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Aerodynamic Drag Analysis of a Passenger Car for Increasing Fuel Economy

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ABSTRACT
As per the reports by Hedges & Company, by 2024, 1.4 billion passenger cars will currently be in use. Most of these people are careless about fuel waste, as maximum fuel consumption is a common problem. Many people must be more careful about this problem because fuel consumption is reduced. One can save a negligible amount of fuel by increasing fuel consumption, but with tremendous respect, if 1.4 billion people save this insignificant amount, it can contribute to the future and society. This paper deals with the aerodynamic drag of passenger cars and the reduction of drag. Reducing drag, wind noise, and noise pollution, as well as avoiding unwanted lift forces and other factors contributing to aerodynamic instability at high speeds, are the main problems of car aerodynamics. Different types of aerodynamic devices were designed with a model passenger car. These include Vortex generators, V-shaped bumper & rear spoiler. The difference between with & without aerodynamic devices shows the reduction in power consumption to overcome this drag. This means the amount of power needed to operate is lower; this proportionally reduces fuel consumption, thus increasing fuel economy. Under considering the optimum condition of the VG, a maximum of 46.65% of power was saved due to overcoming drag force.

Keywords: Aerodynamics; Aerodynamic Devices; Drag coefficient; Vortex; Drag force

1. Introduction

Research on automotive aerodynamics shows that various rear modifications, like diffusers, flaps, guide vanes, and spoilers, are effective for reducing drag and lift, though the results vary. For example, Parab [1] found that using a rear diffuser lowered lift by 34% with only a slight increase in drag. Hassan [2] achieved a 22.13% drag reduction through underbody slicing, and Marklund [3] showed that using diffusers with specific angles—8° for sedans and 5° for wagons—reduced drag by 13%. For flaps and guide vanes, Wahba's [4] study revealed that symmetric airfoil vanes could cut drag by up to 18%, while Aider [5] found that adjusting back angles could reduce drag by 25%. When it comes to spoilers, Bansal & Sharma [6] demonstrated a 2.02% drag reduction and a 6% lift reduction, while Hu & Wong [7] achieved a 1.7% drag reduction and increased negative lift, which improved stability. These studies emphasize how different configurations, vehicle types, and design choices lead to varied aerodynamic benefits.The objective of this study was to study combined effect of various aerodynamic devices in a passenger car for Increasing Fuel economy by the Aerodynamic drag Analysis.

2. Experimental Analysis

Experimental Analysis is stated in the below section which was carried out at Rajshahi University of Engineering & Technology(RUET) Fluid Mechanics labs' with the help of subsonic wind tunnel.

Wind tunnel: Wind tunnels are specialized tube-shaped equipment which allow researchers to have real time experiment such as air moves over a running vehicle on road. Wind tunnel usually have high power fans which flow air through tube where test object is fixed. It actually shows the reaction if the test object moves through air. In this facialities object scale can be adjusted such a vehicle, one piece of a vehicle, a full-size passenger car, or even a common object like a tennis ball. We took a model passenger car for this experiment.

This airflow entering into the test section is turbulent due to the motion of the fan blade design. Fan-blade turbulence does not play a role while the fan is pumping air into the test section or sucking air out of the test section downstream. But turbulent air generates problems in precise experiments, so airflow in the test section needs to be comparatively laminar & free from turbulence. Vertical & horizontal air vanes are tightly spaced to address the turbulent issue.

Important components of a wind tunnel are as follow.

Motor/Fan Driven unit*:* The motor/fan usually generates air flow in wind tunnel which is required to rise in static pressure to offset the overall pressure loss in the remainder of the circuit.

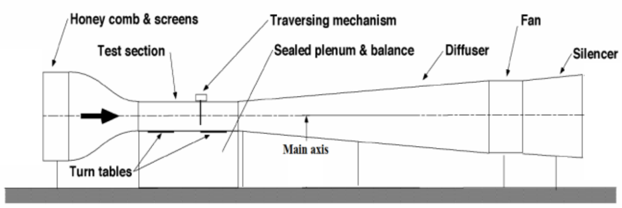

Fig 2.1. Wind tunnel components

Settling chamber and flow straightener*:* Its primary components are screens and honeycomb. Its primary purpose is to lessen turbulence and straighten the flow in the axial direction.

Test Section: This is one of the fundamental elements of a wind tunnel upon which other elements are designed. When the tunnel runs at a specific flow velocity, it is equipped with

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all aerodynamic models. Usually, the wind tunnel is constructed using a variety of test section forms, such as hexagonal, octagonal, and rectangular.

Diffuser: Diffuser is generally known as duct with an increased area attached to the downstream of the test section. It is attached to ensure air passes smoothly out of the test section immediately.

There are various factors that can be used to classified wind tunnels. If the air speed of a wind tunnel is chosen as the classification criterion, wind tunnels fall into the following groups.

- Low speed or continuous type wind tunnel (up to 40 m/s)
- High speed or intermittent/blow down type wind tunnel (600m/s)
- Shock or impulse type wind tunnel (2km/s)
- Free piston shock impulse type wind tunnel (5km/s)
- Expansion tube impulse type wind tunnel (10km/s)

In this experiment, a low-speed wind tunnel was used. A variety of methodologies were employed to compare the actual airflow around the geometry with the theoretical conclusions. The most popular of them are-

Pressure measurements:

If the model has pressure taps, the pressure across its surfaces can be tracked. This only takes into account the usual forces operating on the body, but it can be useful for phenomena which is dominated by strain.

Force and moment measurements:

It is possible to measure lift, drag, lateral forces, yaw, roll, and pitching moments across a range of angle of attack by mounting the model on a force balance.Common curves lik e lift coefficient vs angle of attack can be generated in such way.

2.2 Model development:

The length of the passenger car of our prototype was 20 cm
Maximum height of the passenger car was 5 cm
Width of the passenger car was 8 cm
Frontal area of the passenger car was 44 cm^2

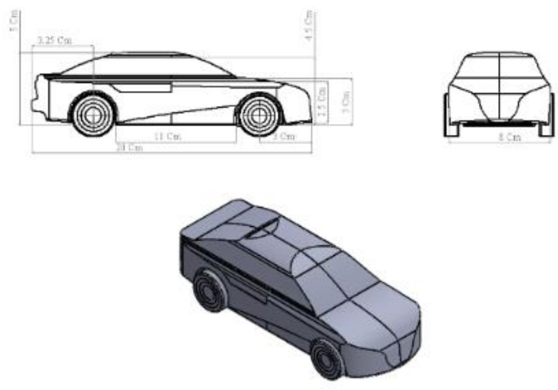

Fig 2.2.1: Design Of Model Passenger Car

2.2.1 Design of Vortex Generators(VG)

2.2.2 Triangular VG

Length of VG = 2h, Height of VG = h,Thickness of VG = d

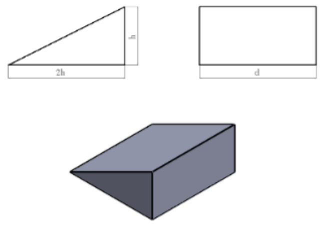

Fig-2.2.2: Triangular VG

2.2.3 Bumped shaped VG

Length of VG = 5h, Height of VG = h, Thickness of VG = d

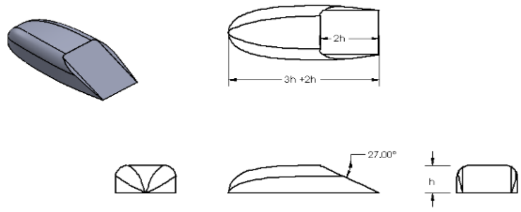

Fig 2.2.3: Bumped Shaped VG

2.2.4 Delta Shaped VG

Length of VG = 2h,Height of VG = h, Thickness of VG = d

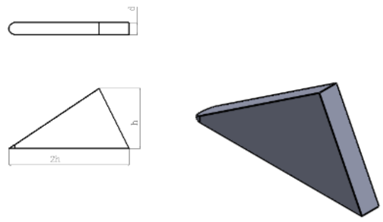

Fig 2.2.4: Delta Shape VG

2.2.5 V shaped Bumper Generally, for passenger car conventionally rounded shaped bumper is used but on heavy vehicle like locomotives, Armored vehicles etc to reduce drag & noise thus to increase the vehicle performance V-shaped bumper is used. For this we decided to use this type of bumper in our prototype passenger car. Design of the V-shaped bumper is given below.

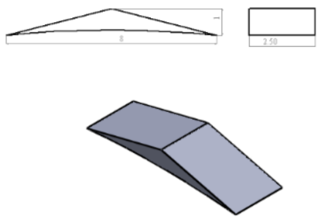

Fig 2.2.6: V-Shaped Bumper

2.2.6 Rear Spoiler

design of prototype passenger car rear spoiler is given below:

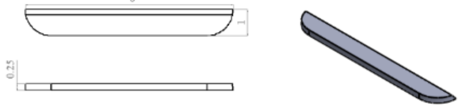

Fig 2.2.7: Rear Spoiler

2.3 Prototype fabricated Passenger Car with Various Add-on-Devices

The prototype of our model passenger car and various add-on-devices were at first fabricated with the help of university wood shop facility. The dimensions of these prototypes are mentioned in Model development 2.2 section of this paper. Fig 2.3.1 shows Prototype fabricated Passenger Car of our experiment.

Fig 2.3.1 Fabricated Model of Passenger Car

2.3.2 Experimental Setup

The model was positioned in the center of the test area with the support by a round stainless-steel beam. This test area measured 30 cm by 30 cm. Length of the wind tunnel was 250 cm overall. To determine the angle of attack, there was a separate angle measurement device. Several additional instrument such as sliding weight, motor, and balance arm etc. was used with the wind tunnel during this experiment. The wind tunnel facility in our fluid mechanics lab is depicted in Fig. 2.3.2.

Fig 2.3.2 Wind tunnel of our laboratory

The counterweight that was positioned across from the bala ncing arm was moved to achieve the null position of the ar m.After starting, the motor was adjusted to a proper air velo city of 53.09 m/s.The balancing arms were moved from the null position by forces applied to the model.The null positio n was restored by moving the sliding weight mas.It may rea d lift and drag forces at place.The speed was gradually raise d.Our wind tunnel's experimental setup with test section vie w is displayed in Fig. 2.3.3, 2.3.4, 2.3.5, 2.3.6.

Fig 2.3.3 Experimental setup of Model Passenger Car

Fig 2.3.4 Experimental setup of Model Passenger Car with Delta Shape VG

Fig 2.3.5 Experimental setup of Model Passenger Car with Delta Shape VG and V Shape Front Air Dam

Fig 2.3.6 Experimental setup of Model Passenger Car with Rear spoiler

Lift coefficient and drag coefficient were calculated by using the following equations [6] where Lift & drag force were directly calculated from experimental faciality.

$$F_L = \frac{C_L A \rho V^2}{2} \quad \text{.....................................(1)}$$

$$F_D = \frac{C_D A \rho V^2}{2} \quad \text{.....................................(2)}$$

This research represents both analytical and experimental findings that evaluate the effects of various vortex generators (VGs) and aerodynamic devices to reduce drag in a model passenger car. Through wind tunnel experiments, different VGs, bumpers, and spoilers were tested to assess their impact on drag force, drag coefficient, and power requirements at different speeds. All practical data collected during these experiments are provided in both tabular and graphical formats to facilitate comparisons across different setups.

3. **Results & Discussion:**

3.1. **Selection of Vortex Generator Shape and Size**

The selection of VG shape and size was crucial for optimizing drag reduction which directly influenced the formation and strength of streamwise vortices. VGs were chosen based on their ability to produce a strong vortex with minimal self-induced drag:

3.1.2 Triangular VGs

Installed at the roof's end, these VGs effectively reduce drag, as shown in Figures 3.1 and 3.2. Their effectiveness suggests that strategically placed VGs can enhance aerodynamic efficiency.

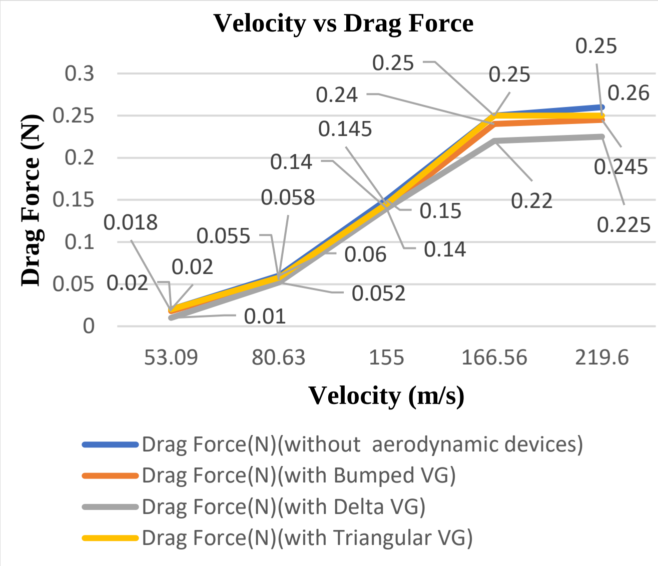

Fig 3.1: Velocity vs Drag Force of Prototype without any aerodynamic device and with various VG

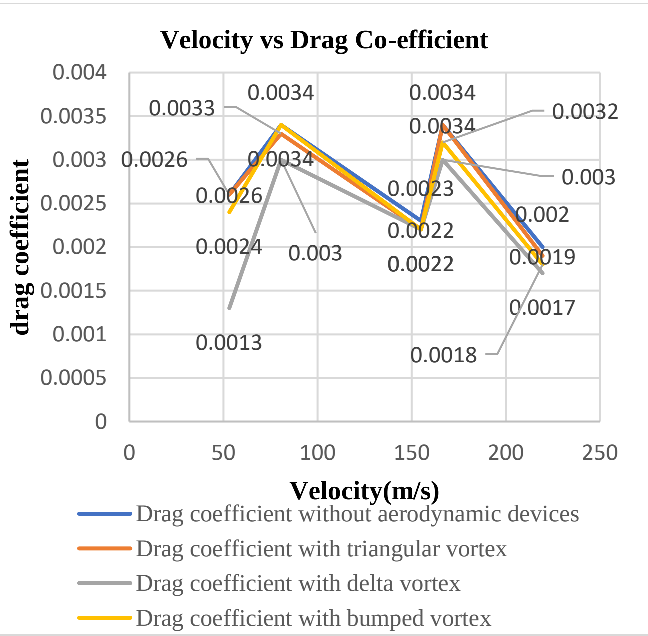

Fig 3.2: Velocity vs Drag Coefficient of Prototype without any aerodynamic device and with various VG

3.1.3 Bump-Shaped VG

A bump-shaped VG with a rear slope angle of 25–30° was selected. This angle is known to generate a robust streamwise vortex in vehicles with a hatchback-style rear window. The front contour of the bump was designed with a smooth curve to minimize drag, while the rear half was cut at approximately a 27° angle for maximum vortex generation. Figures 3.1 and 3.2 demonstrate that bump-shaped VGs reduce drag more effectively than triangular VGs, and Figure 3.3 shows that they also reduce power requirements compared to setups without aerodynamic devices.

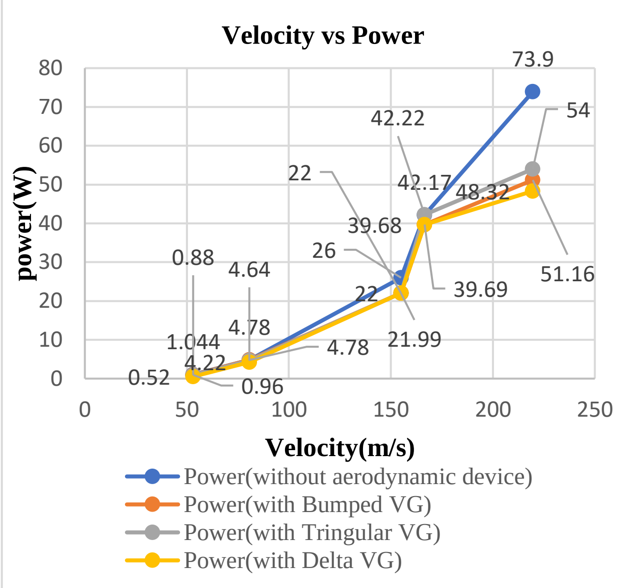

Fig 3.3: Velocity vs Power required to overcome Drag of Prototype without any aerodynamic device and with various VG

3.1.4 Performance of Delta-Wing Shaped VGs

The delta-wing-shaped VG outperformed other designs, demonstrating exceptional drag-reducing capabilities. The following factors contribute to its effectiveness:

Smaller Frontal Area: The compact, streamlined form of the delta wing VG minimizes its own drag.

Strong Vortex Generation: The vortex generated at the delta VG's leading edge maintains strength downstream, avoiding interference with the VG itself. In contrast, the vortex generated by bump-shaped VGs dissipates more quickly due to interaction with the VG structure. This unique design makes delta-wing-shaped VGs highly effective for reducing drag, as illustrated by their lower power requirements in Figure 3.3. These results highlight the potential of delta VGs for future automotive applications.

3.1.5 V-Shaped Bumper Application

A V-shaped bumper, which is more frequently found on heavy armored vehicles than on passenger cars, was used in the study. It was found to be useful in lowering drag by lowering frontal pressure. Figures 3.4 and 3.5 illustrate how the bumper's uneven airflow distribution lowers frontal pressure, which in turn lowers drag force.

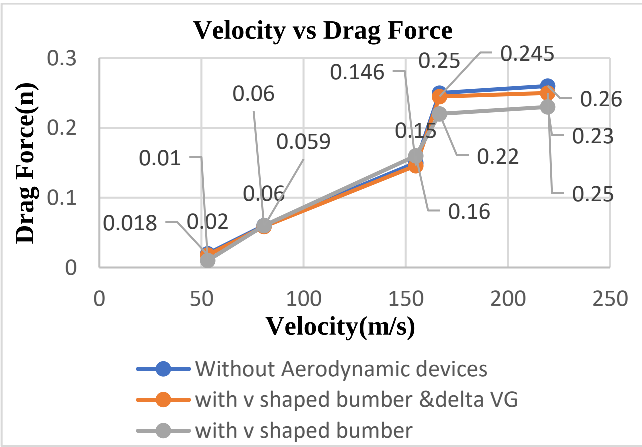

Fig 3.4: Velocity vs Drag Force of Prototype without any aerodynamic device and with V-shape Bumper and Delta VG.

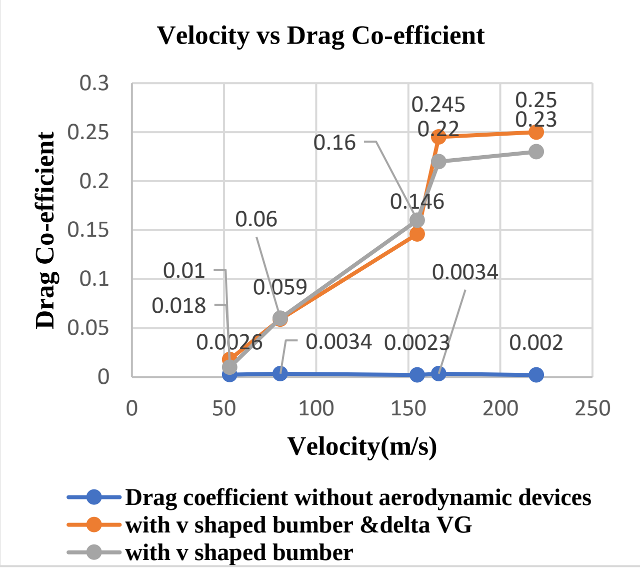

Fig 3.5: Velocity vs Drag Co-efficient of Prototype without any aerodynamic device and with V-shape Bumper and Delta VG.

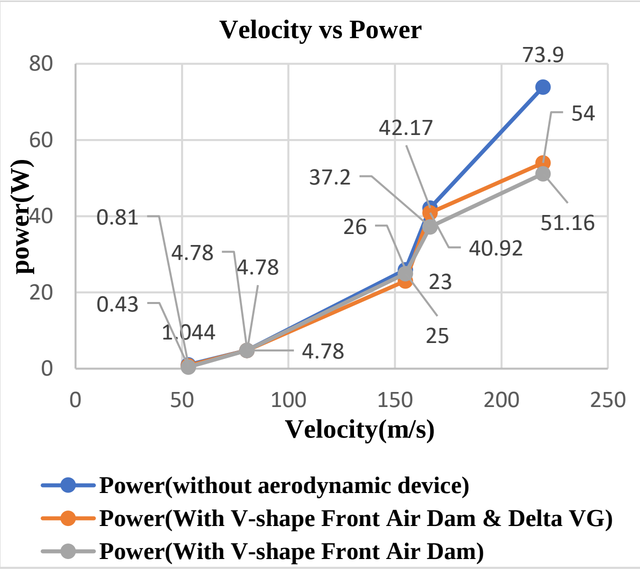

Fig 3.6: Velocity vs Power required to overcome Drag of Prototype without any aerodynamic device and with V-shape Bumper and Delta VG.

Low-Speed Performance (50–150 m/s): The V-shaped bumper, combined with delta-shaped VGs, was more effective in reducing drag at these speeds.

High-Speed Performance (150–250 m/s): The V-shaped bumper alone performed better than when combined with delta-shaped VGs.

Moreover, the V-shaped bumper may reduce lift force at high speeds, which stabilizes the vehicle by counteracting the nose lift observed at speeds up to 60 mph in front-wheel-drive cars. Though no lift measurements were conducted, it is hypothesized that this bumper design will improve stability in real-world conditions.

3.1.6 Rear Spoiler Performance:

The rear spoiler was effective in reducing drag by creating an airflow barrier that increased pressure ahead of it and enhanced flow attachment. This setup helps reduce drag force significantly, as demonstrated in Figures 3.7 and 3.8. By promoting better flow control, the spoiler proves to be a simple yet powerful solution for enhancing aerodynamics in passenger vehicles.

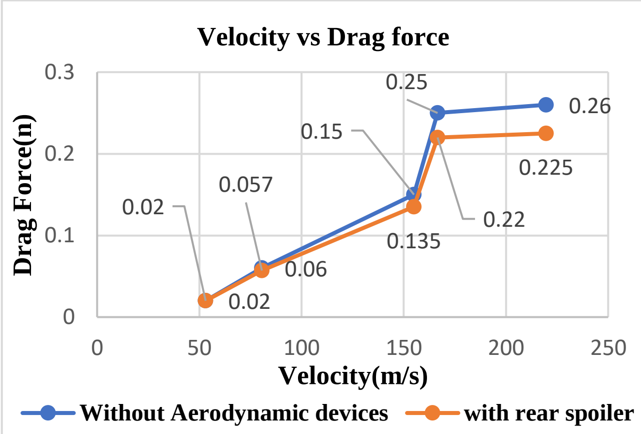

Fig 3.7: Velocity vs Drag Force of Prototype without any aerodynamic device and with Rear Spoiler.

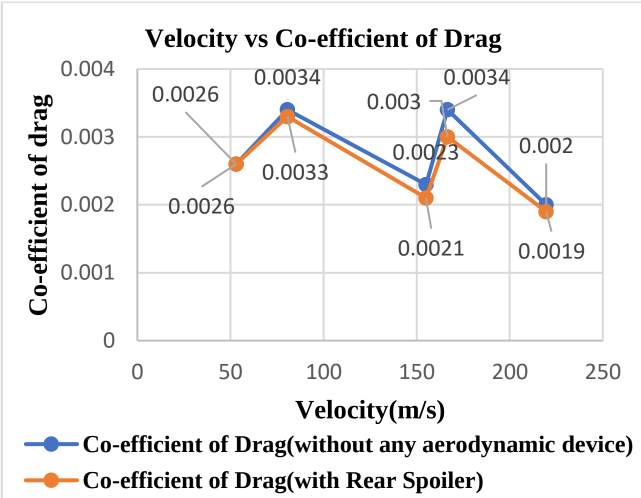

Fig 3.8: Velocity vs Drag Co-efficient of Prototype without any aerodynamic device and with Rear Spoiler.

3.1.7 Impact on Lift Force: An examination of lift forces shows that the aerodynamic devices used to reduce drag also slightly decrease lift, as depicted in Figure 3.10. The lower lift force enhances vehicle stability, an essential factor in achieving safer high-speed performance. This finding further validates the effectiveness of these devices beyond their primary purpose of drag reduction.

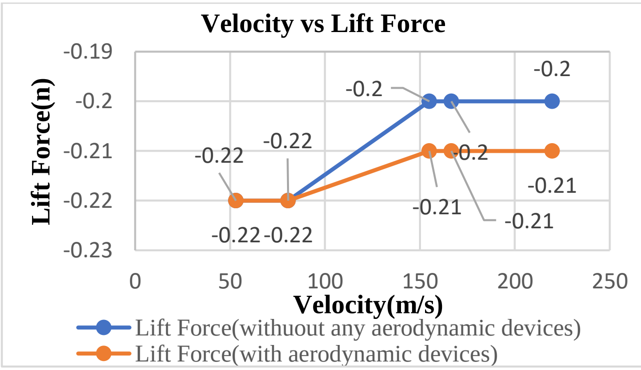

Fig 3.10: Velocity vs Lift Force of Prototype without any aerodynamic device and with various aerodynamic devices.

3.1.8 Optimal Height for Vortex Generators

The height of VGs plays a critical role in balancing drag reduction and vortex strength:

As observed in prior studies, an increase in VG height simultaneously enhances vortex generation and increases the VG's own drag. The optimal height for VGs is approximately 80% of the boundary layer thickness at the vehicle's transition point, calculated here as 0.0025 m based on a boundary layer thickness of 0.0031 m. This optimum VG height balances the benefits of delayed flow separation with minimized drag.

3.1.9 Implementation of Optimal VG Height

Using a 3D printer, delta-shaped VGs with optimal height (0.0025 m) were fabricated from plastic. Experimental data collected using these optimally sized VGs are compared with data from setups without VGs and those with standard delta VGs, as illustrated in the relevant figures. These results show that drag force is minimized at the optimal VG height, reinforcing the importance of height adjustments in VG design.

3.1.10 Efficiency Assessment

The power efficiency of each configuration was assessed by calculating the percentage reduction in power requirements between the baseline vehicle and the modified configurations, following the formula:

$$\text{Efficiency} = \frac{avg.\text{Power}_{w.a.d.} - avg.\text{Power}_{w.out.a.d.}}{avg.\text{Power}_{w.out.a.d.}} \times 100$$

Results indicate that optimally configured VGs, along with the V-shaped bumper and rear spoiler, provide substantial drag reduction, thereby enhancing power efficiency across a range of speeds.

1. Prototype with Delta VG: 25.45% power saving
2. Prototype with Bump-Shaped VG: 22.95% power saving
3. Prototype with Triangular VG: 19.59% power saving
4. Prototype with V-Shaped Bumper: 22.96% power saving
5. Prototype with Rear Spoiler: 23.5% power saving
6. Prototype with Optimal VG Height: 45.65% power saving, the highest observed in this study.

This study highlights the potential for combining aerodynamic devices and optimal VG designs to reduce drag and improve fuel efficiency in passenger cars, setting the stage for advancements in automotive engineering and fluid mechanics.

4. Conclusion:

The conclusions of this study can be summarized into the following:

1. Vortex generators (VGs) were installed slightly upstream of the flow separation point to control the separation of airflow above a passenger car's rear window and enhance aerodynamics. The optimal VG height was found to be almost equivalent to the thickness of the boundary layer (15 to 25 mm), and the best placement plan is to arrange them in a row 100 mm upstream of the roof end with 100 mm between each other. These features do not significantly affect the VGs, and their ideal value ranges are wide. Delta-wing VGs yield better outcomes than other shaped VGs.

2. Using the optimal height of delta VG resulted in a notable increase in fuel and power efficiency. As power and fuel economy are directly equal, reducing power will surely increase fuel economy.

3. The power reduction was slight yet efficient since a new V-shaped bumper design was used in this investigation. This will also increase fuel efficiency, and additional research will further solidify this concept.

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NOMENCLATURE

Symbols	Meaning	Unit
C_D	Co-efficient of Drag	.
δ	Boundary Layer Thickness	M
dA	Cross Sectional Area	m
F_L	Lift Force	N
C_L	Co-efficient of Lift	.
A	Area	m^2
V	Velocity of Air	m/s
P	Density of Air	Kg/m^3
F_D	Drag Force	N
R_E	Reynolds Number	.
d	Thickness	m
$\underline{v}$	Kinematic viscosity	m^2/s
P	Power	W
ŵ	Torque	Nm
N	Rotation	RPM