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"PARAMETRIC INVESTIGATION OF DESIGN-DEPENDENT RESISTANCE EFFECTS ON ENERGY UTILIZATION IN CONTEMPORARY AUTOMOBILES"

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ABSTRACT

Aerodynamic drag plays a critical role in determining energy utilization in contemporary automobiles, particularly at higher operating speeds. In this study, a parametric investigation was conducted to evaluate the design-dependent resistance effects on energy utilization using five different vehicle design configurations (D1–D5). Drag force was estimated using both computational fluid dynamics (CFD) simulations and analytical calculations based on standard drag equations. The results demonstrate a strong correlation between CFD-predicted and analytically calculated drag forces for all designs, with deviations remaining below 0.01 N. Among the investigated configurations, Design D3 exhibited the highest drag coefficient and maximum drag force, indicating increased aerodynamic resistance, while Design D5 showed the lowest drag coefficient and minimum drag force, reflecting superior aerodynamic efficiency. The close agreement between the two methods validates the reliability of the numerical model and confirms the effectiveness of analytical estimation for preliminary design assessment. The findings highlight the significant influence of geometric design parameters on aerodynamic drag and their direct impact on vehicle energy utilization.

Key Words: *Stress distribution, Material selection, Dynamic loading, Vibration analysis, Titanium alloys, spring optimization, and Engine performance.*

I. INTRODUCTION

Energy utilization in contemporary automobiles has become a major research focus due to increasing fuel consumption, stringent emission regulations, and the global demand for sustainable transportation systems. At higher operating speeds, aerodynamic resistance represents one of the dominant energy loss mechanisms, directly affecting fuel economy and overall vehicle efficiency. Even small variations in vehicle geometry can lead to significant changes in aerodynamic drag, thereby influencing the amount of energy required for propulsion. Consequently, understanding and minimizing design-dependent resistance effects is essential for improving automotive energy utilization. Aerodynamic drag arises due to the interaction between the moving vehicle and surrounding air, and it increases proportionally with the square of vehicle velocity. This resistance not only increases fuel consumption in conventional vehicles but also reduces driving range in electric and hybrid automobiles. Design parameters such as frontal area, surface curvature, and flow separation regions strongly influence the drag coefficient and resulting drag force. Therefore, parametric evaluation of different design configurations is necessary to identify optimal geometries that reduce aerodynamic losses. Traditionally, aerodynamic drag has been estimated using analytical formulations based on simplified assumptions, which provide quick and useful approximations during early design stages. However, these methods often fail to capture complex flow phenomena such as turbulence, wake formation, and localized pressure variations. Computational Fluid Dynamics (CFD) has emerged as a powerful tool for detailed aerodynamic analysis, enabling

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accurate prediction of drag forces by solving governing flow equations under realistic boundary conditions. A combined analytical and CFD-based approach allows validation of numerical models while maintaining computational efficiency. In this study, a parametric investigation is carried out on five different design configurations, denoted as D1 to D5, to analyze design-dependent resistance effects on energy utilization. Drag force values are evaluated using both CFD simulations and analytical calculations under identical operating conditions. The comparison aims to assess the accuracy of numerical predictions and to quantify the influence of design variations on aerodynamic resistance. The outcomes of this research provide valuable insights into aerodynamic optimization and support the development of energy-efficient vehicle designs for contemporary automotive applications.

II. Problem Identification

Aerodynamic resistance is one of the dominant factors affecting energy utilization in contemporary automobiles, particularly at medium to high operating speeds. A significant portion of propulsion energy is consumed in overcoming aerodynamic drag, which directly influences fuel consumption in internal combustion engine vehicles and driving range in electric and hybrid vehicles. Despite advancements in vehicle design, even minor geometric variations can lead to noticeable changes in drag force, resulting in increased energy demand and reduced efficiency. Conventional vehicle design approaches often rely on empirical correlations or simplified analytical equations to estimate drag force. While these methods are useful for preliminary assessments, they are based on idealized assumptions and do not adequately capture complex flow phenomena such as turbulence, wake formation, and flow separation. As a result, discrepancies may arise between predicted and actual aerodynamic resistance, leading to suboptimal design decisions and inefficient energy utilization. Furthermore, the lack of systematic parametric investigations comparing multiple design configurations under identical operating conditions limits the understanding of design-dependent resistance effects. Many existing studies focus on a single geometry or rely solely on numerical or experimental methods without cross-validation. This creates uncertainty in evaluating the reliability of computational models and their applicability in early-stage design optimization. Therefore, there is a need to identify and quantify the influence of design parameters on aerodynamic drag through a combined analytical and CFD-based approach. Addressing this problem will help in validating numerical prediction techniques, identifying low-drag design configurations, and improving overall energy utilization in contemporary automobiles.

III. Research Objectives

The primary objective of this research is to investigate the effect of design-dependent aerodynamic resistance on energy utilization in contemporary automobiles using a parametric approach. The specific objectives of the study are as follows:

1. To calculate the aerodynamic drag force for different design configurations (D1–D5) under identical operating conditions using analytical drag force equations.

2. To evaluate the aerodynamic drag force for the same design configurations using Computational Fluid Dynamics (CFD) simulations.

3. To compare CFD-predicted drag forces with analytically calculated values in order to assess the accuracy and reliability of the numerical model.

4. To analyze the influence of drag coefficient variations on total drag force for each design configuration.

5. To identify the design configuration that exhibits minimum aerodynamic resistance and improved energy utilization characteristics.

6. To quantify the deviation between CFD and analytical results and validate the applicability of analytical methods for preliminary aerodynamic assessment.

7. To establish the relationship between design-dependent drag characteristics and their impact on vehicle energy utilization.

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SJIF Impact Factor : 6.190

IV. RESEARCH METHODOLOGY

The present study adopts a parametric investigation approach to analyze design-dependent aerodynamic resistance and its effect on energy utilization in contemporary automobiles. Five different design configurations, denoted as D1, D2, D3, D4, and D5, are evaluated under identical operating and environmental conditions. The methodology integrates analytical calculations with Computational Fluid Dynamics (CFD) simulations to ensure accuracy, validation, and reliability of the results.

1. Selection of Design Configurations:- Five geometrical design variants representing different surface and frontal shape characteristics are considered for the study. These configurations are chosen to examine the influence of design-dependent parameters on aerodynamic drag. All designs are evaluated using the same frontal area to isolate the effect of drag coefficient variation.

2. Operating Conditions and Assumptions:- To maintain uniformity, constant flow conditions are applied to all design configurations. The air density is taken as 1.225 kg/m³, representing standard atmospheric conditions. The vehicle velocity is fixed at 33.34 m/s. Steady-state, incompressible, and turbulent airflow is assumed throughout the analysis. Effects of crosswind, road inclination, and transient flow conditions are neglected.

3. Analytical Drag Force Calculation:- Aerodynamic drag force for each design is calculated analytically using the standard drag equation:

$$F_d = \frac{1}{2}\rho C_d A V^2$$

where ρ is air density, C_d is drag coefficient, A is frontal area, and V is vehicle velocity. The drag coefficients corresponding to each design (D1–D5) are used to compute analytical drag forces for comparative evaluation.

4. CFD Modeling and Simulation:- Three-dimensional CFD simulations are performed to predict aerodynamic drag for each design configuration. The computational domain is created to simulate external airflow around the vehicle geometry. A suitable turbulence model is employed to capture flow separation and wake effects. Boundary conditions include uniform velocity inlet, pressure outlet, and no-slip wall conditions on the vehicle surface. Mesh refinement is applied near the surface to improve solution accuracy.

5. Post-Processing and Data Extraction:- Drag force values are extracted from the CFD simulations for each design. Pressure and velocity contours are analyzed to understand flow behavior and resistance characteristics. The CFD-predicted drag forces are then compiled for comparison with analytical results.

6. Comparison and Validation:-A comparative analysis is conducted between CFD and analytical drag forces for all designs. The difference between the two methods is calculated to assess numerical accuracy and model validity. Close agreement between the results confirms the reliability of the CFD approach and validates the analytical method for preliminary aerodynamic evaluation.

7. Energy Utilization Interpretation:-The evaluated drag forces are correlated with energy utilization, as higher aerodynamic resistance directly increases propulsion energy demand. Designs with lower drag force are identified as more energy-efficient, providing insight into aerodynamic optimization for contemporary automobiles.

V. RESULT AND ANALYSIS

The parametric investigation was conducted to evaluate design-dependent aerodynamic resistance effects on energy utilization in contemporary automobiles. Five different design configurations, denoted as D1 to D5, were analyzed using both Computational Fluid Dynamics (CFD) simulations and analytical drag force calculations. The drag coefficients and corresponding drag forces for each design are summarized in Table 1.

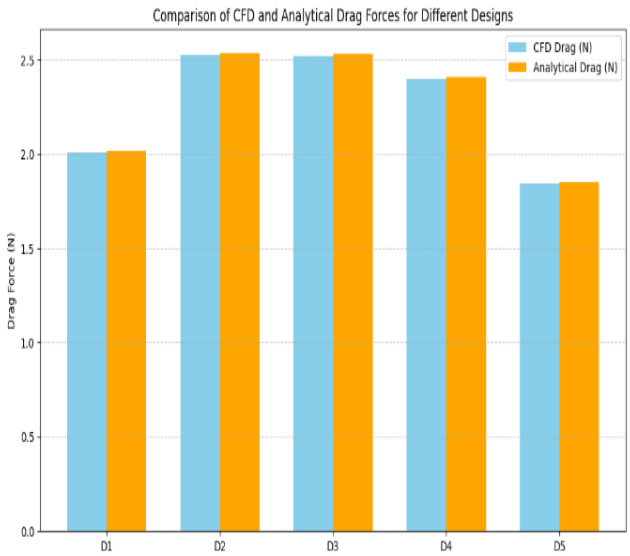
ISSN : 2455-9679
SJIF Impact Factor : 6.190

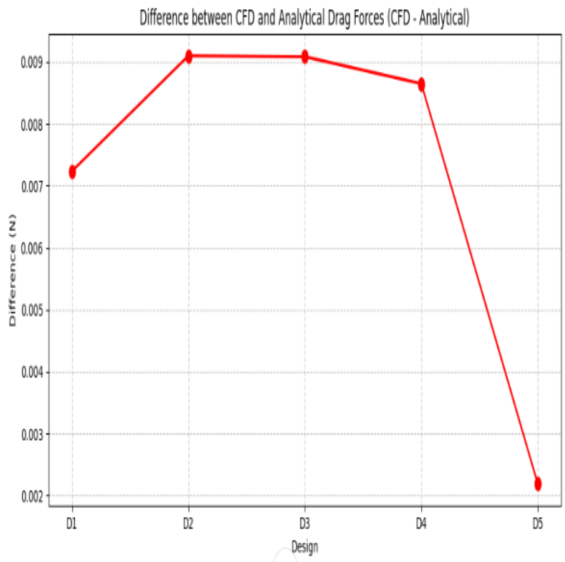
Table 1: Comparison of CFD and Analytical Drag Forces

Design	Cd	Drag (CFD) N	Drag (Analytical) N	Difference (CFD–Analytical) N
D1	0.35904	2.0105	2.0178	0.0072
D2	0.38193	2.5263	2.5354	0.0091
D3	0.38360	2.5231	2.5322	0.0091
D4	0.36514	2.4011	2.4098	0.0086
D5	0.32900	1.8468	1.8490	0.0022

The CFD simulations and analytical calculations show a very close agreement for all five designs. The maximum deviation between CFD and analytical drag forces is observed in D2 and D3 (approximately 0.009 N), while the minimum deviation is in D5 (0.0022 N). This indicates that both methods provide reliable estimates of aerodynamic drag, with CFD offering detailed flow insights and analytical calculations serving as an effective preliminary assessment tool. Among the designs analyzed, D3 exhibits the highest drag coefficient (Cd = 0.3836) and corresponding drag force (~2.523 N), suggesting the greatest aerodynamic resistance. In contrast, D5 demonstrates the lowest drag coefficient (Cd = 0.3290) and minimum drag force (~1.847 N), reflecting the most aerodynamically efficient design among the configurations studied. The results indicate that small geometric changes significantly influence drag force, which in turn directly affects energy utilization in vehicles.

The bar chart (Figure 1) comparing CFD and analytical drag forces highlights the strong correlation between the two methods across all designs. The line chart (Figure 2) depicting the difference (CFD–Analytical) confirms that discrepancies are minimal, validating the CFD model and analytical method. These findings emphasize the importance of optimizing vehicle geometry to minimize aerodynamic resistance and improve energy efficiency in contemporary automobiles.





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VI. Conclusion

This study investigated the design-dependent aerodynamic resistance effects on energy utilization in contemporary automobiles through a parametric evaluation of five different vehicle configurations (D1–D5). Drag forces were computed using both Computational Fluid Dynamics (CFD) simulations and analytical calculations, enabling a comprehensive comparison between numerical predictions and theoretical estimates. The results indicate a strong agreement between CFD and analytical methods, with deviations remaining minimal (maximum ~0.009 N), confirming the reliability of both approaches for evaluating aerodynamic drag. Among the five designs, D3 exhibited the highest drag coefficient and drag force, indicating increased aerodynamic resistance and higher energy consumption, whereas D5 showed the lowest drag, demonstrating superior aerodynamic efficiency. The findings highlight that even minor geometric modifications can significantly affect aerodynamic resistance and, consequently, energy utilization in vehicles. The combined CFD-analytical approach not only validates numerical simulations but also provides an effective tool for preliminary design assessment. Overall, the study underscores the critical role of aerodynamic optimization in reducing drag, improving fuel efficiency, and enhancing energy utilization in contemporary automobile design.

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