

Study of the Effects of Shape, Microstructure, and Surface Coating on the Aerodynamics of Automobiles

Yiliang Zhang *

Anglo-Chinese School International, Singapore

* Corresponding Author Email: yiliang.zhang@acsinternational.edu.sg

Abstract. With the increase of global car sales, total energy consumption rose dramatically. Therefore to prevent severe energy crisis, reduction of the total consumption through improving the efficiency of energy usage is needed. This research paper aims to investigate how the aerodynamics of cars can be influenced by three key factors: shape, surface texture, and surface coatings. Through improved aerodynamics, the efficiency of fuel usage will be increased, thereby reducing the consumption of energy. In general, optimising the shape of the vehicle is able to produce the highest drag reduction rate as compared to surface texture and surface coating, this paper studied how adjusting the shape of the vehicle is able to change the drag coefficient. The paper discussed how surface texture designs are inspired by animals in nature such as sharks and cheetahs, and discussed how the types of surface coatings affect the aerodynamic performance of the vehicle as well.

Keywords: Aerodynamics; Drag; Design; Shape; Microstructure; Surface coating.

1. Introduction

Since the start of the 21st century, the volume of automobile production and purchase reached a height which has never been achieved. In 2024, the automobile market sold 88.3 million automobiles globally. In comparison with the volume in 2023, it has increased by 2.8% [1]. This figure has been boosted by the recovery of the economy after the huge impact of the global pandemic. While 88.3 million cars have been produced and sold, only 25 million cars have been scrapped in 2024, indicating that the volume of automobile stock has increased by over 60 million cars in 2024 [2]. With the large increase in the volume of cars, problems arise road safety, air pollution, and most importantly, in terms of environmental concern, the energy crisis led by large energy consumption.

In order to reduce energy usage, increasing the efficiency of fuel used is the main problem to tackle. One way of approach is to reduce the aerodynamic drag.

Aerodynamics is perhaps the most well-known factor in terms of determining the performance of a vehicle. It represents one of the most difficult, yet fundamental problems for vehicle designers. Aerodynamics influences the design of a wide range of products — from commercial aircrafts and vehicles, both on-land and aquatic, to wind turbines. In the context of vehicles, drag reduction directly correlates with enhanced performance for both on-land and aquatic vehicles. It improves fuel efficiency as well, which results in reduced energy usage thus environmental impact. In terms of wind turbines, reducing the drag means that the blades are able to obtain a larger volume of energy.

An important concept in aerodynamic and fluid mechanics is the boundary layer theory, proposed by Ludwig Prandtl (1875-1953), father of modern aerodynamics [3]. The boundary layer is a thin region of fluid which is adjacent to a surface that plays an important role in determining the aerodynamic characteristics. Within this layer, the velocity increases from zero at the surface (under no-slip condition), to the original value of flow. The boundary layer has two behaviours, laminar and turbulent, they both affect the value of drag. Laminar boundary layers are smooth with low skin-friction drag but separation happens earlier. Turbulent boundary layers are the opposite, high friction, but delays separation. The factor that determines how the boundary layer behaves is influenced by shapes, surface texture and microstructure, and material of the surface coating.

Furthermore, as mentioned above, microstructure and texture of the object also influence the value of drag force. At the microscopic scale, engineered textures can manipulate the boundary layer, delay

flow separation and reduce skin-friction drag. Scientists have taken inspiration from nature, for example, riblets inspired by shark skin have been shown to lower drag by 6-8% in aircraft testing [4].

Besides these, material of the surface coating influences the aerodynamics of the object as well. It changes the wettability, roughness, and varies the energy dissipation at the boundary layer. With smooth, low-friction coatings, it reduces the skin-friction drag.

Therefore, the aim of this report is to discuss the effects of shapes, surface texture and microstructure, and material of the surface coating on the aerodynamics of vehicles, specifically automobiles, and future development and challenges in the field of aerodynamics, in terms of the overall design and specific, fine adjustment to the current models of vehicles.

2. Impact of Shape on Aerodynamics

2.1. Overall Concept

According to the Drag's Equation [5]:

$$W_D = \frac{1}{2} \rho v^2 C_D A \quad (1)$$

For above equation, W_D is drag (N), ρ is the density ($kg\ m^{-3}$) of the medium, v is the velocity ($m\ s^{-1}$) of the airflow, C_D is the drag coefficient, A is the reference area (m^2). The direct correlation of C_D to W_D can be identified. For example, the C_D of a sphere is found to be between 0.07 to 0.5 [6]. When the drag coefficient increases, the value of drag, the force acting in the direction opposite the motion, increases. This means that the shape with the lowest C_D would be the most aerodynamic shape, which allows the maximization of efficiency. Therefore, Ludwig Prandtl, again, spent time and effort, and discovered that elongated, teardrop shape produces the least amount of drag in the early 1900s, based on his boundary layer theory. The C_D of this shape is found to be 0.045 [6]. Bringing the theory to reality, Paul Jaray (1899-1974) applied this theory in automobile designing.

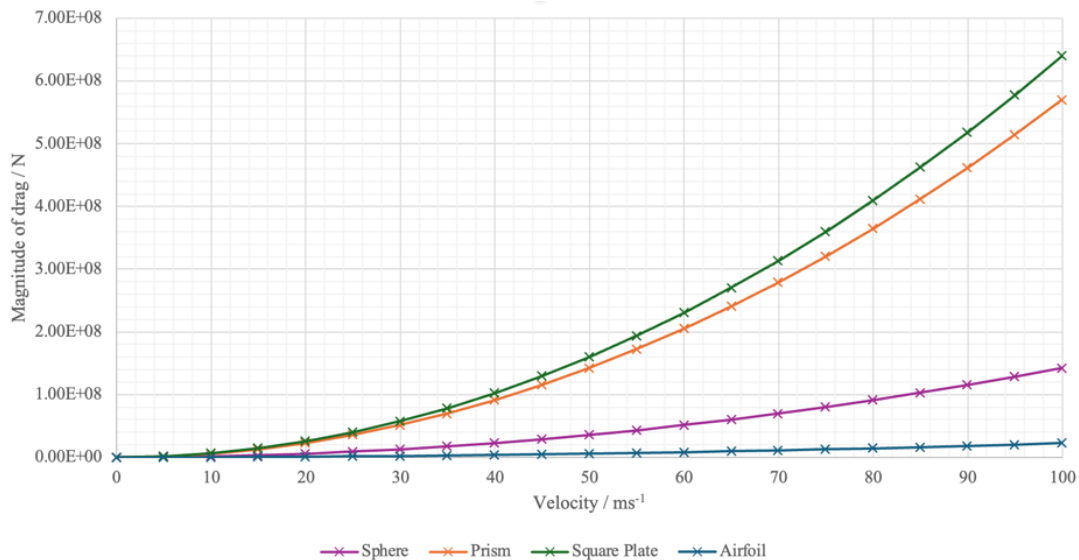


FIG. 1 Graph of magnitude of drag (N) against velocity (ms^{-1}) [7, 8].

FIG. 1 compares the drag force produced under different velocities. The plot of airfoil shows the least drag produced at all speeds, when the value of frontal area and density of air are kept constant.

The most fundamental drag-reduction strategy in automotive aerodynamics is to use streamlined design. Following the Drag's Equation, where C_D depends primarily on body shape. A bluff car body ($C_D \approx 0.38$) [7] has a larger separated wake than a streamlined car body ($C_D \approx 0.24$) [8], as the streamlined car body is able to delay the flow separation, and narrow the low-pressure region. As compared to cars with sharp edges, cars which have smoothly curved roofline and tapered rear, the airflow stays attached near the surface longer for the latter, reducing pressure drag.

2.2. Common Refinements to the Aerodynamics

2.2.1. Leading Edge Treatment

At the front end of a car, by adjusting the leading edge (hood, windshield), it is able to reduce stagnation pressure and prevent early separation of airflow. The equation for stagnation pressure coefficient is [9]:

$$C_P = \frac{p - p_\infty}{\frac{1}{2}\rho v^2} \quad (2)$$

For above equation, C_P is the stagnation pressure coefficient, p is the local static pressure (Pa), p_∞ is the freestream static pressure (Pa), ρ is the density of medium ($kg\ m^{-3}$), v is the freestream velocity ($m\ s^{-1}$). Denominator of the fraction, $\frac{1}{2}\rho v^2$ is the dynamic pressure (Pa). Blunt noses increase the value of C_p , therefore increase the drag produced by the vehicle as well. Rounding the corners and adjusting the angle of the windshield are two methods to improve the leading edge. Both of the methods will allow flow to divert smoothly around the vehicle, lowering maximum C_p .

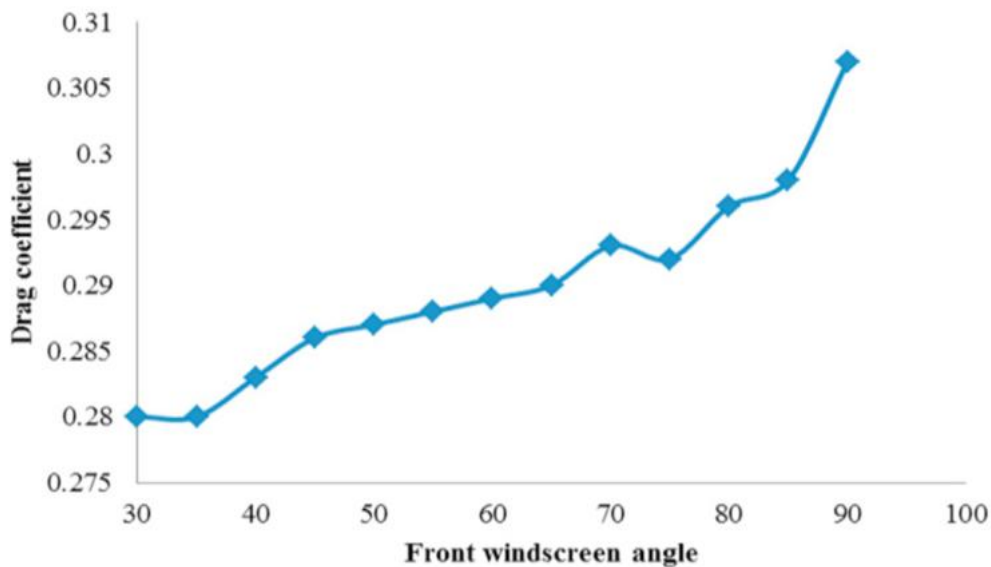


FIG. 2 Graph of C_D against front windscreen angle [10]

FIG. 2 is from a study that investigates Windscreen angle and Hood inclination optimization for drag reduction in cars, done by Vignesh S et al. The study modelled Proton Iswara using CATIA V5 R17 and discovered the relationship between front windscreen angle and drag coefficient, shown in the graph above. Therefore, the study concludes that the optimum angle for the front windscreen of a car is less than 45° , ideally 35° [10].

2.2.2. Trailing Edge Treatment

The trailing edge of cars dictates wake size, and hence pressure drag. According to momentum theory, drag links to the wake velocity deficit through the following equation [11]:

$$D = \rho \int (v_\infty - v)v\ dA \quad (3)$$

The above equation is a variation of the drag equation, where A represents the wake cross-sectional area (m^2). There are a few methods to adjust the trailing edge. By tapering the rear, adding rear diffusers, and adding rear spoiler. A tapered rear end is able to narrow the cross-section of the vehicle gradually, allowing the airflow to converge more smoothly before detaching. This treatment minimizes abrupt separation; therefore, it reduces the size and turbulence intensity of the wake region. This leads to an enhancement in the recovery of pressure at the trailing edge, thereby lowering the overall drag. By delaying the onset of the wake, not only does the streamlined taper ensure reduced

energy loss to vortex formation and be more aerodynamically efficient, it increases the value of ν as well. When ν increases, the value of $(v_\infty - \nu)$ decreases, therefore the value of D decreases.

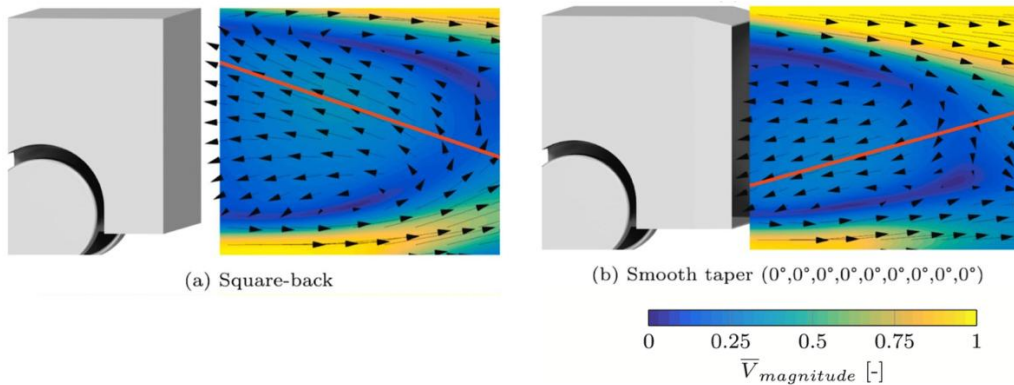


FIG. 3 Comparison of Square-back with Smooth Taper [12]

FIG. 3 indicates the pressure drag behind (a) square-back vehicle and (b) smoothly tapered vehicle [12]. In (a), a strong recirculation region can be identified behind the vehicle, and a wide wake is identified. This indicates that this vehicle has a very high pressure drag, due to the early separation of flow, and the large wake. Looking at (b), it has a smaller recirculation region than (a), and a delayed separation can be identified. The magnitude of velocity in (b) is generally higher than (a), as more yellow regions can be identified in (b).

A rear diffuser is able to smoothen the expansion of airflow under the vehicle, which allows gradual pressure recovery at the trailing edge. By managing the underbody flow transition into the wake, the diffuser is able to reduce turbulence and weaken the strength of vortices shed from the underbody of the vehicle. This treatment will be able to reduce the magnitude of drag produced while maintaining balanced aerodynamic forces.

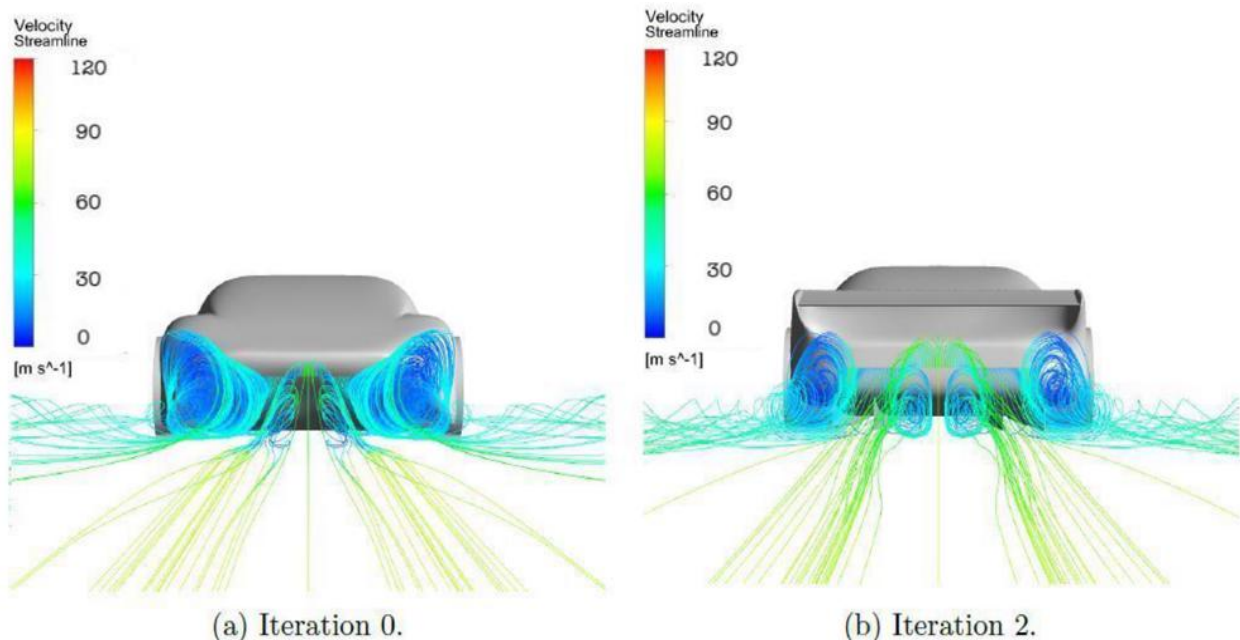


FIG. 4 Comparison of rear diffuser [13]

FIG. 4 is a Computational Fluid Dynamics (CFD) visualisation [13]. (a) shows an unadjusted rear diffuser, while (b) shows a well-designed rear diffuser. Looking at (a), strong vortices can be identified by the two rear wheels, and the low-velocity recirculation zones in the vortices are large. However, in (b), the vortices are visibly smaller, with smaller low-velocity recirculation zones; The wake core shows a higher velocity as compared to (a) as well, which suggests that there is an improved pressure recovery of the vehicle, which means the drag has been reduced as well.

3. The Role of Surface Texture and Microstructure Design

3.1. Overall Concept

In aerodynamics, surface texture and microstructure design are another important factor which determine how airflow interacts with a vehicle. At microscopic level, biomimetic textures influence airflow's behaviour in the boundary layer, it determines whether airflow remains attached to the surface, transitions to turbulence, or early separation as well. By carefully adjusting the presence of grooves, ribs, or periodic patterns, these microscopic changes are able to manipulate the vortex formation, reduce skin-friction drag, and delay wake growth. Scientists take inspiration from nature, such as shark skin, and cheetah's paws. These designs of nature guided scientists to come up with solutions that reduce drag, improve stability, and enhance fuel efficiency in modern vehicles.

3.2. Application of Biomimicry in Aerodynamics

3.2.1. Shark Skin

Shark skin is covered in dermal denticles, tiny scales that are able to direct water into organized streams. These microstructures reduce the intensity of turbulence by aligning vortices in the flow, and this prevents them from merging into larger vortices that produce a larger drag force. In aerodynamics, this technique is mimicked with riblet films applied to surfaces of cars or aircraft. Bhatia et al. have studied drag reduction using biomimetic sharkskin denticles [14].

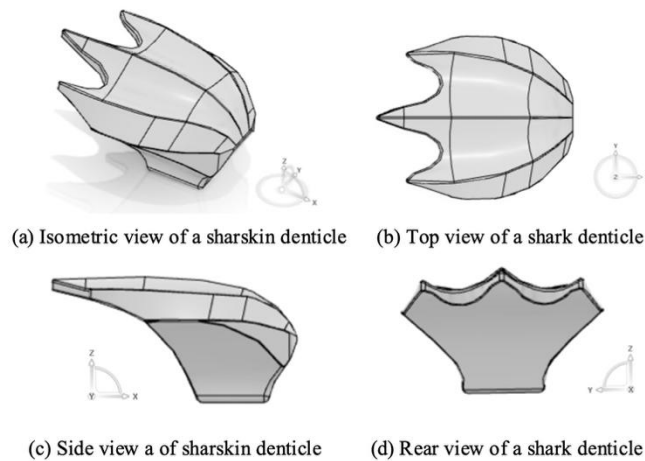


FIG. 5. Illustration of Denticle Model [14].

FIG. 5 shows models which were included in the report done by Bhatia et al. [14]. They have studied two different denticle orientations under different Angle of Attack (AOA) and compared the difference in performance in terms of drag reduction.

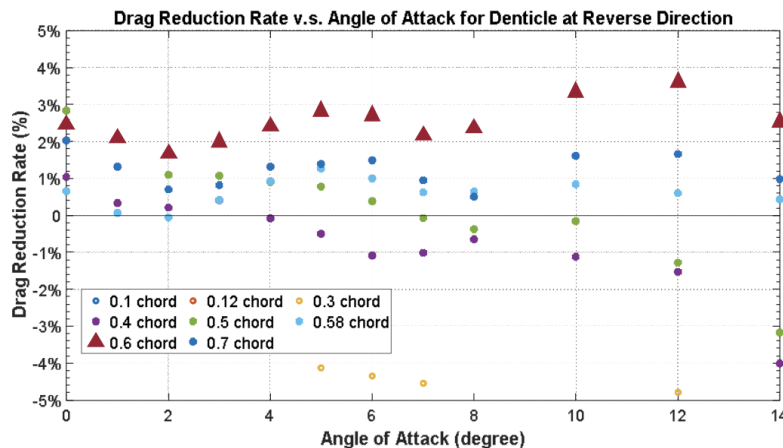


FIG. 6 Graph of Drag Reduction Rate Against AOA (reverse direction) [14].

FIG. 6 displays the rate of drag reduction at different AOA [14], and generally, positive drag reduction rate can be identified. The paper concluded by noting the maximum drag reduction for normal direction shark skin are 3% and 1.5% at 0° and 4° AOA respectively, while for reverse direction, maximum drag reduction is found to be 4.3% and 3.6%, both values were from 12° AOA. Regardless of the extent of drag reduction, shark skin has been proven to improve the aerodynamics of objects.

3.2.2. Cheetah's Paws

Biomimetic tires optimize tire performance to a certain extent by drawing on natural laws or biological mechanisms to guide the design of tire carcass or tread structure. For example, Germany's tire tread structure was designed to mimic the ground contact characteristics of cheetah paws in different movement postures, which synergistically improved the tire's rolling resistance and traction performance [15].

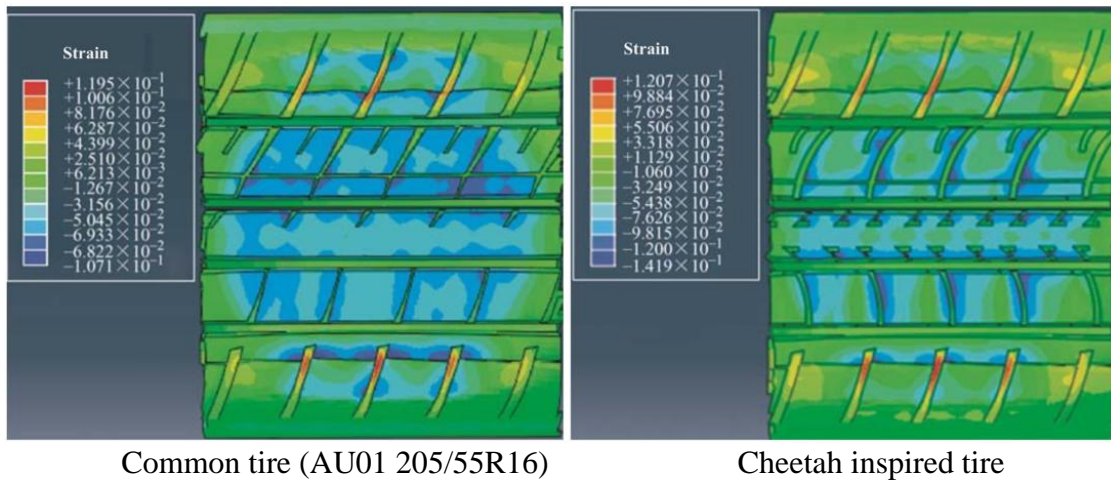


FIG. 7 Comparison between the strain experienced by the two tires [15].

Based on **FIG. 7**, magnitude of strain increased from 0.1195 and 0.1071 of the common tires to 0.1207 and 0.1419 of the cheetahs inspired tire respectively, indicating that the biomimetic design of the tread pattern improves its deformation of the tire when it contacts the ground, thus it improves the tire's traction performance [16].

Table 1. Comparison of Traction Force of Different Tires [16].

Traction Force Indicator	Common tire (AU01 205/55R16)	Cheetah Inspired Tire	Difference
Traction Force / N	2871.406	2924.616	1.85%

Table 1 shows the calculation done by Mei Ye [16], which directly compares the traction force produced by the common tire and the cheetah inspired tire, showing a difference of 1.85%, therefore concluding that biomimetic tread patterns is able to increase the traction of the tire, thereby increasing the efficiency of fuel used.

3.3. Effect of Microstructure Design on the Aerodynamics

3.3.1. Surface Grooves

By definition, surface grooves are linear patterns that's graved onto the surface of an object, and the purpose of doing so is to channel the boundary-layer flow [17]. By guiding the airflow in predictable channels and creating small-scale streamwise vortices, the surface grooves are able to energise the boundary layer, which results in longer attachment of the flow to the surface, preventing early separation. It can be further explained with the following skin friction equation [18]:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho v^2} \quad (4)$$

For above equation, C_f is the skin friction coefficient, τ_w is the wall shear stress (Pa), and $\frac{1}{2}\rho v^2$ is the dynamic pressure (Pa). When surface groove is present, it can effectively reduce the value of τ_w as it is able to produce streamwise vortices near the boundary layer. Therefore, reducing the value of C_f as well.

3.3.2. Microrib Structures

Microrib (riblet) structures are oriented parallel to the flow which is able to reduce skin friction in turbulence flow [19]. Similar to surface grooves, it adjusts and manipulates the vortices to achieve aerodynamic effects, and controls the lateral momentum transfer, therefore it reduces the turbulent shear stress as well. Because the design is at microscale, therefore it minimizes the frontal resistance of the object while maintaining its function.

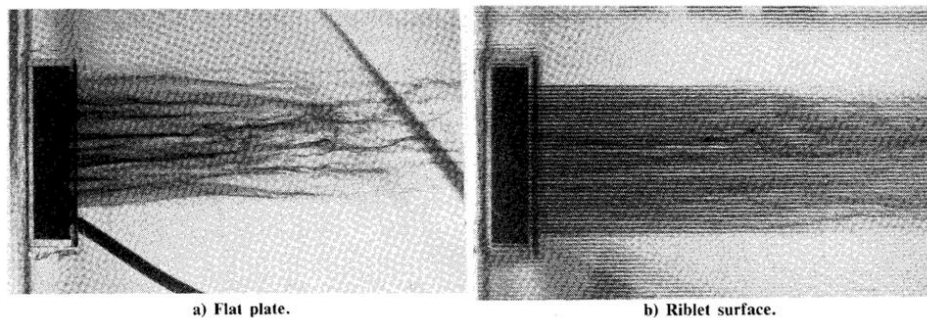


FIG. 8 Comparison of aerodynamic flat surface plate and riblet surface plate [20].

FIG. 8 is from a study done by E.V. Bacher, who studied the turbulent boundary layer modification by surface riblet [20]. **FIG. 8** (a) shows an early transition of airflow into turbulence state, while figure 3.3.2.(b) demonstrates the characteristic of delayed transition to turbulence state. A streamlined, organized airflow can be identified.

4. Effect of Surface Coating & Roughness on Aerodynamics

4.1. Overall Concept

Surface coatings not only have aesthetic and protective functions, it is also an important factor to determine the aerodynamics of an object. As the outermost surface, it has direct contact with the airflow, therefore surface roughness and wettability become the critical factors. In terms of coatings on cars, there are two typical coatings, paint-based coatings and superhydrophobic coatings. The materials each use, and surface texture vary, which therefore affect the surface roughness, and how much drag force each produces. At the same time, environmental conditions, such as rain, also determine how effective these coatings remain in maintaining aerodynamic efficiency over time.

4.2. Paint-based Coating

Paint-based coatings typically consist of a few layers [21], first layer being the primer, which prevents the metal parts of the car from corrosion; second layer is the basecoat, which provides the colour, and outermost layer being the clear coat, which provides gloss, ultraviolet (UV) protection, scratch resistance, and other benefiting factors. To make sure that the car produces less drag, the clear coat needs to have a smooth surface to minimize the surface roughness.

With a smooth surface, the coat is able to prevent early boundary-layer disturbances. Their main advantage is stability and consistency under most driving conditions, and in terms of affordability, it is the most economic coating for most cars. However, degradation through oxidation, scratches, or uneven wear increases the roughness, raising skin-friction drag. Paint coatings perform reliably in dry and wet weather conditions, but accumulation of dirt or water films can increase the roughness thus drag [22]. Therefore, while paint-based coatings are aerodynamically neutral, their long-term performance depends heavily on surface maintenance.

4.3. Superhydrophobic Coating

Superhydrophobic coatings use nanostructures and low-surface-energy materials to repel water, main material being fluoropolymer, to keep the surfaces clean and free of films that disrupt airflow [23]. Their main aerodynamic advantage emerges in wet conditions, where water drops are not able to sustain on the car surface but rolls off, preventing increased drag due to water sheeting. However, in dry conditions, superhydrophobic coatings produce higher drag as compared to conventional smooth paints as shown in **Table 2**.

Table 2. Comparison of Roughness Height of Different Materials [23].

Material	Paint - 1	Paint - 2	Paint - 3	Fluoropolymer	Glass (smooth)
Roughness Height (Ra) / m	3.51×10^{-7}	1.03×10^{-6}	1.48×10^{-6}	5.24×10^{-6}	9.40×10^{-8}

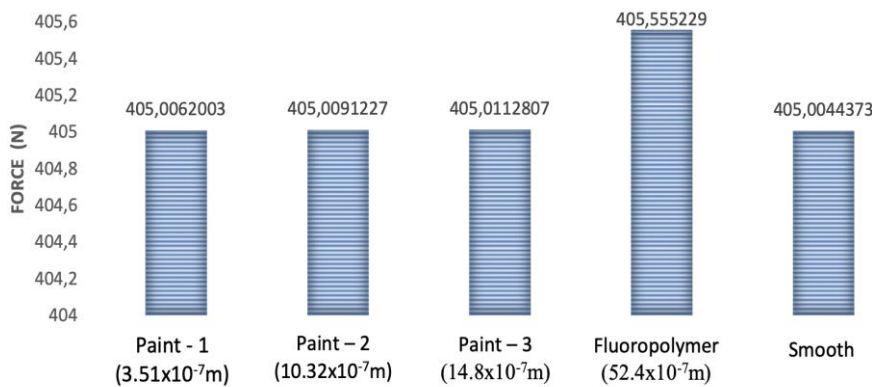


FIG. 9 Average aerodynamic drag forces acting on the vehicle at different roughness values [24].

K. Ermis has done an Aerodynamic investigation of vehicle coating materials, who investigated the magnitude of aerodynamic drag force produced at different roughness under dry conditions. Table 2 defines the value of the roughness of each material, and **FIG. 9** compares the average aerodynamic drag force being produced with each material. From **FIG. 9**, fluoropolymer, as the material with the largest roughness value, produces the highest value of drag force. This indicates the direct correlation of roughness to aerodynamic drag. Another limitation of superhydrophobic paint is durability, these coatings often lose effectiveness under strong or prolonged exposure to UV, which reduces its efficiency.

5. Future Development & Challenges

Looking forward, the future development of aerodynamics of cars is likely to advance along all three categories: shape, surface microstructure, and surface coating. Each area presents opportunities for significant efficiency gains; however technical challenges will also be faced from moving forward.

5.1. Future Development & Challenges – Shapes

In terms of shape, the technology of computational fluid dynamics (CFD) is the main focus of development. As the core simulation technology, development of CFD technology enables further development in aerodynamics. In future, CFD will continue to evolve in a few directions:

Physics-aware Machine Learning (ML). With further development, ML is able to accelerate CFD's predictions of airflow by learning closures for turbulence. Recent reviews summarise methods to do so and general limits [25].

GPU, CFD groups are actively porting solvers to GPU hardware to run higher-fidelity Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) [26]. By enhancing the algorithms for GPU, through creating fewer synchronization points and reworking the algorithms for memory locality, it will allow a faster process of simulation and decrease memory use [26].

However, such innovations present practical challenges. Reliability, accessibility, development and manufacturing cost are the main problems. To achieve ML, a large diversity of existing data is needed, which scientists currently lack, and the expense to obtain more training data is very costly [25].

5.2. Future Development & Challenges – Microstructure

For microstructure design, biomimetic inspiration continues to be a promising field for deeper research and development. Current models of riblets inspired by shark skin, etc. are likely to become more refined through nanofabrication, therefore development of nanofabrication technology becomes essential.

Laser-based nanostructuring is a direction of development for nanofabrication [27]. It allows the production of highly precise riblets, grooves directly on metals or polymers, and with future development, it may be used for larger panels. However, the development cost will be very high.

In future developments, periodic patterns and surface morphologies may achieve 3D-printing directly into body components of vehicles, ensuring precise alignment with airflow [28].

However, the key challenge of this technology or field of exploration is the scalability: microstructured surfaces will lose their effectiveness if it is not manufactured with exact precision across large areas [29]. Therefore, technology with high precision and large coverage of area needs to be developed in order to continue further research on microstructure.

5.3. Future Development & Challenges – Surface Coating

Development in surface coatings, particularly paint-based coating and superhydrophobic technologies, hold a good prospect for enhancing automotive aerodynamics. Possible developments in the future include the integration of nanomaterials such as carbon nanofibers into coatings, which may be able to improve the durability and performance of the vehicles [30].

Additionally, the concept of the "Internet of Paint" (IoP) is being explored, where paint systems incorporate embedded nano-devices for enhanced functionalities [31].

Furthermore, making sure the coatings are able to achieve long-term durability under various environmental conditions [32], such as long term exposure to UV radiation, temperature fluctuations are critical for the practical application of these coatings.

6. Conclusion

In conclusion, this paper examined and listed how the aerodynamics of automobiles are influenced through three main aspects: shape, surface texture and microstructure design, and surface coatings. By analysing each of the categories, this study aims to summarise findings of existing reports and presents how each aspect can be adjusted.

Section 2 explained how the shape of vehicles influences drags through discussion of the drag equation, stagnation pressure, and wake dynamics. It also explained how treatments of leading-edge and trailing-edge are able to lower the stagnation pressure and reduce wake size respectively. Examples of each treatment like adjustment to the front windscreen angle and addition of rear diffuser are included.

Section 3 discussed how biomimetic surface textures such as shark skin denticles and cheetah's inspired tire treads improve aerodynamics by reducing turbulence, drag, and improving traction. It also mentioned about engineered surface grooves and microrib structures that are able to channel airflow, delay separation, enhance vehicle stability, vehicle performance, and fuel efficiency.

Section 4 studied how surface coatings influence vehicle aerodynamics by roughness variation and wettability. Paint-based coatings maintain stable drag performance when smooth but degrade with wear and dirt. Superhydrophobic coatings repel water and reduce drag in rain, but it produces larger drag under dry conditions.

Section 5 outlines the possible Future development and challenges in terms of automotive aerodynamics. Some opportunities are: CFD system enhancement, deeper research into biomimetic microstructures, and integration of nanomaterials in surface coatings.

The purpose of this research is to consolidate knowledge from aerodynamics and fluid mechanics, in order to achieve a higher drag reduction rate and higher fuel efficiency, thus reducing energy consumption. The findings prove that not only factors on macroscopic level make a significant difference, microstructures and coatings may also play an important role in terms of aerodynamics. New electronic vehicles (EV) have also been widely recognised and used, which reduce emission of greenhouse gas. Together, these approaches are able to achieve broader environmental benefits.

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