison of different spoiler configurations at various vehicle speeds. Based on the CFD results and comparative performance analysis, the most effective spoiler design was selected based on;

- Higher lift coefficient
- Lower drag coefficient
- Better vehicle stability

III. CALCULATION

Drag Coefficient (C_D): It is a dimensionless parameter that represents the amount of aerodynamic resistance offered by a body moving through air. It indicates how efficiently the spoiler moves through air foil.

The drag coefficient is calculated using;

$C_D = 2D / \rho V^2 A$

Where; C_D = Drag coefficient

D = Drag force (N)

ρ = Air density (kg/m^3)

V = Air velocity (m/s)

A = Reference area of spoiler (m^2)

Lift Coefficient (C_L): It is a dimensionless parameter that represents the ability of the spoiler to generate lift or downforce when air flows over it. It indicates the aerodynamic effectiveness of the spoiler.

The lift coefficient is calculated using;

$C_L = 2L / \rho V^2 A$

Where; C_L = Lift coefficient

L = Lift force or downforce (N)

ρ = Air density (kg/m^3)

V = Air velocity (m/s)

A = Reference area of spoiler (m^2)

IV. RESULT

The aerodynamic performance of the rear spoiler was evaluated through CFD simulations carried out in SolidWorks Flow Simulation at different vehicle speeds ranging from 40km/hr to 200km/hr. The obtained results include lift force, total force, drag force, dynamic pressure, lift coefficient, drag coefficient and lift to drag ratio for the different spoiler configurations of 7degree and 12degree angle of attack.

The analysis shows the relationship between velocity and aerodynamic forces, which is important for optimizing spoiler geometry to achieve improved vehicle stability and high-speed performance while maintaining acceptable drag levels.

Velocity (m/s)	Speed (km/h)	GG Force Y Lift (N)	GG Force1 Total(N)	Est. Drag (N)	Dynamic Pressure (Pa)	q x A	C_L	C_D	L/D Ratio
11.1	40	171.29	195.47	94.17	75.47	170.55	1.004	0.552	1.82
22.2	80	322.51	488.37	366.72	301.86	682.21	0.473	0.538	0.88
33.3	120	583.52	1009.45	823.71	679.20	1534.98	0.380	0.537	0.71
44.4	160	951.83	1747.65	1465.71	1207.46	2728.86	0.349	0.537	0.65
55.5	200	1423.90	2698.21	2291.91	1886.65	4263.84	0.334	0.538	0.62

Fig.: 7 spoiler simulation results

Velocity (m/s)	Speed (km/h)	GG Force Y Lift (N)	GG Force1 Total(N)	Est. Drag (N)	Dynamic Pressure (Pa)	q x A	C_L	C_D	L/D Ratio

11.1	40	182.00	206.449	97.50	75.47	170.55	1.067	0.572	1.87
22.2	80	387.50	572.965	422.30	301.86	682.21	0.568	0.619	0.92
33.3	120	627.00	1107.26	859.00	679.20	1534.98	0.408	0.560	0.73
44.4	160	1151.41	1917.07	1532.78	1207.46	2728.86	0.422	0.562	0.75
55.5	200	1743.19	2966.41	2400.18	1886.65	4263.84	0.409	0.563	0.73

Fig.: 12° spoiler simulation results

→ Lift Coefficient (C_L) Comparison:

Speed (km/hr)	7° C_L	12° C_L	Δ C_L (12°-7°)	% Advantage (12°)	Better angle
40	1.004	1.068	0.064	6.4	12°
80	0.473	0.568	0.095	20.1	12°
120	0.380	0.409	0.029	7.6	12°
160	0.348	0.421	0.073	21.0	12°
200	0.334	0.409	0.075	22.5	12°

→ Drag Coefficient (C_D) Comparison:

Speed (km/hr)	7° C_D	12° C_D	Δ C_D (12°-7°)	% Drag Penalty (12°)	Better Angle
40	0.552	0.572	0.020	3.6	7°
80	0.537	0.619	0.082	15.3	7°
120	0.537	0.560	0.023	4.3	7°
160	0.537	0.561	0.024	4.5	7°
200	0.538	0.563	0.025	4.6	7°

→ Lift to Drag Ratio (L/D) Comparison – Overall Efficiency:

Speed (km/hr)	7° L/D	12° L/D	Δ L/D (12°-7°)	% Efficiency Gain	Better Angle
40	1.82	1.87	0.05	2.7	12°
80	0.88	0.92	0.04	4.5	12°
120	0.71	0.73	0.02	2.8	12°
160	0.65	0.75	0.10	15.4	12°
200	0.62	0.73	0.11	17.7	12°

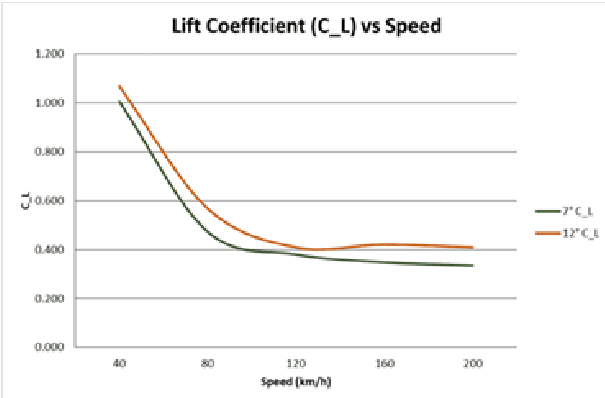
The aerodynamic analysis of the rear spoiler was carried out a spoiler angles of 7° and 12° for different vehicle speeds ranging from 40 km/hr to 200 km/hr. The results from the CFD simulation are tabulated above.

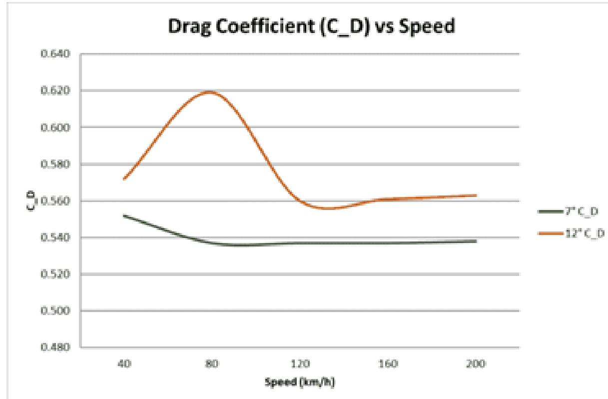
From the Lift coefficient comparison, it is observed that the 12° spoiler angle produces higher lift coefficient values at all speeds as compared to the 7° spoiler angle. This improvement is especially significant at higher speeds such as 160 km/hr and 200 km/hr. This indicates that the 12° spoiler improves vehicle stability at high-speed conditions.

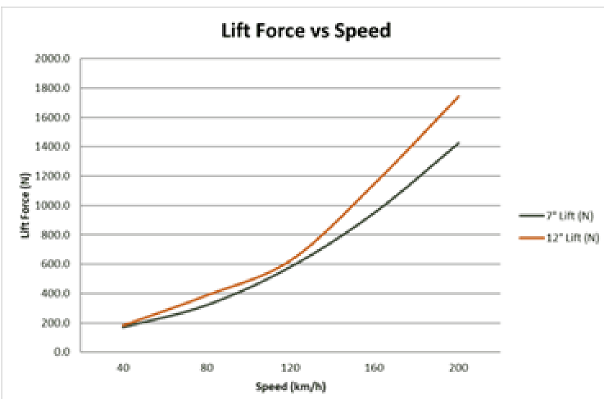
In the drag coefficient comparison, the 12° spoiler angle produces slightly higher drag than that of 7° spoiler angle. The increase in drag is minimum at lower and medium speeds, while maximum drag penalty is observed at 80 km/hr. This indicates that the 7° spoiler angle performs better in terms of drag reduction.

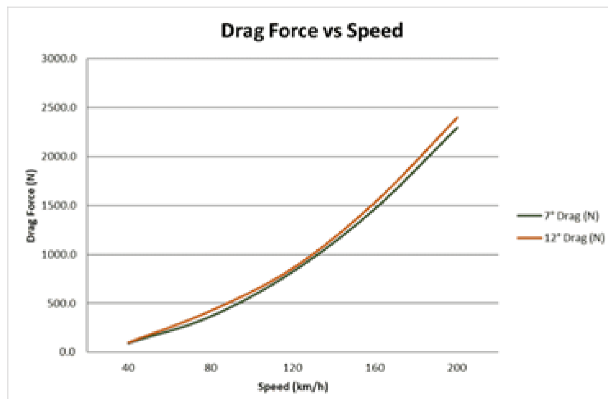
The lift to drag ratio comparison shows that the 12° spoiler angle provides better aerodynamic performance at all speeds. The efficiency gain becomes more at higher speeds. This indicates that the additional lift generated by the 12° spoiler is greater than the increase in drag.

V. GRAPH









VI. CONCLUSION

Criterion	7° Spoiler	12° Spoiler	Recommended
Max Downforce (C_L)	Lower	Higher (+6-21%)	12°
Drag Penalty (C_D)	Lower (Better)	Higher (+4-15%)	7°
Aero Efficiency (L/D)	Lower	Higher at all Speeds	12°
C_D Stability	Very Stable (0.537)	Slightly Variable	7°
Rally Car Suitability	Moderate grip	High grip and Stability	12°

This research focused on the aerodynamic optimization of a rear spoiler by comparing two spoiler angles, 7° and 12°, to evaluate their effect on vehicle performance. The results showed that the 12° spoiler produced higher downforce and better aerodynamic efficiency, which improved overall handling performance. On the other hand, the 7° spoiler produced less downforce compared to 12° spoiler.

Overall, the study concludes that the 12° rear spoiler offers the best balance between aerodynamic performance, vehicle stability and road grip. Therefore, the rear spoiler with angle of attack as 12° is recommended as the optimal design for this project of aerodynamic optimization of a rear spoiler.

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