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Aerodynamics of road vehicles

DEGREE PROGRAMME IN MECHATRONICS
2021

ABSTRACT

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Bachelor's thesis

Degree programme : Bachelors in Engineering Mechatronics

Month Year : December 2024

Number of pages: 30

This literature review thesis is based on the aerodynamic trends of road vehicles such as passenger cars, two wheelers and three wheelers. The science involved in aerodynamics different types of forces that is acted upon on the vehicle is explained. How the variable centre of gravity affects the aerodynamics of a vehicle is found out through already researched books and journals. The different aerodynamical components which can be introduced to modify the forces and different solutions testing methods is discussed in the review as well as the different aerodynamical differences of different vehicles is also discussed. And the thesis is concluded with the upcoming future trend which will influence the aerodynamics advancement. Use of new advancements AI models such as Gemini, Grammarly, ChatGPT is done in the report to paraphrase and shorten some paragraphs and to put the data in table form as well as to generate images.

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1.INTRODUCTION

Aerodynamics derives from greek words aerios meaning air and dynamics meaning force (hall, 2023). Historically the horse buggies and cars of the past were designed in a manner to protect the passengers from rain, wind not taking aerodynamics into account. As the time passed by, and the technology advanced, the aerodynamics science used in the aeroplanes started to be applied in the automotive sector as well. Thus, Aerodynamics was introduced in the automotive sector.

Over time as the engines became more powerful along with the improvement in the condition of the roads, the need for higher speeds and better efficiency motivated the automakers to consider airflow management .By the late 20^{th} century, many produced cars achieved drag coefficient of around 0.25 to 0.30, a feat worthy improvement which in turn reduced the drag related losses The main reason for the introduction of aerodynamics in automotive sector was to reduce the fuel consumption, stability of the car, development of racing vehicles and racing competitions worldwide (Goerge, u.d.).The necessity of aerodynamics is evident at highway speeds, where the resistance of air can constitute more than half of the total opposing forces.

In this literature review we will dive into the science of aerodynamics, its history in different vehicles, different car designs and aerodynamics add Ons that can be modified into the vehicle.

2. AERODYNAMICS SCIENCE

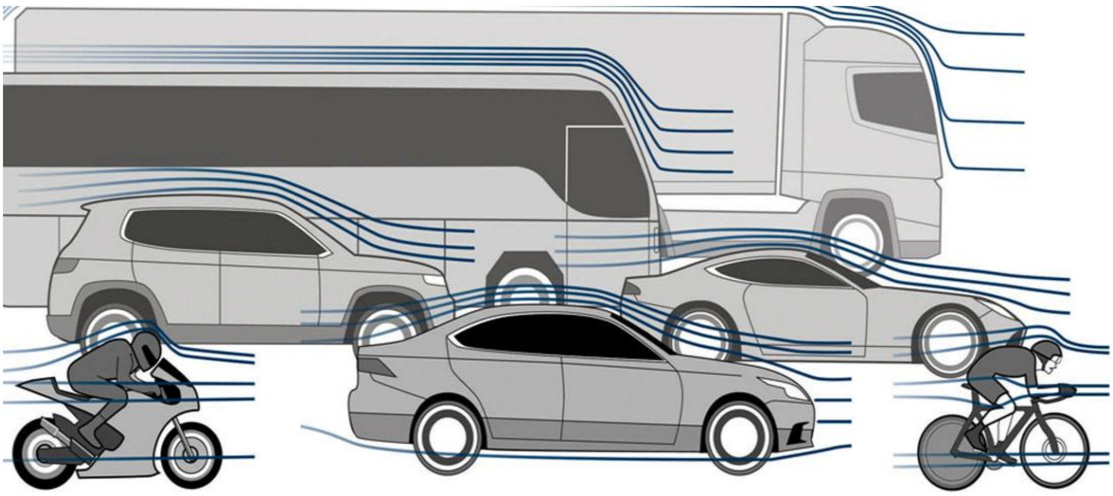


Figure 1: Airflow in different vehicles

(engineers, 2020).

When the vehicle moves through the atmosphere it displaces the layer of air around its surroundings. The vehicle is also subjected to drag force and gravity. When a solid object moves through air or water, drag force is created. It is directly proportional with the velocity that is when the object has high speed, it will experience more drag force.

Measuring the object motion as described in the newton's laws include factors such as an object's mass, its acceleration, weight and external force. Drag force is directly proportional to acceleration, weight of an object depends on the acceleration due to gravity. The mass remains same, but the weight is variable because of this reason. The accelerating vehicle will have increment in its velocity and drag force, it increases to the point where the drag force equals to weight and no more acceleration can occur, meaning as the vehicle moves faster, more air resistance is created, limiting the vehicles acceleration to a certain speed. The goal of aerodynamical science is to reducing drag force while maintaining the stability and control of the vehicle. A vehicle with good aerodynamics experiences less drag force compared to the vehicle with inferior aerodynamic design.

Other important force acting on the vehicle in terms of its aerodynamics is downforce. It is the force that hold the vehicle firmly on the road at high velocity.

Downforce can be achieved by designing the vehicle to create downward force on the tires, which in turn increases stability and traction. Similarly, others force such as lift force and side forces also act on the vehicle.

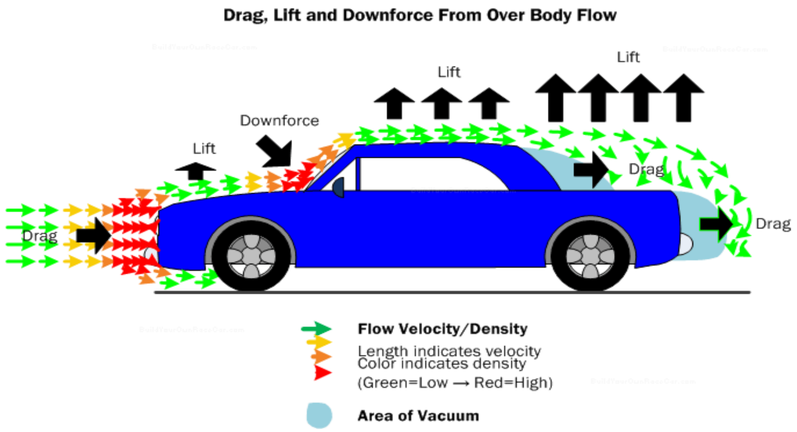


Figure 2: Aerodynamic force s acting on vehicle

(Build your own race car, u.d.)

2.1 Drag Force

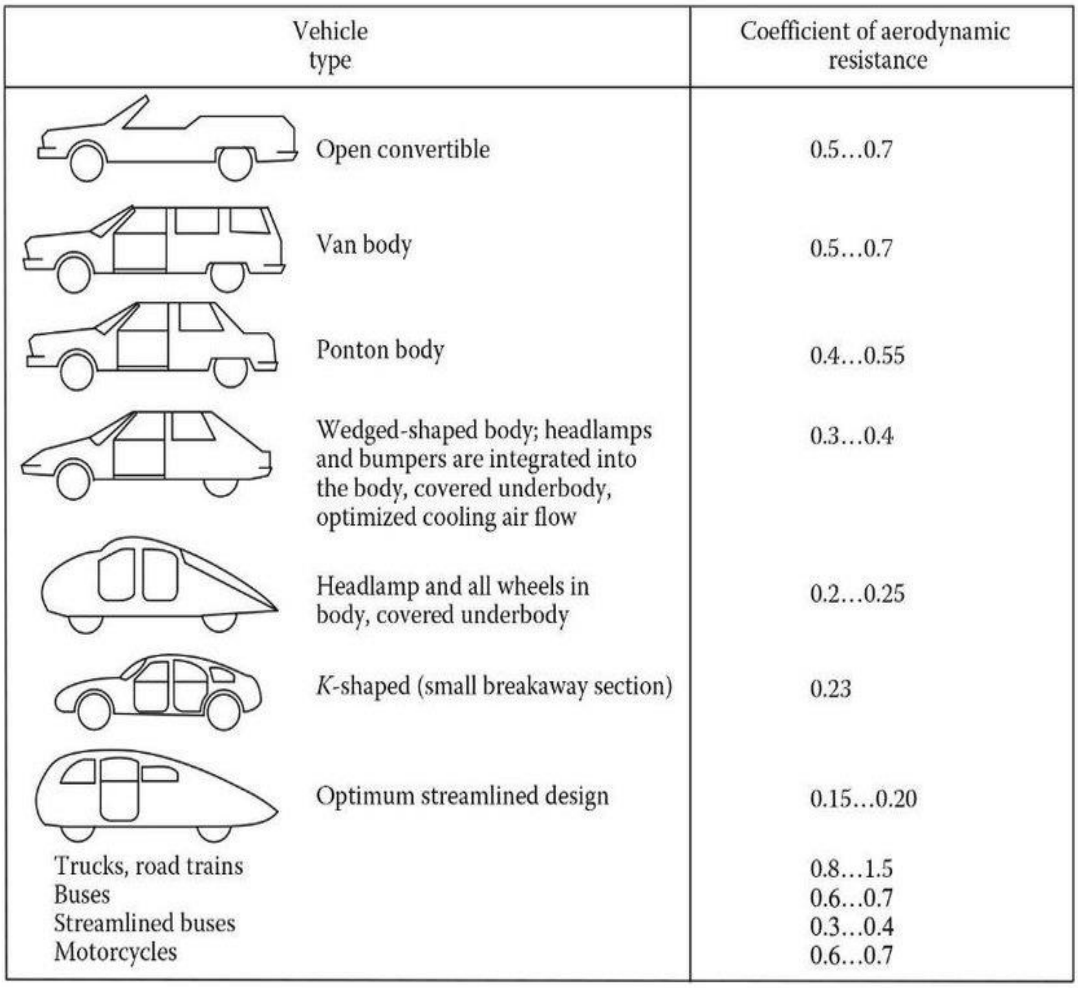
When the vehicles move forward the layer of air opposes the movement and acts against its motion known as drag force. Drag force is generated when the air is displaced by the outer surface of the vehicle as it motions forward (Hucho, 2013). There are three different factors of the total drag force which a vehicle experiences namely pressure drag force, induced drag force and skin friction drag force. Pressure drag is the resultant of the pressure difference between the back and the front of the vehicle (Gillespie, 2013).Pressure drag can be optimised by streamlining the vehicle. Similarly, the viscosity of air flowing through the vehicle surface creates skin drag friction. It is dependent on how rough the surface is and how long the boundary layer is and the layer of thin region of air which is in contact with the vehicle surface first (Hucho, 2013). Another type of drag force created is induced drag force which is generated as byproduct of the vortices induced at the edges of the vehicle around the rear and wing structure of the vehicle. Vehicles with protruding aerodynamic features experiences induced drag force.

Drag force can be calculated mathematically by using formula:

1.Fd =1(P V^2CdA)/2

Here Fd represent Drag force, P Is density of air in kg/m^3, V is velocity of the vehicle in meter per second, Cd is the drag coefficient, and A represents the frontal area of the vehicle in meter square. From the above formula we know that the drag force is directly proportional to the square of velocity which means it is increasingly significant at high speeds. For example, when the speed of the vehicle is doubled, the drag force will increase by four times which in turn emphasizes the necessity of aerodynamic efficiency for high-speed applications. (Hucho, 2013). One of the most critical factors for determining the drag force acting on the vehicle is drag coefficient represent by Cd in the above formula. Drag coefficient is the ratio of drag force to the product of dynamic pressure and the frontal area of the vehicle. The value of drag coefficient is dependent on orientation of the vehicle relative to the airflow, the shape and the roughness of the surface. One important factor for determining the drag coefficient is that it is totally independent of speed of the vehicle, and it solely depends on the vehicle's shape, surface properties and air flow conditions. Drag coefficient has direct impact on the energy efficiency, top speed of the vehicle. Lower drag coefficient results in less requirement of energy to overcome air resistance which in turn has huge implications for energy consumption specially for EVs. For instance, when the drag coefficient is reduced from 0.3 to 0.26, it leads to 5-9% improvement in highway fuel economy (Gillespie, 2013).

In relation to gaining top speed, minimising drag coefficient enables the vehicles to gain top speed since the drag force increases with the square of velocity, so minimal changes to drag coefficient can yield noticeable gains at high speed. Reducing drag force will result in less fuel consumption and lower carbon emissions so it is very relevant in the context of increasingly strong emissions regulations worldwide. The vehicle shape is the primary factor for determining the drag coefficient, streamline shapes like teardrop shape has lower drag coefficient because they reduce the separation of flow also in comparison box shaped vehicles such as SUVs has higher drag coefficient due to increase in pressure drag and turbulence. For example, the streamline tesla model S has drag coefficient of 0.208 whereas a common SUV has drag coefficient ranging from 0.35 to 0.40. Surface roughness has a significant impact on drag coefficient. Mirrors, door handles, roof racks increase drag as it increases turbulent airflow, thus modern vehicles incorporate retractable components to minimize the effect. The underbody aerodynamics influences heavily to the vehicles overall drag. Turbulence is created underneath the vehicle which increases the drag coefficient, to tackle it flat underbody panels and diffusers can smoothen the airflow and reduce drag. Modifications like active grill shutters and spoilers help to control the airflow around the vehicle by optimising the aerodynamics of the vehicle. For example, BMW i8 uses active aerodynamics which in turn has helped it to achieve drag coefficient of 0,26 while maintaining a very polished and visually striking design. There are also challenges in reducing drag coefficient such as it must be balanced with design considerations such as cooling requirements, interior space and aesthetic looks of the vehicle. For example, the low drag coefficient in sport cars is achieved by the compromise of passenger’s comfort. Real world conditions differ from the lab tested drag coefficient because factors like dirt accumulation creates roughness on the outer surface whereas crosswinds result in more turbulence and road conditions effectively increases the drag (Gillespie, 2013). Thus reducing the drag coefficient in this modern times is critical focus for the modernization of the new age aerodynamics vehicles.



Vehicle type	Coefficient of aerodynamic resistance
Open convertible	0.5…0.7
Van body	0.5…0.7
Ponton body	0.4…0.55
Wedged-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3…0.4
Headlamp and all wheels in body, covered underbody	0.2…0.25
K-shaped (small breakaway section)	0.23
Optimum streamlined design	0.15…0.20
Trucks, road trains	0.8…1.5
Buses	0.6…0.7
Streamlined buses	0.3…0.4
Motorcycles	0.6…0.7

Figure 3: Drag coefficient comparison of vehicles

Note: The image is taken from the website research gate ,VEHICLE GEAR SHIFTING CO-SIMULATION TO OPTIMIZE PERFORMANCE AND FUEL CONSUMPTION IN THE BRAZILIAN STANDARD URBAN DRIVING CYCLE - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Drag-coefficients-i-i-i-i-for-different-vehicles-3_fig2_269209164 [accessed 9 Dec 2024]

2.2 Downforce

When the vehicle moves through the air, a vertical aerodynamic force pushes the vehicle downwards it is known as downforce. It improves the tire traction and overall stability of vehicle at high normal and high speed. In terms of motorsports downforce plays an inevitable role as it enables car to maintain control during rapid cornering, acceleration and braking. Downforce is gained by modifying the airflow around the vehicle which in turn creates a differential pressure which increases the normal force acting on the tires (Hucho, 2013).

According to Bernoulli's principle, faster moving air exerts lower pressure compared to slower moving air. Thus, vehicle components like wings, diffusers, splitters can change the airflow to create high pressure beneath the car and low pressure above it, in turn pushing the car more towards the ground effectively.

Figure 4: Image of wing and diffusor

Note: The image is generated using AI Model

Mathematical equation for calculating downforce is represented by

2.Fd = 1(pV^2C_LA)/2

The above equation Downforce is represented by Fd, p is the density of air, V is the velocity of the vehicle, C_L is the lift coefficient which is negative for the downforce and A represents the surface area in which the aerodynamic effect is generated. Coefficient of lift is the measure of the aerodynamic design effectiveness in generating downforce. Negative lift coefficient results in higher downforce creation. Downforce results in increment of normal force on the vehicle's tires maximizing the grip and decreasing the likelihood of vehicle slipping while cornering and accelerating, thus it helps in achieving high speed on the curves without losing control. It also pushes the car closer to the ground, reduces the body lift and decreases the risk of instability at high velocity, so more control of the vehicles can be achieved (Gillespie, 2013). Downforce increments the tire traction which results in shortening of braking distances by allowing the tires to transmit greater forces to the road without locking up. Some of the parts which are used in vehicles to create downforce are Real wings, front splitters, diffusers, canards and winglets. One of the iconic features for generating downforce is rear wings. It creates downforce by manipulating airflow by generating low pressure at the top and high pressure at bottom. It stabilizes vehicles during cornering and when vehicle is in high speed. Angle of attack is important in terms of wings acting to create downforce, how steeply the wing is tilted to the relative incoming airflow determines the downforce and drag. A steeper angle generates more downforce in turn increasing the drag also.

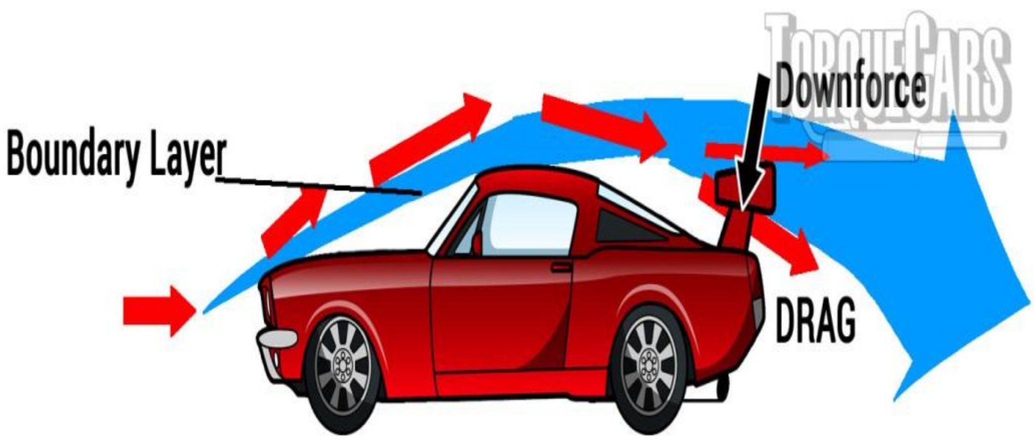


Figure 5:Wings creating downforce

Note: Image taken from google images internet sources depicting the downforce acting on a car

For example, F1 cars uses DRS (Drag reduction system) to adjusts the wing angle dynamically to reduce the drag on straights and maximize downforce while cornering. This advancement has enhanced both speed and handling in the motorsports.

Another component that is important in creating downforce is Front splitters. They are the flat surfaces that extends from the lower front edge of the car. Splitters direct the airflow upward which in turn increases the pressure above and reduces pressure below the car. They also guide the airflow to underbody components such as diffusers, increasing their effectiveness. Combining with other components, splitters help to create overall balance by front end downforce generation (Gillespie, 2013).

Similarly to wings and splitters, diffusers are inevitable for controlling the airflow below the car, it is located below the rear end of the vehicle. Diffusers slow and expand the exiting airflow which causes the pressure drop that forces the vehicle close to the ground. The venturi effect, which accelerates airflow through narrow spaces, is main function used by diffusers to increase downforce without increasing substantial drag (Hucho, 2013). Downforce engineering is applied in field of motorsports, high performance road cars and new age Electric vehicles. For example, McLaren P1 achieves downforce up to 600 kg at 260km/h through a combination of active and fixed aerodynamic components. F1 cars can generate downforce over 1000 kg, thus it shows that downforce is vital for the stability, handling of the vehicle all while minimizing unnecessary drag.

Downforce engineering has its challenges as designing downforce generating components is managing the trade off drag, increased downforce improves grip and handling while creating additional drag which in turn has a effect on the vehicle’s fuel and speed. Dynamic adjustable components such as wings and diffusers based on driving conditions can balance the downforce and drag. For example, Bugatti Chiron has an adaptive rear wing which lowers to minimise the drag during straight line acceleration and raises to provide downforce during cornering and braking (Bugatti, 2020). Koenigsegg jesko features advanced active aerodynamic system which can generate upto 1400 kg downforce at speeds over 250km/hr (Koenigsegg). To incorporate downforce creating components, lightweight and high strength materials like carbon fibre is used especially in high performance vehicles where weight reduction is critical. Thus, the advancement in automobiles shifting towards electrification and automation, the downforce principles is essential to balance safety, efficiency and performance.

2.3 Lift Force

Aerodynamic force which acts perpendicular to the direction of vehicle's motion is defined as the lift force. It is beneficial in the sector of aviation but usually not so desired in road vehicles since it decreases the tire traction and stability, thus in vehicle decreasing lift force is essential for ensuring safe handling of the vehicles especially at high speeds (Hucho, 2013). If the lift force remains unchecked, compromise in performance with reduction in overall driving efficiency and increment in risk factors causing accidents will occur. Scientifically Lift forces follow two principles one: Bernoulli's principle and the newton's third law. In terms of Bernoulli's principle, faster moving air exerts lower pressure so when airflow moves faster over the top of the vehicles than its below, it creates a pressure differential which creates upward lift. The airflow can be faster on top of vehicle due to the curved roofline and sloped design of the vehicle. Similarly, Newton's third law, action reaction principle states the lift force is created as the air is deflected downward by the vehicle, an upward opposite reactive force is exerted, which in turns helps in the generation of lift force (Hucho, 2013). Mathematically, Lift force can be represented by the equation,

3. $F_L = 1(pv^2C_LA)/2$

Here FL represents the Lift force, p represents the density of air, v stands for the velocity of vehicle, CL is the lift coefficient, and A is the projected planform area of the vehicle. The lift coefficient is influenced by the vehicle's shape, the dimensions of the surface, its design features. When the value of the lift coefficient is high it results in undesirable amount of high lift forces for road vehicles and excessive lift force can also impact the braking and the risk of rollover in taller vehicle increases (Gillespie, 2013).

There are factors which causes the lift force to be generated, when the vehicle is designed with curved roof and steeply sloped rear windows, it promotes faster airflow on the top of the vehicle which causes a creation of pressure differential that causes the lift. This effect increases at high speeds as the velocity squared term in the lift equation becomes more significant (Barnard, 2001). When the surface below the vehicle is uneven and has components which is exposed, it creates turbulence which in turn results high pressure under the car and the lift force is generated. This effect is more visible in vehicle with high ground clearances such as SUV’s (Katz, 2016). Thus, aerodynamic instabilities at high speeds cause the airflow separation at the rear end of the vehicle to amplify the lift forces. The sudden change in the airflow direction leads to the creation of vortices which causes further destabilization of the vehicle (Gillespie, 2013). Unlike in Aviation, lift force is not desired in vehicles because of its negative effects such as the decrease in traction of tires and handling as excessive lift reduces the normal force on the tires which compromises the handling particularly during high speed cornering and braking. Lift force also disrupts the vehicle’s centre of gravity which increases the likeliness of oversteering or understeering so the taller vehicles like trucks are vulnerable to lift induced instability (Gillespie, 2013). In order to tackle the effects of lift force, spoilers wings, diffusers, underbody panels, air dams and use of active aerodynamic components is used. Spoilers increases the pressure at the back end of vehicle by generating downforce which mitigates the lift force, diffusers located under the rear end of vehicle also helps in generation of downforce mitigating the effects of the lift force. Underbody panels smoothen the roughness minimising the turbulence beneath the vehicle which in turn reduces the lift. Lift force management is crucial to integrate in passenger cars, sports and performance cars and commercial vehicles such as trucks and buses. Passenger cars use subtle features such as rear spoilers, optimized rooflines to achieve low lift coefficient without the compromission of practicality and aesthetics whereas in high performance sports car great amount of lift force reduction is required to maintain stability during cornering and braking. Thus, the use of advanced diffusers, large wings are used whereas bus and trucks are susceptible to lift due to their size and high ground clearance so they use side skits and roof deflectors to reduce the lift force while improving fuel efficiency (Katz, 2016). As the advancement in automotive technology occurs, lift force management systems will continue to develop using advanced materials, AI based controls and innovative designs to meet the demand of the modern transportation.

2.4 Side Force

It is aerodynamic forces which acts laterally perpendicular to the direction of the vehicle’s motion. Asymmetrical airflow and crosswinds are the main causes these forces. It has a significant effect on vehicle’s stability during cornering and at high speed. The management of side forces is essential for maintaining handling precision and reduction of taller vehicle from being roll overed. Side force is generated due to external factors such as crosswinds or difference in the vehicle’s geometry which causes differences in pressure distribution across the sides of the vehicle. When winds travelling from one direction strikes one side of the vehicle, it creates high pressure zone on the side od the wind and low pressure on the side with no wind which results in later force that can destabilize the vehicle causing it to tilt or drift. The magnitude of side force depends on the vehicle’s geometry, its shape and size for example taller and larger vehicles are more susceptible to the lateral force due their large side profiles. The crosswinds speed also determines the amount of force exerted as the high speed exerts more force in combination to the high velocity of the vehicle. High velocity increases the effects of side force due to the increased relative airflow velocity (Hucho, 2013). Vehicles such as Trucks and SUVs with high centre of gravity are more prone to rollover due the side force effects thus to decrease the risk lowering the centre of gravity through design helps.

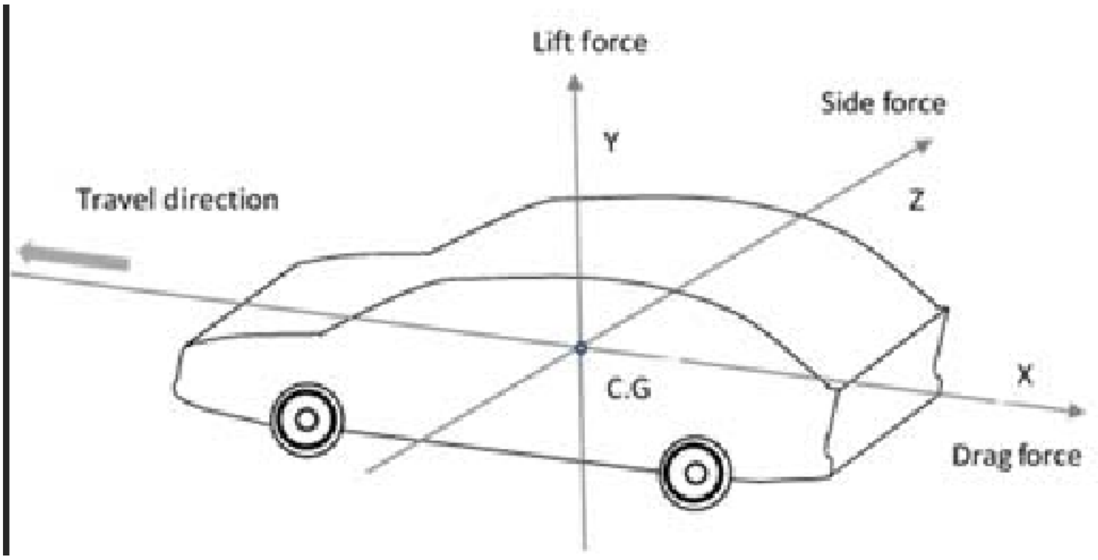


Figure 6: Aerodynamic forces acting on a vehicle

Note: Image taken from website schemantic scholar its URL https://www.semanticscholar.org/paper/Reduction-of-Aerodynamic-Drag-Force-for-Reducing-in-Sivaraj-ParammasivamK/9a798319ced25053f8db3f27a33801dfb5359dc3 depicting the different aerodynamic force acting on the vehicle

Mathematically the side force exerted on the vehicles can be expressed as,

4. $F_S=1(pv^2C_SA)/2$

Here, the Fs represents the side force, p is the density of air, v is the wind or the velocity of the vehicle, Cs is the coefficient of side force and A represents the projected side area of the vehicle (Katz, 2016).

Centre of gravity, vehicle geometry, crosswinds conditions and the speed of vehicle are the factor in which the side forces are dependent on. These all factors impact on the handling, stability and causes safety risks on a vehicle. Thus, to decrease the impact of side forces the vehicle design and geometry is important, aerodynamic streamlining with rounded edges and tapering at the back of the vehicle reduces the surface area exposed to the crosswinds which in turn minimizes its effect. Symmetrical design ensures equal airflow around the vehicle which reduces the unbalanced pressure differentials. Aerodynamic components such as adjustable fins and spoilers and systems such as crosswind assist available in cars such as Mercedes Benz S class, actively applies braking to specific wheels to stabilize vehicle during the storm.

Implementation of advanced Electronic Stability control (ESC) systems hep to detect the side forces and helps the driver by applying selective braking to counter drift and tilt caused by crosswinds. Vehicles such as BM2 X5 employs it to minimize side forces in real time to improve the handling and safety (Katz, 2016). Adaptive steering and suspensions systems adjusts steering angle to counter lateral displacement caused by the side forces whereas the adaptive suspension system lowers the vehicle's centre of gravity in during high speed decreasing the chances of the vehicle rolling over (Gillespie, 2013).

3.CENTER OF GRAVITY ANALYSIS OF VEHICLES

A three dimensional point where the mass is evenly distributed, that point is referred to as Center of gravity. It is described in terms of three axes, Longitudinal, lateral and vertical axis. Longitudinal axis is along the vehicle's length from front to back, lateral axis extends across the vehicle's width side to side and the vertical axis ranges from the ground top to bottom. W here the center of gravity is located determines the weight distribution of the vehicles from front to back and side to side balance, its resistance to rolling over and handling characteristics such as responsiveness during braking, turning and acceleration of the vehicle. Center of gravity depends on the type of vehicle, such as passenger car tends to have low central CG for balance and comfort whereas Sports car have extremely low CG, SUVs and trucks tend to have higher CG because of the increased ground clearance which in turns improve their off road capabilities but compromise the on road stability. Similarly in Electric vehicle the battery pack are usually placed under the floor resulting lower CG. The cargo and load placement also alters the CG of the vehicle dynamically. For example, loading heavy cargo on the roof increases the CG reducing stability whereas properly distributed cargo lowers the CG and improves balance (Barnard, 2001). Heavier components of vehicle such as engine and battery packs if positioned lower reduces CG whereas the chassis design of lightweight materials like carbon fiber for roofs and upper components lowers the CG while maintaining structural integrity. Vehicles with adjustable suspension can lower their CG dynamically increasing stability during high speed travel.

For static calculation of CG, the longitudinal CG can be calculated by using the formula,

1.$X_{CG} = (W_{rear} * L)/(W_{Total})$

Here , Xcg is the longitudinal distance of the Cg from the front axle, Wrear is the rear axle weight, L represents Wheelbase and Wtotal is the overall total weight of the vehicle (Hucho, 2013).

Whereas, the vertical CG determines the height of Cg above the ground,It is measured by tilting the vehicle and observing the shift in weight. Mathematically it is calculated by using the formula,

2.**$H_{CG} = (\Delta W * B) / (W_{total} * \tan\theta)$**

Here Hcg represents the vertical height of the center of gravity, ΔW represents the shift of weight between the axles, b represents the wheelbase and θ is the tilt angle. The upper mentioned formulae calculate the static CG which is based on the vehicle design and load distribution when the vehicle is in stationary position. The lateral Center of gravity is the side to side weight distribution that ensures balanced handling.

Vehicle	Type	Weight (kg)	CG Height (mm)	Front-to-Rear Weight Distribution
Tesla Model S	Electric Sedan	2,200	460	48% Front / 52% Rear
Toyota Prius	Hybrid Sedan	1,395	520	60% Front / 40% Rear
Jeep Wrangler	SUV	2,000	650	52% Front / 48% Rear
Porsche 911 Carrera	Sports Car	1,500	330	38% Front / 62% Rear
Ford F-150	Pickup Truck	2,500	700	60% Front / 40% Rear

Figure 7: Static CG data

Note: Data collected from car websites and tabelized using AI model

From the above table, Tesla Mode S has low CG based on its underfloor battery placement and minimizes lateral weight transfer which in turn reduces the body roll and improving the tire grip especially during cornering whereas Jeep wrangler has high CG because it is focused on high ground clearances for off road performance bit requires stability control systems for counter roll over risk during sharp turns and emergency maneuvers. The Porsche 911 carrera has a rear based weight distribution and extremely low CG which makes it ideal for high speed cornering also the front biased Cg of Toyota prius increases the front axle load under braking which improves the stopping power but reduces the rear stability. Thus from the above data it is clear that low mounted components reduces the vertical CG, symmetrical weight distribution across the lateral axis results in balanced handling and use of light materials lowers the CG without compromising the aesthetics of the vehicle.

When the vehicle is in motion, the center of gravity is dynamic that refers to the behaviour and apparent location of CG since it shifts due to cornering, acceleration and braking. Static CG is fixed based on the vehicle’s design and load distribution, but the dynamic CG is based on the weight transfer, external forces such as aerodynamic effects and the suspension characteristics. Dynamic CG is important for optimizing stability and performance in vehicles. The dynamic Cg depends on the weight transfer which occurs when the vehicle’s load changes from one set of wheels to another due to external forces. For example during acceleration, the dynamic CG shifts backward increasing the load on the rear wheels whereas during braking the it shifts forwards increasing load on the front wheels whereas during cornering the cg shifts laterally resulting more load on the wheels outwardly. The vertical height of CG directly affects the magnitude of weight transfer, when it is higher it results to more weight transfer there is reduced traction which in turn results in the risk of rolling over. Dynamic weight can be calculated in different scenarios mainly during accelerating, braking and while cornering. Let’s look at the mathematical formula for each scenario
During Acceleration it is calculated by,
3.

$$W_{\text{rear}} = W_{\text{static rear}} + \frac{W \cdot h_{\text{CG}} \cdot a}{L}$$

Here W_{rear} represents the dynamic load on the rear axle of the vehicle, $W_{static\ rear}$ is the load when the vehicle on the rear axle when it is stationary. W represents the vehicle weight whereas h_{CG} is the static CG height above the ground, a is the acceleration rate of the vehicle and L is the wheelbase which is the distance between the front and rear axles of a vehicle.

While braking the dynamic weight is calculated by,

4.

$$W_{\text{front}} = W_{\text{static front}} + \frac{W \cdot h_{\text{CG}} \cdot a}{L}$$

W_{front} represents the dynamic load on the front axle and $W_{static\ front}$ the load on the front axle of the vehicle at rest. W is the vehicle weight and a is the decelaration rate and L is the wheelbase.

When cornering the lateral weight transfers due to the centrifugal force so here centrifugal force is calculated by,

5.

$$F_c = \frac{m \cdot v^2}{r}$$

Where m is the mass of the vehicle, v is the velocity of the vehicle and r refers to the radius of the turn,

The lateral weight transfer is calculated by,

6.

$$\Delta W = \frac{W \cdot h_{\text{CG}} \cdot F_c}{\text{Track Width}}$$

Parameter	SUV	Sports Car
Static CG Height (h_{CG})	600 mm	300 mm
Track Width	1,600 mm	1,800 mm
Rollover Threshold	$\frac{1{,}600}{2 \cdot 600} = 1.33$	$\frac{1{,}800}{2 \cdot 300} = 3.00$
Lateral Weight Transfer (ΔW)	Higher due to high h_{CG}	Lower due to low h_{CG}

Figure 8: comparison of lateral weight transfer

Note: Data collected from the sources and tabelised using AI model

Thus from the above table it is evident that the SUVs have higher dynamic CG, making more prone to rollover while sharp cornering and sport cars maintain low cg and has better stability and cornering performance.
Avanced tools and techniques such as Telemetry systems, Finite element analysis (FEA) and CFD integration are used to provide valuable insights into the complex dynamics of vehicle motion and dynamic CG. Thus, the center of gravity is relational to the aerodynamics of the vehicle.

4.EFFECT OF AERODYNAMICS ON THERMAL MANAGEMENT, COOLING OF VEHICLE

Heat is created in vehicles from the engines, electronics, frictional force from the brakes and batteries. All of these must be controlled to sustain the performance, safety and longevity of the vehicle. Thus, aerodynamics plays a vital role in maintaining cooling airflow without increasing the excessive drag force.

Internal combustion engines rely on radiators and intercoolers which suck in air through the front grills due to which the pressure drops and turbulence causing increase in drag. Traditionally to tackle this large and open grills were used sacrificing the aerodynamic efficiency for cooling but in the present day active grill shutters which can remain closed at high speeds is used to reduce drag and they will open when the vehicle needs cooling, balancing these needs improves the fuel economy maintaining the temperature of the engine. The placement and size of cooling inlets affects both aerodynamic and thermal efficiency of a vehicle. Similarly in Battery operated and electric vehicle, although they produce less heat in comparison to the engine vehicles, their battery packs and electronics have narrow operating temperature window. As we know overheating causes the loss of battery life and its effectiveness and cold batteries may suffer from reduced performance and charging rates. So electric vehicles often designed airflow channels to cool batteries fraction of what the engine vehicles need. With the less demand of cooling. Electric vehicles can close off the grill opening which reduces the coefficient of drag and improves its range. Some electric vehicles use liquid cooling system or heat pumps which depends less on the external airflow. By creating differentiation in thermal management from aerodynamic design, the aesthetics of the vehicles can be streamlined for the benefit of both range and efficiency though in hot weather or while fast charging strategic airflow management remains essential. Whereas in heavy trucks and high performance vehicles, they require braking cooling to prevent brake fade. Brake fade is caused by the buildup of heat in the braking surfaces due to the changes and reaction in the brake system components. For cooling purposes, the brake ducts channelize air from the front of the vehicle to the wheel wells, cooling the rotors and calipers. Wheel design also has impact on brake cooling airflow. Wheels which has spokes that channel air toward the brakes improve heat dissipation without needing larger drag inducing vents. Some vehicles use active ducts or flaps which only comes into play when the threshold of the brake temperature exceeds and closes again to restore the aerodynamic efficiency. In future advancement in autonomous self driving vehicles may need to incorporate sensor cooling systems which needs airflow over the lidar or radar units in the vehicles. These demands need to be taken into consideration when developing future project. Active systems such as autonomous opening of the vent, closing and redirection of airflow based on real time temperature readings can also be incorporated as a future trend in terms of aerodynamics and thermal management of a vehicle which are deeply interconnected. Thus, managing these needs remains a challenge as well as opportunity for foreseeable future.

5. FUEL EFFICIENCY AND AERODYNAMICS CO RELATION

Aerodynamics directly influences the fuel efficiency of vehicles. At highway speeds, the drag determines the energy consumption, decreasing drag coefficient helps in improving cutting emissions, improving mileage and increasing sustainability. At higher velocities the drag force tends to be the primary load. As a generale rule of thumb reducing drag coefficient by 0.01 can produce about a 0.5 to 1 percent improvement in highway fuel economy depending on the vehicles baseline drag coefficient, mass and powertrain efficiency (G.Sovran, 2012). Thus, over a lifetime of a vehicle, these improvements adds up significantly, with hundreds of litres of fuel saved and resulting lower carbon dioxide emissions.

Looking back at history, in the 1970s family sedans had Drag coefficient around 0.45, they were struggling to get the mileage on the vehicles which ranged from 8.50 km per litre to 10.63 km per litre on the highway. By the 2000s similar sized cars had their drag coefficient lowered to approximately to 0.30 enabling them to achieve mileage of 12.74 km/l to 14.88 km/l. In present day, advanced gasoline, hybrid or diesel models routinely surpass 17 km per liter on highways mainly due to the streamlined shapes and careful airflow management of the vehicles (Hucho, 2013).

In terms of hybrid vehicles and EVs they achieve drag coefficient around 0.25 which was significantly better than contemporary rivals. This Aerodynamic edge contributed to its high fuel economy ratings. In electric vehicle like tesla model 3 which has drag coefficient of approx. 0.23 leveraged low drag to extend range, which translated to more kilometres per charge and less demand on the battery pack.

Strict global emissions regulations and rating systems such as the European union commissions target pushes the manufactures to seek efficiency gaining possibility. Thus, reducing aerodynamic drag is one of the most essential ways to comply to this regulations. Achieving a lower drag coefficient helps the manufacturers to avoid huge fines and meet the customer expectations for greener vehicles. Given this regulatory environment, aerodynamic research garners significant investment and attention. Manufacturers hold competitive advantages when they master aerodynamic refinement enable their vehicle to meet or exceed regulatory targets without overly compromising performance and aesthetics of the vehicles.

In terms of commercial vehicles such as vans, delivery trucks etc fuel savings directly translates to financial gains and profits. A truck which has its aerodynamics optimized to save 5 to 10 percent fuel will produce large cost reductions over its service life, especially given the high annual mileages and kilometres travelled involve. Aerodynamic optimisation and improvement in commercial vehicles results in significant economic and environmental impacts.

In terms of electric vehicles, aerodynamic efficiency becomes even more essential. Without engine vibration and noise, acoustic comfort and efficiency takes center stage at highway speeds. Since Ev’s battery is heavy and expensive, reducing aerodynamic drag allows the same mileage with smaller battery or can extends range for the same given battery size. Thus, this can tackle range anxiety in EV owners and make it more appealing to a broader market segment.

In terms of hybrid vehicles, the engine switches on and off depending on load conditions. Lower drag can reduce the frequency of engine activation at highway speeds leaning more on the electric motor and reducing fuel consumption further. Aerodynamics gains ensure that hybrids and plug in hybrids reach impressive fuel efficiency figures. Thus, the relationship between aerodynamics and fuel efficiency is a deal breaker in modern vehicle design. Reduction in drag coefficient converts to tangible savings measured in either litres of fuel saved, grams of co2 or kilometres of additional range of EVs.

Hence intensifying the importance of aerodynamics in achieving sustainable, cost effective and user friendly mobility.

6.COMPUTATIONAL FLUID DYNAMICS(CFD) IN VEHICLE AERODYNAMICS

Computational fluid dynamics revolutionized the field of vehicle aerodynamics by numerically solving the governing equations of flow of fluid. It is a powerful tool used in automotive engineering to simulate and analyse how air or other fluids flows around and through a vehicle. CFD provides detailed insights into complex, three dimensional flow structures without need for a full scale prototype, Over past years, CFD has transitioned from a niche research tool to a mainstay in automotive aerodynamic development.

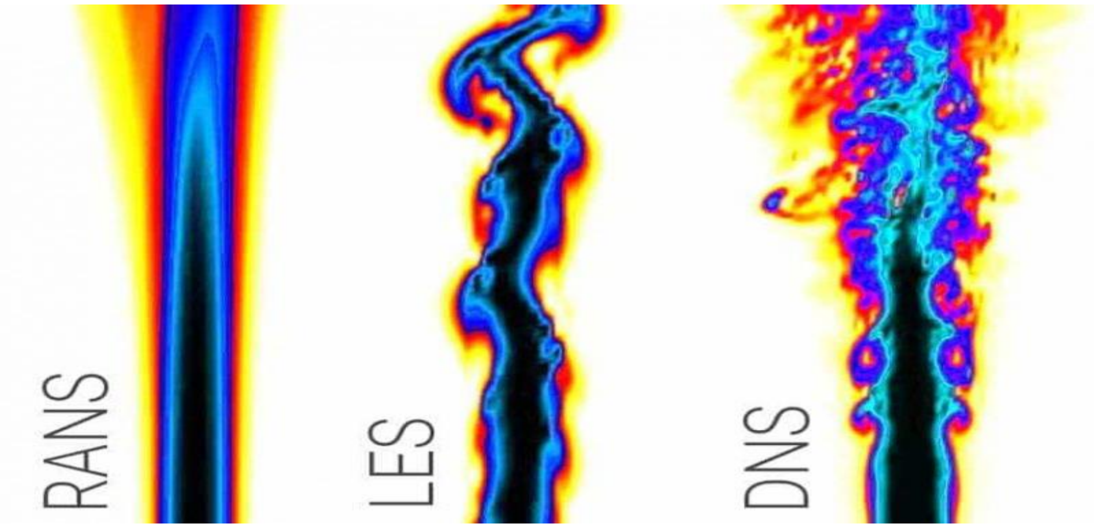


Figure 9:RANS, LES, DNS CFD modelling

Note: Image is downloaded from internet source ideal simulations and its url is https://www.idealsimulations.com/resources/turbulence-models-in-cfd/

Most industrial CFD simulations rely on Reynolds-Averaged Navier-Stokes (RANS) methods. RANS models use time-averaging techniques and turbulence models, but they don't directly simulate the choatic swirling motions of turbulence. Instead they use statistical methods to approximate the effects of turbulence on the overall flow. RANS simulations are computationally less expensive than LES or DES, making them suitable for many engineering applications especially when a steady solution is sufficient but the limitations with RANS model is that it can struggle with accurately predicting flows with complex separation, strong unsteadiness or large scale turbulent structures (idealsimulations, u.d.).

For greater accuracy, higher-fidelity methods such as Large Eddy Simulation (LES) or Detached Eddy Simulation (DES) resolve larger turbulent structures and rely on models for only the smallest scales. LES provides more time-accurate flow details, capturing transient events and complex vortex dynamics. LES is generally more accurate than RANS for flows with unsteady features separation and large scale turbulence, in terms of computational cost LES simulations are computationally expensive than RANS because it requires finer grids and smaller time steps (idealsimulations, u.d.).

DES, a hybrid approach, applies RANS modeling in boundary layers and LES in separated regions, balancing accuracy and cost. While these advanced methods demand more computational resources, they can predict aerodynamic coefficients within ±1–2% accuracy and offer richer flow field information, guiding delicate design decisions.

The quality of CFD results depends heavily on mesh generation and turbulence modeling. Meshing is the process of dividing the computational domain that is the space around the vehicle in this case into smaller,discrete cells or elements. These cells form the grid or mesh on which the CFD solver will perform the calcuations (Cadence , u.d.). Engineers use body-fitted meshes with refined boundary layer cells to accurately capture velocity gradients near surfaces. Wake refinement regions ensure vortices and separated flows are adequately resolved. Mesh convergence studies verify that further mesh refinement does not significantly change results, ensuring numerical stability and reliability.

Selecting an appropriate turbulence model is another critical step. The k-ε(k-epsilon)model, long a standard in industry, is robust but may struggle with flow separation predictions. Here K represents the turbulent kinetic energy and ε represents the turbulent dissipation rate which is the rate at which turbulent kinetic energy is converted into thermal energy basically how fast the turbulence is dying out.This model is computationally inexpensice and good for predicting flows with relatively simple geometrics and without strong separation but it is less accurate for flows with complex separation,strong curvature or adverse pressure gradients.

The k-ω SST(K-omega shear stress transport) model often performs better in adverse pressure gradients, while Reynolds Stress Models provide more detailed turbulence anisotropy at higher computational cost. The choice depends on the complexity of the flow and the balance between accuracy and turnaround time. Similarly K indicates the turbulent kinetic energy, ω represents the specific dissipation rate which is rate of dissipation of turbulent energy per unit volume. The SST refers to shear stress transport, it combines with k-ω model which performs well near the walls of the vehicles and with the k-ε model which performs better in the freestreamto create a more robust and accurate model. Generally this model is more accurate than k-ε for flows with separation, adverse pressure gradients, and near-wall effects.This model is Better at predicting flow behavior in boundary layers and Can be more computationally expensive than k-ε, though still less demanding than LES and sometimes be sensitive to freestream values of ω. The choice between these models depends on the specific flow characteristics and the desired level of accuracy.

Starting with k-ε For relatively simple flows and when computational cost is a major concern, the k-ε model can be a good starting point. Whereas ,consider k-ω SST If the flow involves separation, adverse pressure gradients, or complex geometries, the k-ω SST model is likely to provide more accurate results.

These are just two of many turbulence models available. Since The field of turbulence modeling is constantly evolving, new and improved models to better capture the complexities of fluid flow is being developed by researchers.

After running CFD simulations, the experimental data should be validated and its validation remains essential. Thus Wind tunnel testing is one of the validation methods used and it provides force measurements, surface pressure distributions and flow visualisations that CFD can compare against (Hucho, 2013). If any differences occur the manufacturers can refine mesh, adjust turublence model and revisit boundary conditions which in turn ensures that CFD is not a black box tool but a credible design tool. Thus the use of CFD and wind tunnel testing for validation accelerates the develeopment of the vehicle and lowers the cost.

7.WIND TUNNEL TESTING

Figure 10: Wind tunnel testing of a car

Windtunnel testing is the foundational technique for evaluating and optimizing the aerodynamics of road vehicles. In this experiment, airflow conditions are controlled by researchers to replicate the real world situations and they can isolate and measure the aerodynamic forces with its help before road testing and production of the vehicle (Barnard, 2001).The primary target of wind tunnel testing is to understand and modify the aerodynamic attributes of road vehicles. It focus on drag reduction, lift and stablity control,thermal management and cooling,cabin comfort and noise reduction of a vehicle.

There are different type of wind tunnel setting for purpose of testing , Some of them are open loop and closed loop tunnels. Open loop tunnels draws in ambient air, which makes them simper and less costly whereas Closed loop tunnels recirculate air for more stable conditions and better test to test repeatablitliy (Hucho, 2013).

Scale specific tunnels consists of full scale tunnels and model scale tunnels , full scale tunnels enables researchers to test the entire vehicles in real conditions whereas the model scale tunnels facilitate early concepy evaluations.

There are specialised tunnels made on certain facilities which are adapted for unique assessments , climate tunnel can replicate extreme temeperature and humidity whereas acoustic tunnels focus on isolating and analyzing aerodynamic noise generation.

Eventhough windtunnel testing is a powerful tool, It possesses challenges such as cost and time constraints and tunnel wall inteference where the walls can infuence the airflow patterns, which can change the results of the test. Even though adaptive walls and different methods of correction are present, perfectly replicating open road conditions remain a technical challenge (Hucho, 2013). To fully benefit from the wind tunnel testing results, researchers use its data complementary with other methods such as CFD and on road testing and validation under real world conditions which translates to tangible advantages for both customer and the manufacturer. In essence, wind tunnel testing remains a critical experimental pillar. By combining precise measurements, advanced visualization techniques, and realistic simulations of on-road conditions, wind tunnels validate designs, refine CFD tools, and ensure vehicles meet the highest aerodynamic standards before hitting the market.

8. AERODYNAMICS OF DIFFERENT VEHICLE CLASSES

Different vehicles don't put the same amount of emphasis on aerodynamics. While passenger cars focus on low drag to save fuel and make the ride more comfortable, trucks, buses, motorcycles, and other niche vehicles face different challenges and opportunities. Figuring out how aerodynamics works across this wide range of situations shows how general and flexible aerodynamic principles are.

Passenger cars are the standard example of how to improve aerodynamics. Most modern sedans has drag coefficeint values between 0.25 and 0.30, which is a big improvement from decades ago. Some strategies to achieve this are smooth underbodies, carefully shaped rooflines, flush glazing, and minimal protrusions .

Coupes often have lower Cd values because their rooflines are smoother, can achieve drag coeffiecent as low as 0.23 to 0.25. Some practicality is lost in coupes in exchange for better aerodynamics, such as less headroom in the back. This is fine for their performance-focused market segment.

With large underbody panels, thin mirrors (or cameras), and aerodynamic wheels, hybrid and electric sedans can lower Cd even more, sometimes getting close to 0.20.

SUVs and crossovers are popular because they have roomy interiors and seats that are higher up. However, their bigger frontal areas and boxier shapes make them harder for aerodynamics design. Most of the time, their Cd is between 0.30 and 0.35. Even though these numbers are higher than those for sedans, they are still much better than those for traditional SUVs, which used to be higher than 0.40. Smart underbody treatments, streamlined roof rails, and active grill shutters can all help to reduce SUV's drag. Tapered rooflines and small rear help to shrink the wake. Even with all of these efforts, it is harder to get very low Cd values because of the shape. Still, lowering drag coefficeint by 0.02 to 0.03 can make a big difference in fuel economy or range, especially given SUV’s Popularity.

Minivans have the same problems. Because they are boxy and need a lot of cargo space, they can't be tapered very much. Still, careful shaping of the front end, design of the wheel arches, and smoothing of the underbody can make the car more aerodynamic, which can improve fuel economy and noise levels inside.

Buses and heavy trucks ,tractors have different aerodynamic regimes. In the past, their high drag coeffeicient values were caused by their large frontal areas and bluff trailer shapes. At highway speeds, even small drops in Cd save alot of fuel because of how far people drive every year.

Truck aerodynamic improvements include roof fairings that connect the tractor to the trailer, trailer side skirts which stop turbulence under the body, and boat-tail extensions that smaller the wake. These steps can cut drag by 10% or more, which can save each truck thousands of litres of diesel each year.

Buses has better aerodynamics when the edges are rounded, the roof profiles are smoothed, and underbody panels are smoothened . Every improvement in aerodynamic efficiency makes electric buses more useful by increasing their range and lowering the number of times they need to be charged.

Two and three wheeled vehicles present unique aerodynamic challenges. The rider's body shape creates variability and turbulence. Motorcycles with no body enclosures have significantly higher CdA (Cd × frontal area) that is drag coeffiecient multiplied by frontal area, values than streamlined cars, ranging from 0.60-0.80 m^2. Tucking in the rider's posture can significantly reduce CdA, increasing top speed and fuel efficiency. Fairings and windscreens protect riders from high-speed airflow, increasing comfort and stability. Sports bikes use aerodynamic fairings to reduce drag and maintain control at high speeds, whereas commuter scooters use simpler front shields to improve comfort. However, complexity arises as riders move, changing the aerodynamic profile dynamically.

Three wheelers and microcars, which are popular in some areas due to their low cost, struggle with crosswind stability due to their small size and lightweight. Adding small fairings or minor shape optimizations helps to maintain stable handling. Aerodynamics in these segments frequently prioritize stability and rider comfort over extreme drag reduction.

9.CONCLUSIONS

Aerodynamics in road vehicles has progressed from a peripheral styling consideration to a core technical discipline that influences efficiency, performance, comfort, stability, and environmental impact. Over the last century, researchers and engineers have refined theoretical principles, devised sophisticated experimental methods, and used computation to better understand and optimize airflow around moving vehicles. What began as a desire for faster top speeds and better fuel economy has evolved into a broad field that influences all aspects of vehicle design and operation. This literature review has demonstrated how aerodynamics underpins a variety of concerns. Drag, lift, and unsteady flow phenomena are understood through the lens of fundamental fluid mechanics. Historical progress, from early streamlining efforts to the integration of CFD and machine learning, demonstrates a never-ending quest for efficiency and control. Modern vehicles use carefully sculpted body shapes, smooth underbodies, flush glazing, and subtle spoilers to reduce drag coefficients from more than 0.5 in the past to around 0.25 or lower today. This literature review has demonstrated how aerodynamics underpins a variety of concerns. Drag, lift, and unsteady flow phenomena are understood through the lens of fundamental fluid mechanics and boundary layer theory. Historical progress, from early streamlining efforts to the integration of CFD and machine learning, demonstrates a never-ending quest for efficiency and control. Modern vehicles use carefully sculpted body shapes, smooth underbodies, flush glazing, and subtle spoilers to reduce drag coefficients from more than 0.5 in the past to around 0.25 or lower today. However, aerodynamic development is never static. Emerging challenges, such as electrification, autonomy, connectivity, and evolving regulations, are shaping the aerodynamic landscape. Electric vehicles, which rely on maximizing range while minimizing battery costs, strive for ever-lower Cd values. To reduce fleet energy consumption, autonomous vehicles must integrate sensors without compromising airflow, maintain stability in dynamic conditions, and cooperate in platoons. Active aerodynamic devices and morphing surfaces enable real-time optimization by adapting to speeds, load conditions, and environmental factors. Similarly, the role of aerodynamics extends beyond the vehicle itself. Environmental factors such as crosswinds, rain, snow, and soiling present engineers with the challenge of ensuring reliable performance in real-world conditions. Sustainable mobility necessitates not only reduced fuel consumption or increased EV range, but also overall lifecycle improvements from manufacturing to end-of-life. Aerodynamic efficiency directly contributes to lower emissions and energy consumption, aligning automotive design with global sustainability objectives and climate initiatives.

In essence, automotive aerodynamics has evolved continuously, shaped by the interactions of technology, legislation, market forces, and environmental imperatives. Engineers and researchers ensure that future road vehicles not only use less energy and emit fewer pollutants, but also provide drivers and passengers with safer, quieter, and more comfortable rides. As transportation evolves under the pressures and opportunities of the twenty-first century, aerodynamics remains a cornerstone, demonstrating the synergy between science, engineering, and the human desire for progress.

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