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Mathematical Modelling of Sedan Vehicle Front-End Profiles for Aerodynamics Efficiency Analysis

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ABSTRACT

The study utilizes mathematical modelling and statistical analysis employing the central composite design (CCD) sampling technique to improve vehicle front-end (VFE) aerodynamics. Seven critical characteristics, including windshield angle, hood edge height, and bumper centre height, are examined for their influence on drag coefficient (Cd). The model-based calibration (MBC) toolbox in MATLAB builds a response model that captures parameter interactions and drag coefficient effects. The fitness function minimizes root mean square error (RMSE) and maximizes R-Squared (R^2), yielding RMSE values of 0.0065 for Cd and R^2 values of 89.2%. Analysis of Variance (ANOVA) demonstrates that windshield angle and hood edge height are the most important factors affecting drag coefficient (Cd), with significant interactions with bumper centre height. Improving aerodynamic stability by refining the windshield angle, hood edge height, hood length, and bumper center height enhances safety by minimizing turbulence during vehicle operation. This study advances prior research by integrating a detailed CCD-based modelling approach with multi-parameter interaction analysis, providing a more precise and predictive framework for optimizing VFE geometry. The novelty lies in the identification and development of a vehicle front-end design that highlights the front-end design profiles that contribute to the aerodynamics efficiency. Vehicle manufacturers will be better informed on which influential parameters to tweak in the frontal design to reduce drag.

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INTRODUCTION

As sustainability in the automotive industry continues to progress, enhancing fuel efficiency while upholding safety standards is paramount. A car's aerodynamics is greatly impacted whether it is fuel efficient or not, especially when the drag coefficient (Cd) increases (Romero et al., 2024). Drag reduction plays a crucial role in lowering energy consumption, enhancing fuel efficiency, and increasing the operational range of vehicles during regular use (Sivaraj et al., 2018). In tandem, the safety of pedestrians has been receiving more focus especially when low-speed collisions often happen within a city context. Since aerodynamics performance and pedestrian safety are the two critical considerations in vehicle front-end design, addressing both in a unified approach is essential (Kausalyah et al., 2014).

This investigation aims to develop a holistic approach to streamline vehicle front end engineering design focused on drag reduction and pedestrian protection. It employs central composite design (CCD) sampling to examine key variables such as bumper lead (BL), bumper center height (BCH), hood leading edge (HLE) and windshield angle (WSα) (Kausalyah et al., 2015). Some of the identified variables are known to play a significant role in determining the aerodynamic profile of the vehicle, as well as the severity of injury to a pedestrian on impact.

In the interest of fulfilling these dual aims, statistical metrics and mathematical modelling are leveraged to cultivate predictive function prototypes. These prototypes will provide a quantification of precisely how vigorously formative qualities connect to meaningful outcomes like the Cd and the head injury criterion (HIC). HIC has been a long serving metric for risk of head injury in car-to-pedestrian impacts and serves as the basis for passive safety assessment and an architectural imperative of crashworthiness with respect to aerodynamics (Rowson & Duma, 2022). The primary focus is on identifying the trade-offs that are involved in reducing drag while also minimizing injury risk. This is done to ensure that improving one does not unintentionally damage the other.

The research employs advanced optimization tools, MATLAB, and Design Expert software in a stepwise manner to determine the relationship of design parameters impacting the results. Analysis of variance (ANOVA) methods assess the individual contribution of each variable to the aerodynamics performance of the vehicle. The key parameters highly influential on outcomes are the windshield angle, bumper center height, hood length, and hood edge height. By analyzing these factors, the study will generate detailed response surfaces guiding the evolution of front-end designs optimized for Cd.

By focusing on aerodynamic efficiency, this research aims to improve the design of energy-efficient vehicles. This study will identify key parameters that influence aerodynamic drag and optimize the vehicle's front-end profile to minimize air resistance. Ultimately, this research will contribute to the development of more fuel-efficient and environmentally friendly vehicles with specific parameters highlighted as design guidelines for the automotive sectors at large.

METHODOLOGY

Mathematical Modelling and Statistical Diagnostics

The mathematical modelling phase of this research employed the CCD sampling technique to generate computational experimental runs. CCD was chosen for its flexibility, ability to be run sequentially, and suitability for capturing both linear and quadratic effects. Its adaptability to different experimental regions of interest and operability makes it ideal for modelling complex interactions in vehicle front-end design. CCD sampling was used as it facilitates designing speed while building the geometry of the vehicle models. The first step of the method is model based calibration (MBC) model fitting, specifically focused on the design of experiment part, when a single-factor approach is selected. The number of components, fixed at

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7, corresponds to the seven parameters that define the front-end profiles. Afterwards, the minimum and maximum parameter values are entered, taking into consideration the corresponding minimum and maximum values for each parameter.

To obtain the Cd, the sedan vehicle model was designed using CATIA V5R21 and thereafter imported into ANSYS 2024 R1 for aerodynamic simulation. Within ANSYS, each model was enclosed in a fluid domain—an air volume designed to replicate real-world wind conditions. This enclosure followed standard proportions, extending three vehicle lengths (12,600 mm) in all directions from the model, including the front, rear, sides, and above, to ensure simulation accuracy (Azman et al., 2025). This setup enables realistic replication of airflow dynamics around the vehicle and allows for an accurate assessment of aerodynamic performance.

After completing the simulation, drag coefficient values were extracted from the ANSYS environment. Report definitions for these variables were configured to ensure consistent and reliable data collection. The results were exported into Microsoft Excel and subsequently imported into MATLAB for further analysis. This integration allows for structured data handling and facilitates deeper insights into aerodynamic behavior. Design-Expert software was also used in parallel to develop the mathematical model and conduct ANOVA, offering insight into the relative influence and interaction of design parameters.

In order to generate a response model for the Cd, the data is inserted to the MBC model toolbox. A polynomial subclass of the linear model class is chosen with an interaction order of 2, as this captures the interactions between pairs of design variables. Higher-order interactions (e.g., involving three or more variables) are not considered because their inclusion would unnecessarily increase model complexity without providing substantial improvements in model accuracy for the current design objectives.

The model setup for the response model is shown in Fig 1, which illustrates the key components and configuration used to generate the response surface.

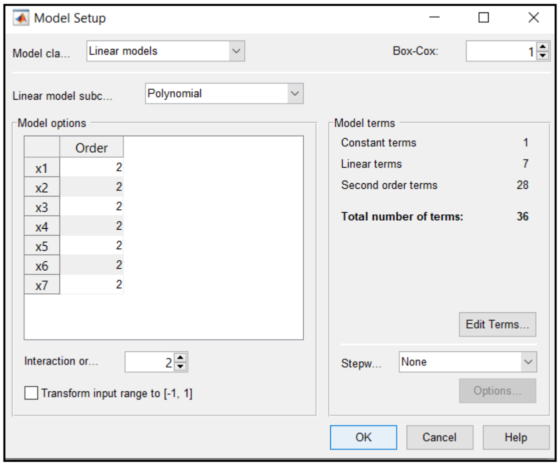

Fig. 1. Model setup for the response model.

A desired low Root Mean Square Error (RMSE) value and a high R^2 is deemed acceptable to represent the objective function (Kambezidis, 2012; Sapra, 2014). The response model in Fig 2 shows a sample illustration of the interaction that occurs between two characteristics of the front end of the car. At the end of this response model, a fitness function will be generated.

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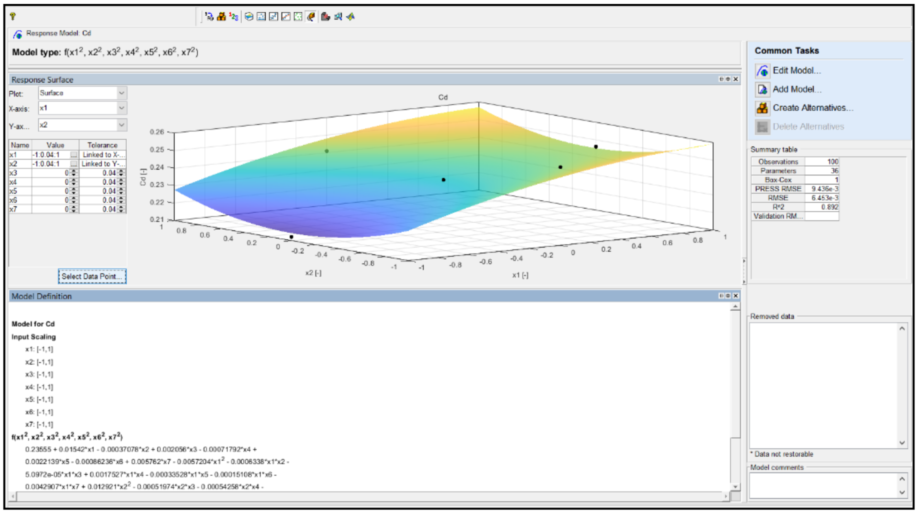

Fig. 2. Response model using MBC toolbox.

VFE Significant Parameter Identification

This study focuses on identifying the parameters that contribute to the aerodynamic performance in vehicle design. These vital frontal dimensions were selected based on previous studies where the vehicle front-end's profile was investigated for its safety in pedestrian impact (Kausalyah et al., 2014; Mizuno, 2005). Seven key parameters related to modelling the frontal geometry of vehicles were included in these dimensions: bumper lead (BL), bumper center height (BCH), hood leading edge (HLE), hood length (HL), windshield angle (WSα), hood angle (Hα) and hood edge height (HEH). An illustration of these seven parameters is presented in Fig 3, which depicts the components required for analysis and the parametric description is shown in Table 1.

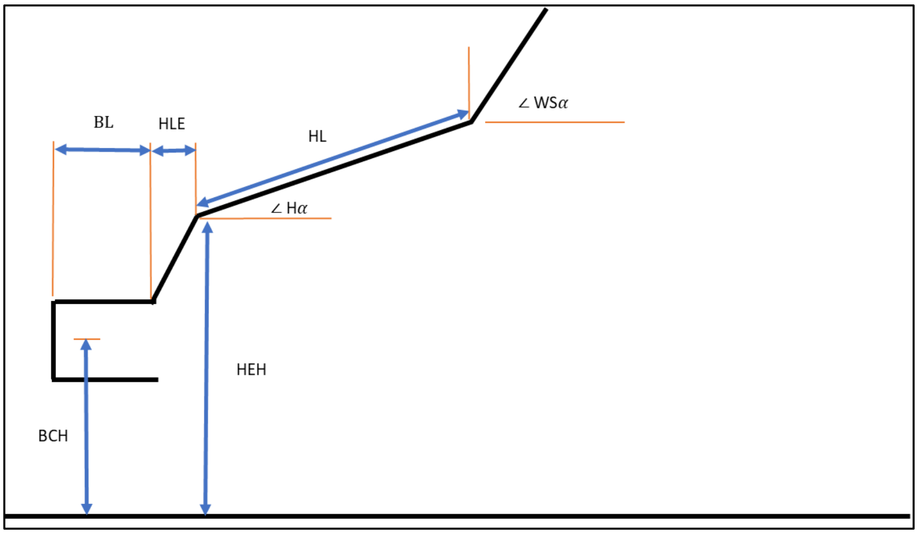

Fig. 3. Seven parameters of sedan vehicle.

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Table 1. Parameter table (mm, degrees)

x	Parameter	
x_1	WSα (degrees)	Windshield angle
x_2	BL	Bumper lead
x_3	BCH	Bumper centre height
x_4	HLE	Hood leading edge
x_5	HL	Hood length
x_6	Hα (degrees)	Hood angle
x_7	HEH	Hood edge height

Statistical investigations are then performed to determine which features have the most influence on aerodynamics performance, so that these parameters can be analyzed effectively. A summary of these parameters is shown in Table 2, along with the uncoded values (mm or degrees), minimum, median, and maximum extents. This is the basis of the CCD methodology where the model with parameter interactions can be used to effectively expedite the design process.

Table 2. Uncoded parameter analysis: minimum, median, and maximum values

Parameter	x_1 (degrees)	x_2 (mm)	x_3 (mm)	x_4 (mm)	x_5 (mm)	x_6 (degrees)	x_7 (mm)
Minimum	29	10	435	50	635	11	565
Median	34.5	30	475.5	100	917.5	14.5	702
Maximum	40	50	516	150	1200	18	839

In the CCD framework, coded values of −1, 0, and 1 are given to the minimum, median, and maximum values of these parameters, respectively. For instance, x_1 (windshield angle) has uncoded values from 29 mm (minimum) to 40 mm (maximum), and a median of 34.5 mm. These coded values streamline the process of designing and analyzing the experiment without losing precision.

RESULTS AND DISCUSSION

Mathematical Modelling and Statistical Diagnostics

Using three crucial metrics, observations, RMSE, and R^2, the MATLAB model fitting approach for a linear model, polynomial response surface method, produced significant discoveries as shown in Table 3. The analysis employed 100 data point runs to train the model. It is beneficial to have such a large dataset since it provides the model with a large amount of information upon which to learn, hence enhancing its robustness and accuracy. Moreover, the RMSE, which measures the differences between predicted and actual values, yielded a value of 0.0065. The low RMSE score denotes close agreement between the model's predictions and observed values, on average. Consequently, the model showed a high degree of accuracy in capturing each of the variations observed in the dataset (Willmott & Matsuura, 2005).

Eventually, the R^2 statistic, which indicates how much variance in the dependent variable (output) can be accounted for by the independent variables (input) in the model, had a value of 0.892. A score of 0.892 for the R^2 indicates that the independent variables utilised in the model are capable of explaining about 89.2 percent of the variability in the dependent variable. Despite there being a moderate level of agreement between model and data, which tells us that the model in fact accounts for a good part of the variation in data, there is still more work to be done in order to get an even higher R^2 value and hence a more accurate fit (Figueiredo Filho et al., 2011). This could be accomplished through the use of a more robust sampling method, which may better capture the complexity of the underlying data.

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Table 3. Summary table for Cd

Response model	Drag coefficient
Observations	100
Parameters	36
Box-Cox	1
PRESS RMSE	0.0094
RMSE	0.0065
R^2	0.892

The RMSE of the design is low and falls within a range that is considered acceptable. Based on the R^2 values, CCD designs produce a tight curve fit with a fitness of 89.2% for Cd the value.

Following the utilisation of the MBC model toolbox within MATLAB, the objective function that was produced is presented in Equation 1.

$$\begin{aligned} y1 = {} & 0.23555 + 0.01542\, x_1 - 0.00037078\, x_2 + 0.002056\, x_3 - 0.00071792\, x_4 + \\ & 0.0022139\, x_5 - 0.00086236\, x_6 + 0.005762\, x_7 - 0.0006338\, x_1x_2 - \\ & 0.00005097\, x_1x_3 + 0.0017527\, x_1x_4 - 0.00033528\, x_1x_5 - 0.00015108\, x_1x_6 - \\ & 0.0042907\, x_1x_7 - 0.00051974\, x_2x_3 - 0.00054258\, x_2x_4 - 0.000037634\, x_2x_5 - \\ & 0.00047638\, x_2x_6 - 0.00082267\, x_2x_7 - 0.00088615\, x_3x_4 + 0.0010497\, x_3x_5 + \\ & 0.000885\, x_3x_6 - 0.0032283\, x_3x_7 - 0.00043491\, x_4x_5 - 0.00071972\, x_4x_6 - \\ & 0.00057204\, x_4x_7 - 0.0013632\, x_5x_6 - 0.0010402\, x_5x_7 - 0.00060376\, x_6x_7 - \\ & 0.0057204\, x_1^2 + 0.012921\, x_2^2 - 0.0054718\, x_3^2 + 0.0038889\, x_4^2 + 0.0019623\, x_5^2 - \\ & 0.003140\, x_6^2 - 0.0011771\, x_7^2 \end{aligned} \tag{1}$$

VFE Significant Parameter Identification

Analysis of variance (ANOVA)

This approach was utilized in designing the objective function for Cd which led to a model that incorporated statistical evaluation by means of an ANOVA through the Design-Expert software (Al Shami & Wang, 2023). The ANOVA results indicated that the model's F-value of 15.05 is statistically significant, with a mere 0.01% probability of such a high value arising from random variation (Kim, 2017). It is thus confirmed that this model accurately reflects dependence relationships between input variables and the response. Key terms in the model were drawn out from the p-values, with x_1, x_3, x_5, x_7, x_1x_4, x_1x_7, x_3x_7, and x_2^2 significant as their p-values were less than 0.0500. These are the terms that are indispensable for forecasting the drag coefficient and greatly improve model accuracy.

In contrast, terms with p-values greater than 0.1000 were considered insignificant parts of the model, which contributed nothing valuable (Heston & King, 2017). x_1x_2, x_1x_5, and other such terms can be considered for the model refinement process removal. Elimination of those non-significant terms from the model tends to improve its conciseness without sacrificing accuracy, particularly when these extra terms serve only to give support and stability for its hierarchy. Hierarchical support guarantees that specific terms, despite lacking individual significance, are retained in the model to facilitate higher-order interactions or effects. The F-values and p-values for the vehicle design factors that have a substantial impact on the Cd are presented in Table 4.

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Table 4. ANOVA results: Drag coefficient and parameter interaction sensitivity

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	0.0219	35	0.0006	15.05	< 0.0001	Significant
x_1-Windshield angle	0.0157	1	0.0157	376.83	< 0.0001	
x_2-Bumper lead	9.07E-06	1	9.07E-06	0.2179	0.6422	
x_3-Bumper centre height	0.0003	1	0.0003	6.7	0.0119	
x_4-Hood leading edge	0	1	0	0.8168	0.3695	
x_5-Hood length	0.0003	1	0.0003	7.77	0.007	
x_6-Hood angle	0	1	0	1.18	0.2817	
x_7-Hood edge height	0.0022	1	0.0022	52.62	< 0.0001	
x_1x_2	0	1	0	0.6173	0.4349	
x_1x_3	1.66E-07	1	1.66E-07	0.004	0.9498	
x_1x_4	0.0002	1	0.0002	4.72	0.0335	
x_1x_5	7.20E-06	1	7.20E-06	0.1728	0.6791	
x_1x_6	1.46E-06	1	1.46E-06	0.0351	0.852	
x_1x_7	0.0012	1	0.0012	28.29	< 0.0001	
x_2x_3	0	1	0	0.4151	0.5217	
x_2x_4	0	1	0	0.4524	0.5036	
x_2x_5	9.07E-08	1	9.07E-08	0.0022	0.9629	
x_2x_6	0	1	0	0.3488	0.5569	
x_2x_7	0	1	0	1.04	0.3116	
x_3x_4	0.0001	1	0.0001	1.21	0.2761	
x_3x_5	0.0001	1	0.0001	1.69	0.1978	
x_3x_6	0.0001	1	0.0001	1.2	0.2767	
x_3x_7	0.0007	1	0.0007	16.02	0.0002	
x_4x_5	0	1	0	0.2907	0.5917	
x_4x_6	0	1	0	0.796	0.3756	
x_4x_7	0	1	0	0.5029	0.4808	
x_5x_6	0.0001	1	0.0001	2.86	0.0959	
x_5x_7	0.0001	1	0.0001	1.66	0.2019	
x_6x_7	0	1	0	0.5602	0.4569	
x_1^2	0.0001	1	0.0001	1.83	0.181	
x_2^2	0.0004	1	0.0004	9.33	0.0033	
x_3^2	0.0001	1	0.0001	1.67	0.2004	
x_4^2	0	1	0	0.8454	0.3613	
x_5^2	8.96E-06	1	8.96E-06	0.2152	0.6443	
x_6^2	0	1	0	0.5512	0.4606	
x_7^2	3.23E-06	1	3.23E-06	0.0775	0.7817	
Residual	0.0027	64	0			
Lack of fit	0.0027	43	0.0001			
Pure error	0	21	0			
Cor total	0.0246	99				

Note: The values in bold indicate the parameters for which the p-values are less than 0.0500.

The significance level for these parameters is $p < 0.05$. Parameters x_1, x_3, x_5, and x_7 dictate the angle of the windshield, the height of the bumper center, the length of the hood, and the height of the hood edge, respectively. Among them, the most substantial impact on Cd is exerted by x_1 (windshield angle) and x_7 (hood edge height), whereas the least significant impact is exerted by x_3 (bumper center height).

Additionally, several cross-interactive parameters that contribute to Cd include:

- $x_1 \times x_4$ (interaction between windshield angle and hood leading edge)
- $x_1 \times x_7$ (interaction between windshield angle and hood edge height)
- $x_3 \times x_7$ (interaction between bumper center height and hood edge height)

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Despite the fact that certain factors might not have an independent impact on Cd, the cumulative effects of these qualities, when combined with the effects of other parameters, can be rather considerable. This examination explores how diverse factors, including the angle of the windshield (x_1), the hood edge height (x_7), the hood length (x_5), and the bumper center height (x_3), influence the drag coefficient, ranked from the most to the least critical influencers, as an outcome of the objective function $f(x)$.

Parametric analysis -single and interaction parameters

Windshield Angle (x_1)

Fig 4 clearly shows how windshield angle correlates to drag coefficient in an unexpected way. While a shallow 29° windshield produced the lowest drag (-1), the steepest 40° windshield saw a sharp increase in Cd (1). This suggests that incremental adjustments can significantly impact airflow and aerodynamics.

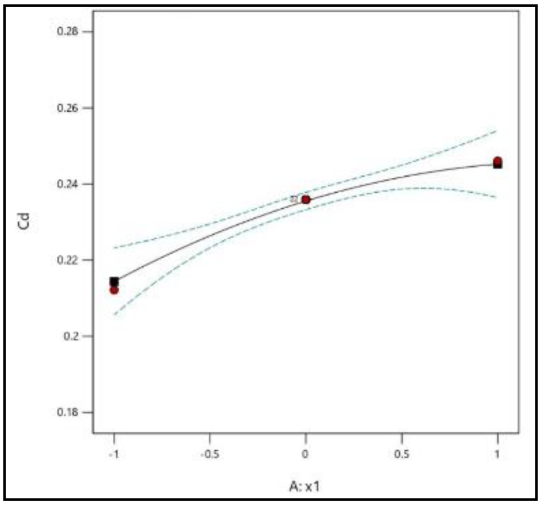

Fig. 4. Single parameter of windshield angle.

The Cd valuation is approximately 0.215 at lower angles and 0.245 at greater angles. The dashed blue line denotes the confidence range, which depicts the range of conceivable values for the actual Cd. The width of this range widens somewhat at the ends, exhibiting more uncertainty in the prediction at extremely low or high windshield angles. A reduced windshield angle enhances the vehicle's aerodynamics, facilitating smooth airflow and lowering drag. An elevated angle disrupts airflow, leading to increased turbulence and drag (Wang et al., 2025). This underscores the necessity to modify the windshield angle to enhance aerodynamic efficiency.

The graph ties in perfectly with Gao's research, showing that decreasing the incline of the windshield allows for better airflow with less separation and thus less wind resistance (Gao, 2023). Higher angles, on the other hand, disrupt the smooth flow, inducing turbulence and higher Cd values. Here, synchronising the optimisation of the angles of the windshield and the hood has been shown to greatly improve aerodynamic efficiency. These conclusions confirm the results of this study by emphasising how the windshield angle should be optimised to improve vehicle efficacy.

Overall, both in graphs and substantiated by previous studies, wind resistance is reduced when the windshield angle is lowered, while the drag coefficient is dramatically increased with an angle increase due to airflow separation. This highlights just how crucial the angle at which one optimises the windshield is for a vehicle's performance potential.

https://doi.org/10.24191/jmeche.v22i2.5492

Hood Edge Height (x_7)

Fig 5 depicts the relationship between drag coefficient (Cd) and hood edge height (x_7). A modest increase in Cd is seen as the hood edge height increases from 565 mm (lower, -1 designation) to 839 mm (higher, 1 designation). This suggests that a higher hood edge boosts air resistance, resulting in added drag. At the minimum elevation, the Cd concentration is about 0.225, whereas at the maximum it is approximately 0.24.

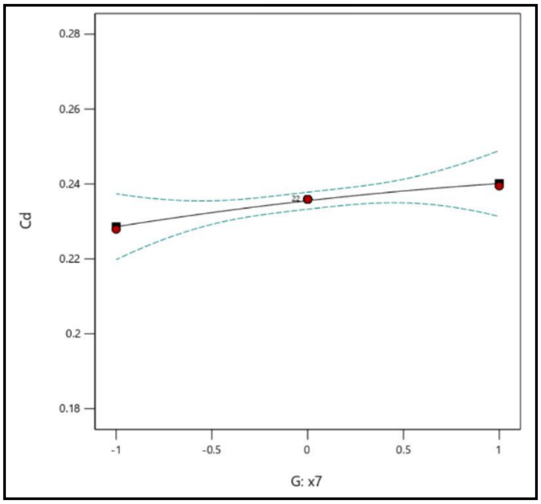

Fig. 5. Single parameter of hood edge height.

The dotted light blue lines indicate the self-assurance interval, exemplifying the scope of potential Cd values, while the black line illustrates the tendency of Cd fluctuations. The real data points are represented as red dots. The graph illustrates that increasing the hood edge height significantly raises the drag coefficient (Cd). This is because a higher hood edge can disrupt airflow, resulting in increased turbulence and resistance, lowering the vehicle's aerodynamic efficiency. It is preferable to maintain the hood edge height lower within an ideal range in order to reduce drag.

A study by Buckfire (2023) found that vehicles with higher and blunter front ends are more dangerous for pedestrians. This is due to the fact that taller, blunter hoods increase the impact zone, which makes injuries more severe, particularly to the hips, torso, and head (Buckfire, 2023). The study also found that flat hoods with angles of 15° or less increase the probability of fatal accidents by 25% compared to sloping hoods. Vehicles higher than 35 inches are riskier because they produce severe head injuries, whereas vehicles with blunt front ends generate more frequent and severe torso and hip injuries.

To summarise, both the graph and the study emphasise that larger hood edges lower aerodynamic efficiency (higher Cd) while simultaneously increasing pedestrian injury chances. Vehicle makers should prioritise lowering hood heights and constructing sloped, aerodynamic front ends in order to increase safety and performance.

Hood Length (x_5)

Fig 6 shows the relationship between hood length (x_5) and drag coefficient (Cd). As the hood length grows from 635 (indicating -1) to 1200 (indicating 1), the Cd trended slightly upward, demonstrating that longer hoods can produce a minor increase in aerodynamic drag. This can be attributed to the fact that

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longer hoods tend to increase the vehicle's frontal area and alter airflow dynamics, leading to higher pressure drag as the flow becomes more turbulent or separated over the extended surface. The black line indicates the Cd trend, whereas the red circles and black squares show simulation data points. The dashed blue lines represent the confidence interval, which indicates the range in which the actual data is likely to fall.

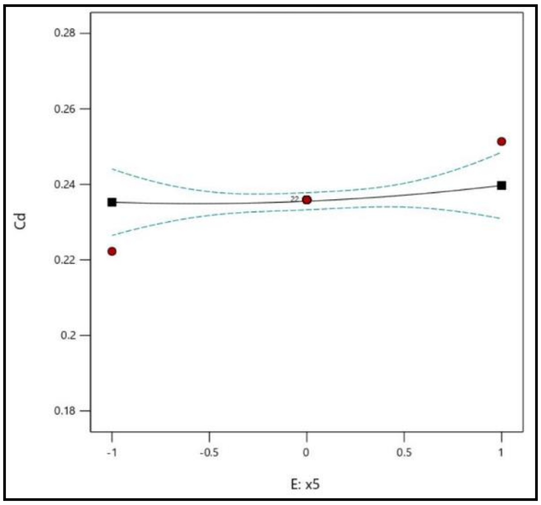

Fig. 6. Single parameter of hood length.

Aerodynamic drag is marginally increased by longer hoods, potentially decreasing efficiency. Hood length should be optimised by vehicle designers to preserve aerodynamic performance without sacrificing safety or structural elements. This discovery corresponds with Fu’s study, which underscores the significance of meticulously engineering vehicle front-ends to minimize aerodynamic drag. Previous studies indicate that altering front features, such as reducing the hood's height or tweaking the angle of the front windshield, can substantially enhance aerodynamic performance (Fu, 2023).

Both the graph and Fu's research unmistakably show that even small incremental changes in the length of the hood or the geometry of the front end will have a measurable impact on how many Cd it produces (Fu, 2023). Optimizing these characteristics improves vehicle efficiency without sacrificing interior room or structural integrity. A simple set of these few tweaks can greatly increase the efficiency and fuel economy of a vehicle.

Bumper Centre Height (x_3)

This graph in Fig 7 shows bumper centre height (x_3) plotted against drag coefficient (Cd), a performance metric that describes the aero efficiency of a car. The results demonstrate that raising the bumper centre height from 435 (low, -1) to 516 (high, 1) gives a slight decrease in Cd. In other words, raising the bumper height could also reduce aerodynamic drag, to some extent.

With the lowest position of the bumper (x_3 = 435), the highest value of Cd is obtained, and the lowest value of Cd is obtained with the highest position of the bumper (x_3 = 516). This trend indicates that a taller bumper centre enables air to flow more freely around the front end of the vehicle, reducing turbulence and thus dragging. The minor curvature of the line indicates a non-linear effect, which means that the impact of bumper height on Cd varies over the range.

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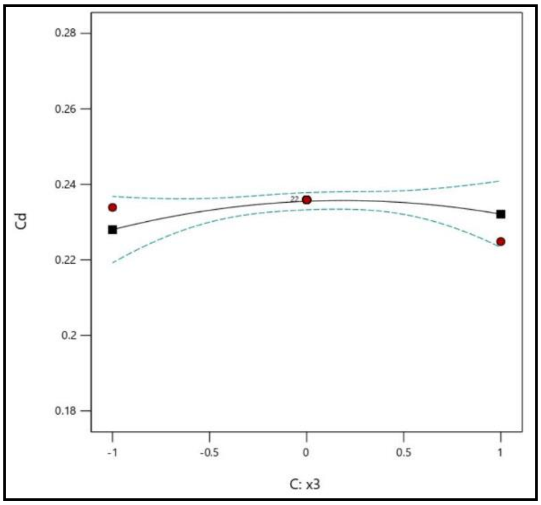

Fig. 7. Single parameter of bumper centre height.

This result is consistent with the graph since it shows how raising the bumper height can improve aerodynamic performance and have an impact on pedestrian safety. However, the study emphasised that impact speed is still the most important element in determining damage severity. To summarise, the graph illustrates the aerodynamic advantages of higher bumper placements, while research by Otte & Haasper (2007) highlights the safety consequences and the trade-off between protecting pedestrians and optimising vehicle design for aerodynamics (Otte & Haasper, 2007).

Windshield Angle (x_1) and Hood Edge Height (x_7)

Fig 8 visually portrays how fluctuations in the windshield angle and the height of the hood edge simultaneously sway the drag coefficient of the automobile.

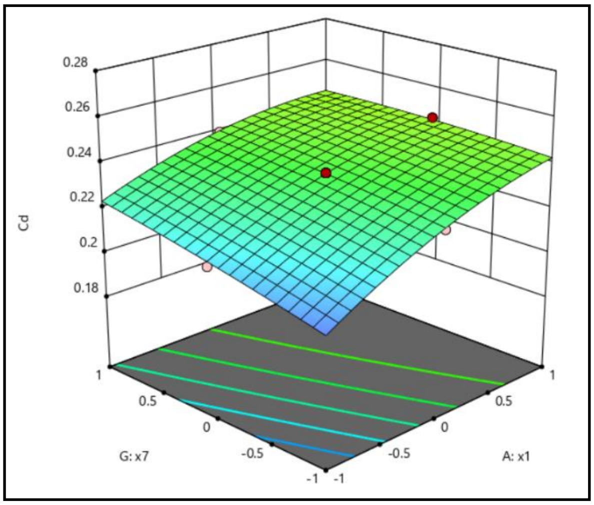

Fig. 8. Interaction parameters between x_1 and x_7.

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The 3D surface plot indicates that the drag coefficient amplifies along with x_1 and x_7, with the green and yellow parts of the graphic exhibiting the maximum amounts. This propensity implies that a more severe windshield angle and an uplifted hood perimeter culminate in considerable disruptions to airflow, ultimately in overstated turbulence and amplified drag.

The low Cd values shown by blue regions in the graph correspond to the minimized values of both x_1 and x_7. This suggests a potentially more favourable aerodynamic condition where the vehicle experiences less persistent turbulent air, potentially reducing drag. Additionally, the contour lines at the bottom of the figure highlight overlapping elements. The contour spacing decreases for increasing x_1 or x_7, indicating a stronger increase in drag. It also validates the synergetic effect of these two parameters on aerodynamic performance as well as the need to improve them jointly to achieve an optimum.

Gangad's research examined the correlation between windshield angle and hood inclination, revealing that the coefficient of drag (Cd) significantly rises when the windshield angle exceeds 45° (Vignesh et al., 2019). This study does not consider the hood edge height (x_7), which is critical for aerodynamic performance.

The Insurance Institute for Highway Safety diligently studied pedestrian fatalities linked to various vehicle designs. Their findings showed that those with hood heights over 40 inches tall brought about approximately 45% more mortalities compared to their more petite peers with hoods of 30 inches or under that sloped gradually. In the study that was carried out by the Insurance Institute for Highway Safety, it was shown that flat hoods, which have a slope of less than or equal to 15°, have a 25% higher risk of fatality when compared to sloping hoods (Insurance Institute for Highway Safety & Highway Loss Data Institute, 2023).

To summarize concisely, reducing the angle of the windshield while simultaneously lowering the hood edge height promotes aerodynamic efficiency while also improving pedestrian safety by weakening potential hazards that could cause injury. This underscores the stark necessity of effectively harmonizing both elements for the purpose of responsible vehicle architectural design.

Bumper Centre Height (x_3) and Hood Edge Height (x_7)

The joint impact of bumper centre height (x_3) and hood edge height (x_7) on drag coefficient (Cd) is exhibited in Fig 9. The 3D surface layout indicates that as x_3 and x_7 increase, the drag coefficient rises, signifying amplified aerodynamic drag. The peak Cd values, signified by the green areas on the graph, emerge when both parameters reach their maximum amounts. As a result of turbulence and compromised airflow, this clearly demonstrates that higher bumper centre and hood edge heights deteriorate aerodynamic performance.

By contrast, the blue regions of the graph indicate lower Cd, which means improved aerodynamic performance. This is done with a minimum of both the bumper centre height and the hood edge height. If the value of these parameters decreases, the turbulence is decreased and the airflow around the vehicle is smoother. This interaction is also highlighted by the contour lines at the base of the plot, as the lines in the lower x_3 and x_7 regions are more widely spaced compared to higher parameter regions, where they are much closer together, indicating that much turbulence and drag is generated.

The study by Matsui et al. (2011) on the impact of vehicle bumper positioning in vehicle-to-pedestrian collisions supports similar findings. The results demonstrate that lower extremity injuries are more likely to occur in bumper side member collisions as compared to centre impacts. Foam materials surrounding the stiff front cross member mitigate the likelihood of tibia fractures in frontal hits, but their efficacy is diminished in lateral impacts due to reduced foam thickness. The frontal configuration of a vehicle influences the risk of ligament injuries, with flat designs such as 1-Box automobiles mitigating these hazards. The research indicates that bumper placements in front of primary longitudinal beams ought to be

https://doi.org/10.24191/jmeche.v22i2.5492

incorporated into automotive safety evaluations to improve pedestrian safety. This underscores the necessity of reconciling aerodynamic efficiency with pedestrian safety in vehicle design. Alterations in vehicle design, including reduced hood heights and the integration of slanted front ends, are an essential necessity to integrate both aerodynamic efficiency and pedestrian safety in the design of the vehicle front end (Insurance Institute for Highway Safety & Highway Loss Data Institute, 2023).

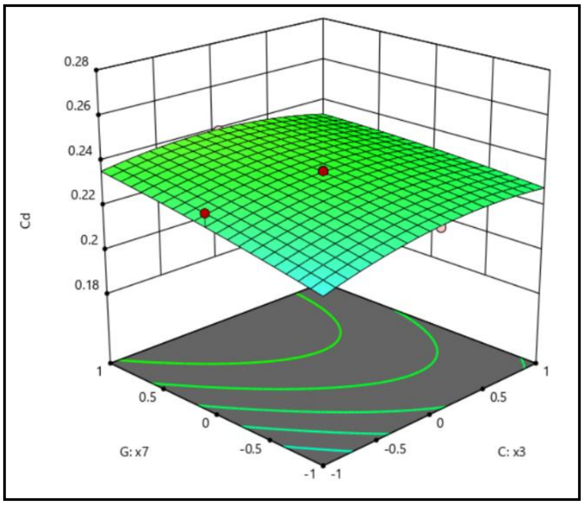

Fig. 9. Interaction parameters between x_3 and x_7.

In summary, both investigations are directly connected to the trends depicted in Fig 9. Increasing bumper centre height (x_3) and hood edge height (x_7) results in elevated aerodynamic drag (Cd) and is associated with heightened pedestrian injury hazards. There is a need to enhance aerodynamic efficiency while ensuring pedestrian safety is not compromised.

Windshield Angle (x_1) and Hood Leading Edge (x_4)

As parameters, the scatter columns in Fig 10 relate to drag coefficient (Cd), windshield angle (x_1), and hood leading edge (x_4). The 3D surface plot shows that when the windshield angle and the leading edge of the hood are both greater, the drag coefficient goes up. This means that there is more aerodynamic resistance. The change can be seen on the surface colour gradient, from blue (low Cd) to yellow-green (high Cd). The results reveal that Cd is sensitive to values of x_1 and x_4; hence, these parameters have to be changed to enhance aerodynamic performance.

At the bottom of the graphic, a contour plot gives some more interesting insights. Drag values were at their lowest when both the windshield angle and hood leading edge height were significantly decreased. With the increase of x_1 and x_4, the contour lines became concentrated, indicating a large quantity of Cd was raised. The point of this visual emphasis was to convey the idea that both parameters need to be reduced to their absolute minimum in order to optimize airflow, reduce drag, and enhance the efficiency of the vehicle. The conclusions presented in Fig 10 are consistent with our hypothesis that these formative aspects have consequential effects on an automobile's aerodynamics.

Numerous studies show similar results, which is reinforced by some relative CFD analysis work conducted (Abdellah & Wang, 2017). Their research suggested that increasing the windshield angle and reducing the overall vehicle height could significantly reduce the car's drag coefficient (Cd). They show that changing both the windshield angle and the shape of the car body improves aerodynamics.

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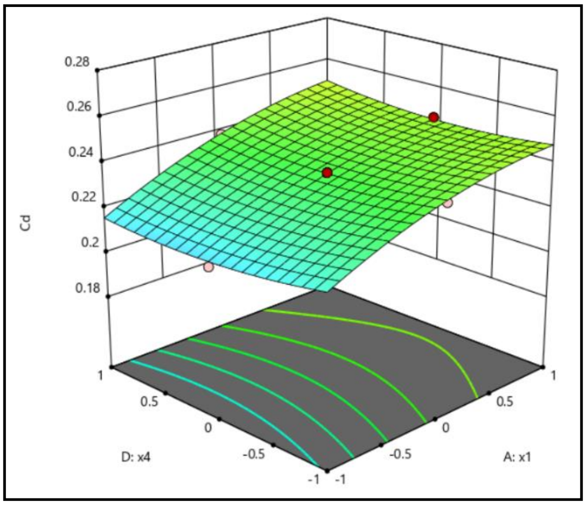

Fig. 10. Interaction parameters between x_1 and x_4.

As a result, both the first analysis and the one in Fig 10 show that the variables related to the angle of the windshield (x_1) and the leading edge of the hood (x_4) need to be changed to make the car more aerodynamic. Lowering these parameters means reduced drag and thus better fuel efficiency and performance. Such insights provided critical guidance while developing future vehicle designs by emphasizing the importance of evaluating both simultaneously to achieve the best aerodynamic performance.

CONCLUSION

This study focuses on optimizing front-end parameters of the vehicle to enhance aerodynamic efficiency. Previous researches have explored interactive parameter analysis in the interest of drag reduction, but none thus far have taken the approach to combine as many as 7 key parameters (Mizuno, 2005) to study its effect on vehicle aerodynamic efficiency. In this research effort, the analysis determined that the windshield angle, hood edge height, hood length, and bumper position were meaningful predictors of drag. The model created within MATLAB exhibited strong accuracy ($R^2 = 0.892$), indicating that the variables chosen did a good job of explaining variance in performance. Moreover, lower root mean square error (RMSE) values suggested that predictions were close to actual data and thus supported the approach used in the present work.

Windshield angle (x_1), hood edge height (x_7), hood length (x_5), and bumper centre height (x_3) were some of the individual values that were pinpointed in the single and interactive parameter analysis as important parameters for aerodynamic performance. This underscores the importance of optimizing these parameters to reduce drag. Collaborating with car makers would help make practical strides to enable more optimized vehicle designs with enhanced aerodynamic performance. This research outcome greatly stresses the importance of built in vehicle design factors to improve aerodynamics efficiency instead of merely relying on external add on features commonly used to reduce drag. External fixtures such as rear spoilers, vortex generators, and diffusers have been widely used to enhance airflow and minimize drag (Palanivendhan et al., 2021). However, these add-ons often compromise aesthetic integration and may not provide consistent aerodynamic benefits across varying conditions. In contrast, past studies such as those by Gao (2023), Fu (2023), Matsui et al. (2011) and Abdellah & Wang (2017) have investigated certain built-in frontal profile features, including hood curvature and bumper inclination in efforts to reduce drag

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and improve vehicle performance. However, their scope was limited to only a few parameters. This study extends that approach by examining a more comprehensive set of seven built-in front-end design variables, offering a broader and more detailed understanding of how integrated design modifications can contribute to aerodynamic efficiency.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders. One of the authors, Kausalyah Venkatason is a section editor of the Journal of Mechanical Engineering (JMechE). The author has no other conflict of interest to note.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: **study conception and design**: A.N., K.V.; **data collection**: A.N.; **analysis and interpretation of results**: A.N., K.V., S.S.; **draft manuscript preparation**: A.N., K.V., S.S. All authors reviewed the results and approved the final version of the manuscript.

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