Design and Integrating Aerodynamic Analysis of Car Side Mirror and Manufacturing Through Fused Deposition Modeling

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Abstract

The shifting automobile industry has resulted in important changes in the approaches and processes for producing a variety of products. As we move forward, the world is pivoting towards 3D printing, moving beyond traditional approaches. The production of a large number of new elements makes it difficult to uphold older designs and to create customized offerings with lower time and cost. The purpose of this research is to combine aerodynamic simulation with fused deposition modeling to improve the design and fabrication of automotive side mirrors and to increase their aerodynamic performance and structural integrity. This research aims at developing a hybrid conceptual model that integrates the simulation to enhance sustainable manufacturing breakthroughs within the automotive Industry. SolidWorks was used to develop the Models with the 0.02m, 0.04m, and 0.05m of width were examined to observe the overall increase and decrease of drag at 60 kph of velocity. 0.03m is the width of the conventional model, which is analyzed through Ansys Fluent Computational Fluid Dynamics (CFD) software. The findings of this research show that the combination of aerodynamic analysis with fused deposition modeling remarkably improves the design and function of automotive side mirrors, leading to better aerodynamic performance and 17 % less drag force on the optimized Model with a 0.02m width. The research demonstrates that advanced manufacturing methodologies hold the promise to enhance vehicle elements, creating a solid base for more environmentally friendly and efficient designs.

Keywords—Mirror optimization, Fused Deposition Modeling, Additive Manufacturing, 3D Printing, Polylactic acid (PLA)

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1 Introduction

Aerodynamics is a key component in improving fuel economy, which is something that the new car projects aim to achieve [1]. There are substantial hurdles for the automotive industry in maximizing vehicle aerodynamic performance, particularly associated with external elements, including side mirrors. Side mirrors may be necessary for both safety and visibility, but they are responsible for close to 5% to 10% of a vehicle's total aerodynamic drag [2]. This impacts negatively on fuel consumption and simultaneously contributes to carbon emissions, which is an important problem in the push for significant sustainable initiatives [3]. Another possibility is to decrease the car's resistance to motion through the air. When the speeds become more than 37 miles per hour (60 kilometers per hour), the drag plays a significant role. Numerous components of the vehicle contribute to the drag. Car side-view mirrors are an example of such a component [4]. There have been a wide variety of mirror designs and criteria that have been investigated. Olsson [4] discussed a variety of side mirror models with varying housing curvature, gap, reference mirror, as well as the car without a mirror, and concluded that there is a reduction of drag due to up wash effect. Olsson also conducted a study that concentrated on the various side mirror components that influence aerodynamic drag. The side mirrors of a Mercedes-Benz A-Class from the first generation of 2000 were simulated. According to CFD data, side mirrors add 0.012 to the drag coefficient. The flow rate was 50 m/s, and the turbulence severity was 0.01%. As aerodynamic drag

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is largely shape-dependent, a more streamlined body shape can help reduce it. Approximately 45 percent of an automobile's total aerodynamic drag is exerted on its upper half. The side mirror is an example of an upper-body part that adds unnecessary resistance. Because of its shape, a turbulent wake is created behind the side mirror if the body is not streamlined [5]. Researchers have worked to find out the effect of mirror drag on the fuel economy within the city as well as on the highways. Since most highway travel is done at a constant cruising speed, it seems reasonable that this type of travel would result in better fuel economy [6]. Furthermore, a flat back mirror and a hemispherical rear mirror, both 13 centimeters in diameter, were taken into consideration. At 60 and 120 kilometers per hour, the drag coefficient was calculated analytically. Fuel savings of 7.33 and 29.3 liters per year can be preserved with the hemispherical rear view mirror due to its reduced aerodynamic drag [7]. Classic design techniques typically do not completely make use of advanced computational tools to boost aerodynamic performance, which leads to subpar designs, neglecting the complexities in airflow around side mirrors. On top of that, the fabrication processes for these components may not take advantage of modern additive manufacturing techniques, including fused deposition modeling (FDM), which allows for creating lightweight and complex geometries unattainable with conventional methods [8, 9]. Despite the possible advantages of meshing aerodynamic analysis with FDM, there continues to be a hole in thorough methodologies that successfully connect these techniques to better the design and manufacturing of automotive side mirrors. Lacking these types of integrated strategies limits innovation and the realization of more efficient, sustainable automotive designs [10]. Undertaking aerodynamic analysis along with fused deposition modeling (FDM) for the production of car side mirrors requires attentive optimization approaches across a variety of domains. Latest developments in computational fluid dynamics (CFD) have permitted exact simulations of airflow around side mirrors, helping to uncover ideal shapes and angles that greatly reduce drag, promoting improved fuel efficiency [11]. The ability to do rapid prototyping through the iterative approach of CFD helps lower material waste and production expenditures by enabling the examination of a variety of designs before initiating physical production. FDM delivers exclusive advantages in the fabrication of complex shapes that traditional manufacturing methods cannot achieve. There is a strong relationship between the structural integrity, surface quality, and the important optimization of print parameters, including layer height, infill density, and toolpath strategies [12]. Choosing the right materials carries great importance; using light materials that are tough leads to higher performance and satisfies safety requirements. Newly published research underscores the essential requirement to bring together sustainable approaches, particularly the application of recycled materials in FDM processes, to reduce environmental effects. A framework that fuses aerodynamic analysis with innovative manufacturing methods will enhance side mirror performance and also support larger sustainability efforts within the automotive industry [13]. Managing drag effectively and boosting fuel efficiency depend heavily on aerodynamic performance, and new research highlights the role that mirror shape and positioning play in airflow management. These days, advanced computational fluid dynamics (CFD) simulations are routinely used to enhance these parameters, which allows for the evaluation of several designs under real driving situations [10].

Advancements on the FDM end, specifically in materials science or polymers and composites, have allowed the creation of lightweight but very strong side mirrors. Authors have described various filament types they have considered, including carbon fiber reinforced polymers that enable a reduction in weight while also increasing stiffness and damping at the same time. Furthermore, due to the versatility in the design freedom of FDM, one can manufacture intricate phenomenal shapes that may lead to better aerodynamics [13]. The aerodynamic analysis with FDM is noted in the current literature to present synergistic opportunities in that it opens the possibility of iterative design cycles that improve both design performance and manufacturability. Thus, the use of this holistic strategy helps manufacturers produce side mirrors that meet regulations and consumer preferences for design and functionality. The unity of technology is outlining a direction for better automotive parts to give optimization in the automotive market [14].

Recent innovation in conventional car side mirrors manufactured through FDM has pointed out PLA as a viable option. The thermoplastic called attention PLA is globally used due to its eco-friendly characteristics and operational processing from corn starch and other renewable materials. In the past five years, they have focused on enhancing the mechanical properties and thermal stability of PLA to meet the severe requirements of the automotive sector. Combined with Glass fibers and other nanoparticles, the tensile strength, toughness, and thermal degradation temperature of PLA can be substantially increased. These improvements are important for side mirrors, which are subjected to dynamic loads and changes in temperature during the use of the vehicle. Moreover, RL contained in PLA contributes to decreasing vehicle weight, while it is a unison with the industry desire for increasing fuel efficiency [10, 12].

Computer analysis performed on the PLA side mirrors has indicated that the aerodynamic strategy can work effectively when optimized through CFD [15]. Research shows that the greater detail of the geometric design helps in increasing the performance of the vehicle by lowering the drag coefficients. This is a key driver for acceptance because patterns of surface treatments, such as coatings for UV stability and cosmetic appearance, all conform to PLA [16]. New discoveries presented here reveal that an LCA is useful when choosing material, and note that PLA is environmentally favorable because of its higher durability than ABS or polycarbonate. However, the integration of aerodynamic analysis with material science forms a strong possibility of tweaking PLA formulation, which makes PLA a worthy candidate for automobile components of the future. While the sector is transitioning toward sustainable solutions, the role of PLA in providing design and manufacturing of car side mirrors for future improvement is being positioned for further development [17].

A mathematical and computational model has been performed in this regard to analyze the drag value and the use of PLA. Suzuki Alto 660-CC is the subject of this discussion, and specifically the mirror of the car. The study further reveals that even slight changes in the design of edges and modifications to the radius or inclination of the edges, as well as the addition of gutters and edges, width, all affected the flow of air around the mirror of the vehicle. Such technology enables us to create physical prototypes at high speed, in particular based on the information from the computer-aided design (CAD). Also, AM does not require the standard tools or code that are required in other conventional manufacturing processes. Additive manufacturing is an industrial process of making three-dimensional items from digital files containing information that shows how items should be built [18-21]. This is in contrast to the traditional manufacturing technology, which is typically known as subtractive manufacturing. In recent years, a number of low-cost and accessible FDM printers have been designed, manufactured, and made available for purchase on the market. These machines are able to produce a variety of thermoplastic prototypes. FDM, or fused deposition modeling, is one of the most popular technologies in additive manufacturing (AM) because of its ability to rapidly build three-dimensional solid objects with complex geometries [22-24]. The merits of FDM are that it is easy to change the material, that it can be operated without supervision, that it is inexpensive, that it minimizes size, and that it operates at a low temperature [25]. Despite the fact that FDM is mostly utilized for prototyping, the possibility of applying the process has further improved. This is due to the gradual development in procedural and material aspects. The parts must possess adequate mechanical qualities before they can be used in production. However, increasing the product's mechanical performance typically results in a reduction in printing speed, as well as an increase in the cost and the level of quality [26, 27]. Thickness, raster angle, build orientation, and air gap are some of the process characteristics that can affect the mechanical properties, surface polish, and geometric precision achieved by the FDM process [28]. The number of people using 3D printers has increased tremendously in recent years, and there is every indication that this trend will carry on for some time to come. The prototyping stage of a product's development, as well as the stage of manufacturing the same product, can both benefit from the utilization of a 3D printer. To make a wide variety of items, which can include anything from components needed in the automotive field, a 3D printer is being used.

The purpose of this research is to combine aerodynamic simulation with fused deposition modeling to improve the design and fabrication of automotive side mirrors and to increase their aerodynamic performance and structural integrity. This research aims at developing a hybrid conceptual model that integrates the simulation to enhance sustainable manufacturing breakthroughs within the automotive Industry

2 Materials and Method

2.1 Material

The combination of its light properties and its chemical resistance, alongside good dimensional stability, qualifies it as a suitable choice for several automotive parts. PLA's simplicity of printing, as well as its relatively affordable price compared to additional engineering thermoplastics, make it more attractive. Consequently, it could also be observed that PLA has the advantage of being biodegradable. This is carried along with the growing trend of sustainability in the automobile market and has potential for lowering ecological impacts. Nevertheless, the temperature sensitivity and the possibility of UV degradation make it difficult to use in high-stress and outdoor conditions. However, there are certain restrictions on the application of PLA in automotive manufacturing, such as limitations to the size and function of the parts being produced and the part geometries that can be produced using PLA; effectively, the applicability and versatility of PLA in automotive manufacturing appear to be increasing with its use in interior and exterior panels.

PLA can be used to design dashboards in panels, door panels, center console, car side mirrors, and air vents in the interior environment. It is for this reason that the vehicle will be lighter, and its fuel efficiency and emissions will be better. Moreover, due to the plurality of shape and pattern-making abilities, PLA can corroborate the formation of exclusive and modifiable indoor aesthetics.

For exterior application, it makes it possible to produce things like grills, spoilers, and trim pieces from PLA. This means that its tiny form might well enhance the vehicle's aerodynamics and lead to a reduction in fuel consumption. Due to the essential requirement for prolonging the longevity of its UV sensitivity, some form of protection or sealant might well be required. In operational applications of plastics, PLA finds applications in the auto industry, like under-hood components, connectors, and housing. The chemical resistance means it's well-suited for components that touch oils, greases, and other liquids within the automotive field. On top of that, the dimensional stability of PLA means that components do not change their shape or stop functioning over time.

Polylactic acid (PLA) is the most frequently used material in 3D printing processes. Lactic acid is the source of the biodegradable polymer known as PLA. The best thing about this material for 3D printing is how easy it is to use and how well it works [29]. It needs a lower temperature to extrude than ABS; it does not distort much when it is being printed, and it sticks well to the platform, so it does not need a heated base. Neither does it smell bad nor give off dangerous fumes when printing, unlike ABS. PLA tends to wrap at temperatures above $60°C$. The glass transition temperature of PLA is $60-80°C$ [30-32].

PLA was chosen as the prototype since it is dimensionally stable, printable, and good for testing geometry, and it fits within a short period of time. Nevertheless, the low glass-transition temperature, combined with the low UV resistance, of PLA does not make it suitable for a long-term outdoor application, particularly in the automotive sector, where the parts must be exposed to direct sunlight, high temperatures, and weathering. To this end, side-mirror housings are normally manufactured in the form of production-ready units based on materials like ABS or ASA, which have higher capabilities of withstanding heat, greater impact strength, and enhanced UV stability properties vital in ensuring durability and safety in the real world.

TABLE 1: Polylactic Acid Properties

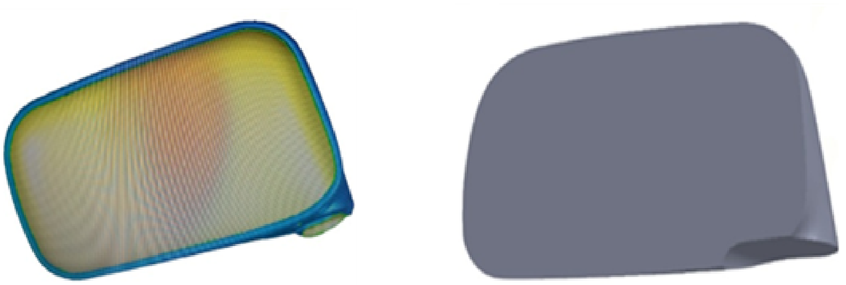
Physical Properties	Polylactic Acid
Tensile Strength	21–60 MPa
Density	1.21–1.25 g/cm3
Ultimate Strain	2.5–6 %
Glass Transition Temperature	60–80 °C
Melting Point	150–162 °C

2.2 Methodology

A thermal scan, as shown in Figure 2(a), was performed on the side mirror of the automobile (Suzuki Alto 660 cc) in order to determine the exact surface dimensions of the 3D conventional model. National Institute of Design and Analysis (NIDA), Lahore, carried out 3D model scanning. For this purpose, NIDA used a 6-axis Baces3D M100/6 scanner, which has the accuracy of ±0.060mm. Furthermore, NIDA converted the traditional model into a stereolithography (.stl) data file so that further investigation could take place. A 3D scanner is capable of digitally capturing a wide variety of surface types, including free-form surfaces, progressively altering profiles, and curved component shapes. 3D scanning was performed on the geometry of these components so that information could be obtained concerning cluster spots. The software offers a technique for accurately surfacing three-dimensional digital models, which paves the way for reverse engineering, product design, rapid prototyping, and analysis based on three-dimensional scan data utilizing polygon meshes.

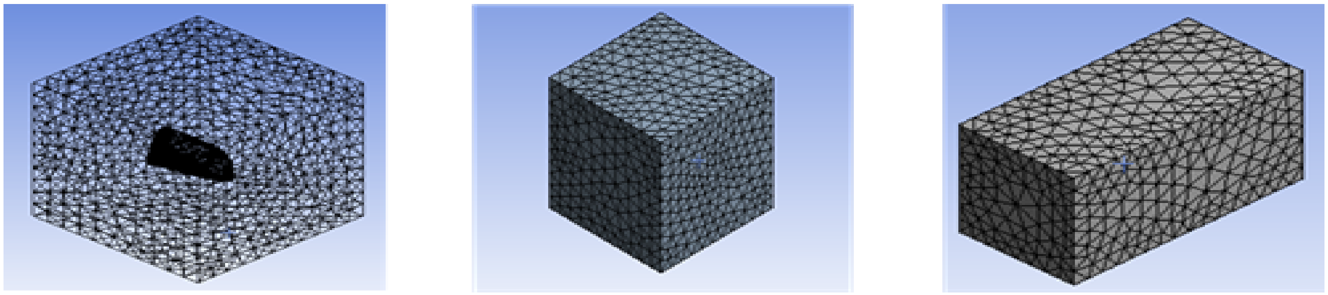
Some holes or other geometric flaws in the CAD model were discovered during the 3D scanning of the standard model. To gain complete access to the model and to achieve optimal outcomes, we must eliminate any imperfections and seal the hole in the CAD model. The tetrahedron mesh type was used to analyze the models (Figure 3), as this is most suitable for curved surfaces. Conducting mesh independence research is one way to find out if the simulation findings were autonomous of any particular mesh by running numerous simulations with different mesh resolutions and checking to see whether the results change. This kind of research is crucial for understanding the fundamentals of the CFD simulations together with the underlying mathematics. One can perform a mesh independence analysis to discover whether the mesh density affects the outcomes.

The numerical simulations employing the SST K-Omega model, also known as the SST K-Omega two-



(a) Scanned model (b) 3D Model after CAD clean up

Fig. 1: Scanned and 3D Model after CAD clean up



(a) Mirror body Meshing (b) Internal Fluid Domain Meshing (c) External Fluid Domain Meshing

Fig. 2

equation model, are best suited for higher air volume flow rates and the flow near the walls, particularly in aerodynamics. The two-equation SST k-omega turbulence model, which simulates eddy viscosity, has several applications. The Wilcox k-epsilon and k-omega models are combined in this hybrid model. The blending function activates both the k-epsilon model within the free stream and the Wilcox model near the wall. Below is a list of the equations for the SST K-Omega turbulence model. The equation for Turbulence Kinetic Energy is as follows.

$$\frac{\delta k}{\delta t}+U_j\frac{\delta k}{\delta t}=P_k-\beta^* k\omega+\frac{\delta}{\delta x_j}[(v+\sigma_k v_T)\frac{\delta k}{\delta t}] \tag{1}$$

The Specific Dissipation Rate is as follows.

$$\frac{\delta\omega}{\delta t}+U_j\frac{\delta\omega}{\delta x_j}=\alpha S^2-\beta\omega^2+\frac{\delta}{\delta x_j}[(v+\alpha_\omega v_T)\frac{\delta}{\delta x_j}]+ 2(1-F_1)\sigma_\omega^2\frac{1}{\omega}\frac{\delta k}{\delta x_i}\frac{\delta\omega}{\delta x_i} \tag{2}$$

Equation 3 shows the F1 Blending Function as follows:

$$F_1=tanh\{\{min[max(\frac{\sqrt{k}}{\beta^*\omega y},\frac{500v}{y^2\omega}),\frac{4\sigma_\omega^2 k}{CD_{k\omega}y^2}]\}^4\} \tag{3}$$

Note: F1 $=$ 1 inside the boundary layer and 0 in the free stream $CDk\omega$

$$CD_{k\omega}=max(2\rho\sigma_{\omega^2}\frac{1}{\omega}\frac{\delta k}{\delta x_i},10^{-10})$$

Equation 4 represents the Kinematic Eddy Viscosity:

$$v_T=\frac{a_1 k}{max(a_1\omega,SF_2)} \tag{4}$$

Equation 5 represents the Second Blending Function.

$$F_2=tanh[[max\frac{2\sqrt{k}}{\beta^*\omega y},\frac{500v}{y^2\omega}]^2] \tag{5}$$

Finally, equation 6 describes P_k (Production Limiter), as follows:

$$P_k=min(\tau_{ij}\frac{\delta U_i}{\delta x_j},10\beta^* k\omega) \tag{6}$$

Model C, which is the desired model, is printed by the Ender 3 Max 3D printer as shown in Figure 3. Nozzles possess an opening of 0.01mm and print at $140-150°C$ while bed temperature reaches $60°C$. Meanwhile, slicing was done using the Cura engine.

Fig. 3: Optimized 3D printed model

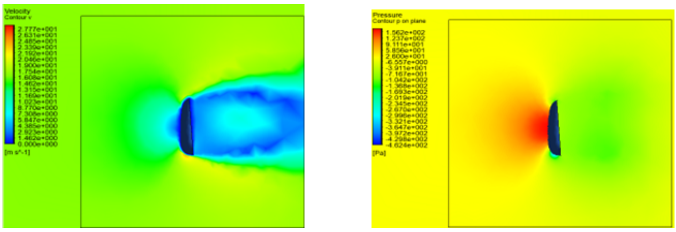
3 RESULTS AND DISCUSSIONS

The findings and the discussion on the same in this study delve into the important implications of merging aerodynamic analysis with manufacturing potentials provided by fused deposition modeling (FDM). The research mainly aims at investigating and optimizing the aerodynamic performance of side mirrors of cars, using computational fluid dynamics (CFD) simulations to study airflow patterns, drag minimization potential, as well as the effect of the model width variation on the aerodynamic performance. Later production using FDM underlines the feasibility and accuracy that can be applied to make prototype aerodynamic mirrors. Here, the accuracy and reliability of CFD predictions are exhaustively discussed, and so are the feasibility, material performance, and surface finish aspects that come with prototypes produced via FDM. In general, the combination of CFD, width variation investigations, and FDM has good potential to increase the vehicle aerodynamic efficiency, and they also provide cost-effective, customizable, and fast prototyping solutions that can be applied to the automotive industry.

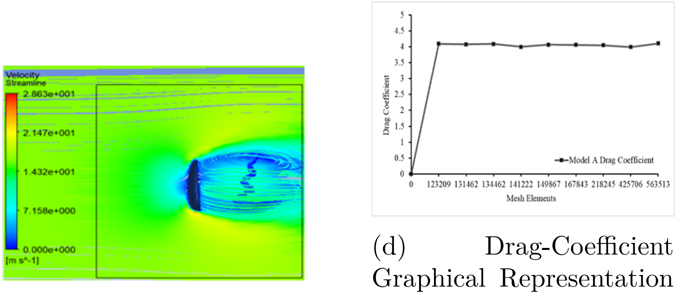
The speed of the simulation of 60 km/h was chosen because it includes the conditions of the most common urban driving, as vehicles spend a significant part of their working time. This rate gives a realistic foundation in validation of design models, to enable realistic evaluation of major aerodynamic properties of the models, including boundary-layer development, wake behavior, pressure distribution, and numerical stability. Whereas the aerodynamic drag increases more significantly in the higher speed range, the given work aims at confirming the base aerodynamic performance in the conditions of commonly used city operating conditions, and longer simulations on the case of increased highway speeds will be conducted in the future.

TABLE 2: Dimensions of all models

Parameters	Model A	Conventional model	Model B	Model C
Length	0.1524m	0.1524m	0.1524m	0.1524m
Height	0.1143m	0.1143m	0.1143m	0.1143m
Width	0.02m	0.03m	0.04m	0.05m



(a) Pressure contour (b) Velocity contours



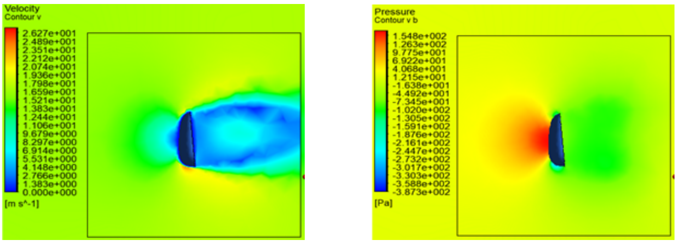
(c) Streamlines (d) Drag-Coefficient Graphical Representation of model A

Fig. 4

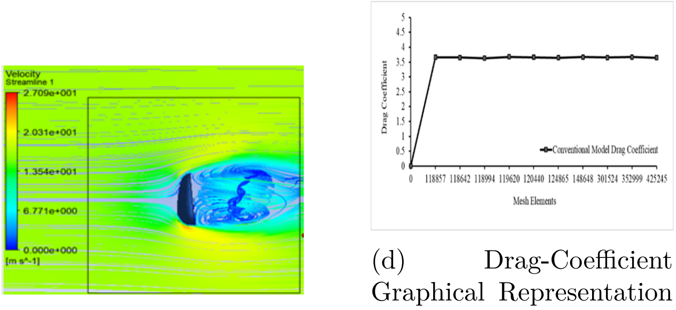
The pressure contour, velocity contours, as well as the streamlines profile of a model A at 16.67 m/s are shown in Figure 4. Peak pressure has increased as the width of the model is reduced compared with the conventional model. Streamlines represent that the velocity has increased from the edges. With the increase in the number of elements, the value of drag is keeping it self-constant, which means that even after decreasing the mesh size, there will be no effect on the value. 4.06 is the average value of drag from this study.

The pressure contour, velocity contours, as well as the streamlines profile of a Conventional side mirror at 16.67 m/s are shown in Figure 5. Whenever the flow approaches the front wall of the mirror, the standard mirror displays high pressure, which slows down the air flow and lessens the separation of the boundary flows. 3.65 is the average value of drag generated from this study.

The pressure contour, velocity contours, as well as the Streamlines profile of model B at 16.67 m/s are shown in Figure 6. Streamlines represent that the velocity has decreased from the outer surface, which represents the smoothness of the body, as well as the

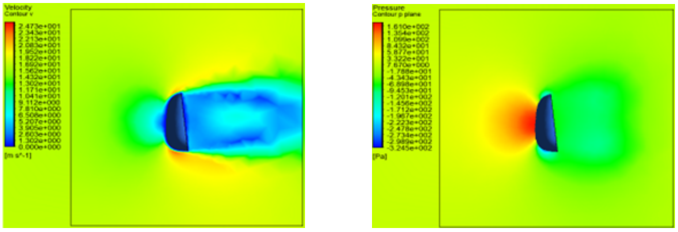


(a) Pressure contour (b) Velocity contours

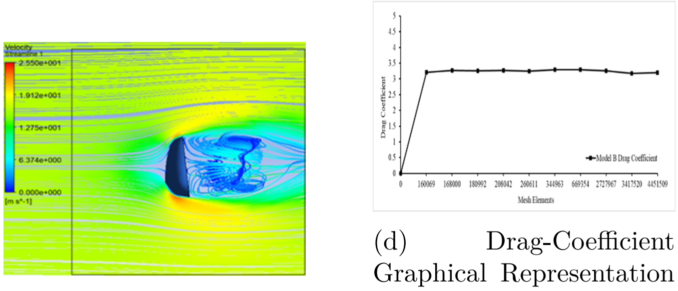


(c) Streamlines (d) Drag-Coefficient Graphical Representation of conventional model

Fig. 5



(a) Pressure contour (b) Velocity contours

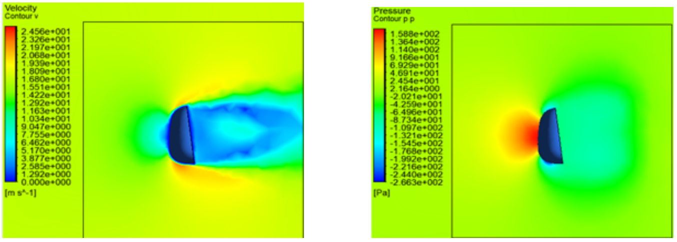


(c) Streamlines (d) Drag-Coefficient Graphical Representation of model B

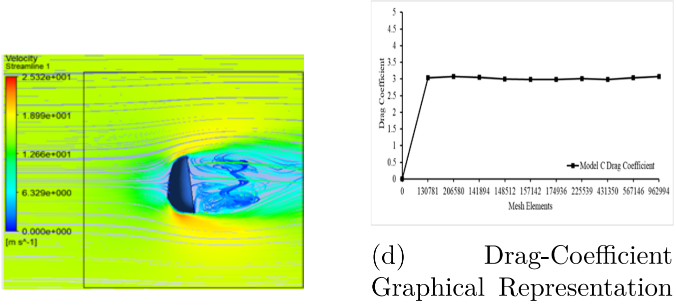
Fig. 6

drag coefficient, which is reduced to 3.24, which is the average value of drag collected from the concerned study.

The pressure contour, velocity contours, as well as the Streamlines profile of model C at 16.67 m/s are shown in Figure 7. Streamlines represent that the velocity has decreased from the outer surface, which represents the smoothness of the body, as well as the drag coefficient, which is reduced considerably, and



(a) Pressure contour (b) Velocity contours



(c) Streamlines (d) Drag-Coefficient Graphical Representation of conventional model C

Fig. 7

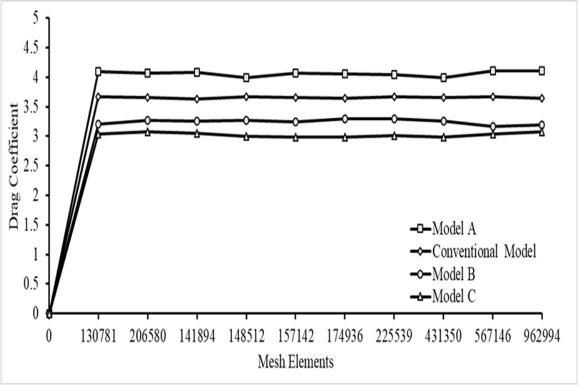


Fig. 8: Comparative analysis of all models

3.02 is the average value of drag, which is collected from the concerned study.

Figure 8 shows the comparative graphical representation of the drag coefficient. This clearly indicates that the drag value of model A is more than the reference or the conventional model; model B is on a low level of drag, but the most suitable and satisfying model is model C, which possesses the least drag coefficient value.

This graphical representation (Figure 9) illustrates the percentage increase and decrease in the value of drag-coefficient. The drag-coefficient of model A is 11.12% more than that of the conventional model. On the other hand, the drag coefficient of model B is 11.14% less than that of the conventional model. At last, model C decreases the drag coefficient by 17.28%

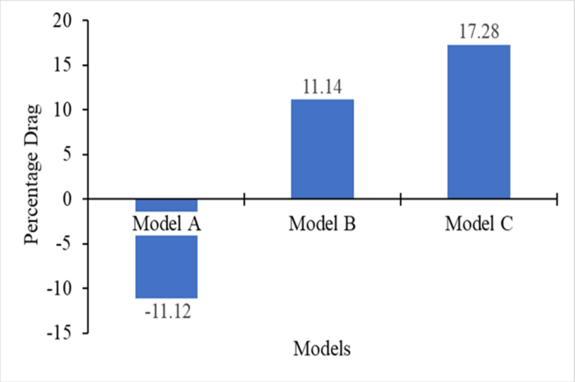


Fig. 9: Percentage improvement

with respect to the conventional model.

4 CONCLUSION

The purpose of this research was to develop, improve, and manufacture a side mirror for a Suzuki Alto 660CC utilizing fused deposition modelling with PLA. The research was conducted at the University of Engineering and Technology in Lahore, Pakistan. This study was made achievable by simulating multiple models of side mirrors based on their potential to reduce drag, the complexity of their design, the functionality of their design, the cost of their design, and the endurance of their design. After completing three CAD models in SOLIDWORKS, they were imported into ANSYS, where constant speed was used to conduct the analysis. At first, a regular model was printed out with 3D printing software and used. In the end, one particular optimal design was selected for continued development based on a number of criteria, including the possibility for manufacturing, usefulness, affordability, and weight. During the course of the examination of several models, the following findings were discovered. Model A is a reduced model, which, in comparison to the normal model, results in an eleven percent increase in the overall drag. The improved model B, which lowers the drag by 11%, is denoted by the letter B. The model C is the one that has been determined to be the most optimal, and a drag drop of 17% has been noted; this will contribute to improving the overall performance of the vehicle.

- Model A is a reduced model that increases the overall drag by 11% compared with the conventional model.
- Model B is an optimized model that reduces the drag by 11%.
- Model C is found to be the most optimized one, and a drag drop of 17% is observed, which will contribute to enhancing the overall performance of the vehicle.

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