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An experimental study on drag reduction of aftermarket additions on an SUV

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An Experimental Study on Drag Reduction of Aftermarket Additions on an SUV

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by

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PUBLIC PRESENTATION

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Abstract

Over recent years, the awareness of climate change has become more prevalent worldwide and one major contributor to global warming has been the use of transportation. Vehicles contribute to global warming by releasing petroleum based emissions such as significant amounts of carbon dioxide and numerous other harmful environmental pollutants. SUVs contribute to the emissions problem more so than sedans, since they have lower gas mileage and need more gasoline regularly. The main functionality of sport utility vehicles, or SUVs, includes hauling or off-roading and fuel efficiency is not always the focus in the design process. However, aerodynamic enhancements could improve fuel efficiency with minor adjustments through the addition of features such as fairings attached to the back of the SUV, underside air dams, wheel covers, and/ or full underside coverage of the SUV. This project aims to test various aerodynamic features on a 2006 Range Rover Sport, in order to identify which additions will reduce drag the most and result in improved fuel efficiency. The testing process utilizes the wind tunnel located in the Advanced Thermal-Fluids Laboratory at James Madison University (JMU). The drag coefficient of the model SUV, paired with the addition of various features, provided evidence of drag reduction. Final results show that the addition of all air dams or just front and side air dams prove to have the most significant reduction in drag. With about 19% drag reduction, fuel efficiency is improved, therefore, consumers can benefit in the long run by having a more fuel-efficient vehicle, without sacrificing the spacious design of an SUV and helping reduce their vehicle's emissions.

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Introduction

Vehicle emissions have been highlighted as a major contributor to global warming and climate change. The transportation industry has been a significant contributor to greenhouse gases, which lead to global warming. In 2014, the transportation sector contributed about 26% of the United States' carbon dioxide emissions, demonstrating that transportation plays a significant role today both economically and environmentally[1]. In order to combat the air pollution caused by vehicle emissions, various automotive companies have attempted to address this problem. Some temporary solutions range from hybrid or electric vehicles to improved aerodynamics of the vehicles. Aerodynamics of vehicles is a potential environmental solution that could be further enhanced to improve fuel efficiency and reduce the releases of vehicle emission.

History of Vehicle Aerodynamics

Large vehicles, like SUVs, tend to release more emissions than sedans, due to the fuel consumption of the vehicles. Sedans have an advantage over SUVs since they have higher gas mileage, which means sedans release less greenhouse gases compared to SUVs. Additionally, improving SUV aerodynamics could increase gas mileage, which would potentially result in less air pollution that leads to global warming. Although, carmakers have been improving SUV fuel efficiency in various ways, but their focus is not usually on the aerodynamics of the vehicle as much as it is for sedans and race cars. One of the first SUVs to come onto the market, before World War II, was the Chevrolet Carryall Suburban in 1935 (Figure 1)[2].

Figure 1. 1935 Chevrolet Carryall Suburban

The box-like shape in Figure 1, shows that aerodynamics was not the main consideration in the design of the vehicle. In 1941, the Willy's Jeep, a U.S. military vehicle, was produced during World War II and later evolved into a civilian vehicle. The jeep was created for rough terrain, but was not considered an SUV due to its open concept design. The 1946 Willy's Jeep Station Wagon came out after the war ended and proved to be an extremely similar design to the Suburban.

In the 1950s and 60s, vehicle aerodynamics were still not emphasized by engineers and automobile designers. There were ideas floating around in the automotive industry, but due to the extremely low oil prices, boxy vehicles were satisfying to most customers. Many people cared more about having stylish cars, that doubled as hauling vehicles, rather than fuel efficiency, and many still do. However, when the energy crisis occurred in 1974, the embargo caused the price for a barrel of oil to go up from \$3 to \$12[3]. In response, aerodynamic vehicles began hitting the automotive market at a much faster rate[4].

The first use of the concept of aerodynamics was used in the design of aircrafts. From those designs, some car companies started creating racing vehicles, which incorporated a boat tail design[5]. As race cars became faster, their designs were used to influence the designs of everyday economical vehicles, such as sedans and SUVs. Once the rise of the use of aerodynamics in the design of cars emerged, automotive companies have continued to take design risks, to create vehicles that are different from the "normal looking" vehicles available in the market. Slowly, the designs improved and became more complex, but the basic concepts are still present.

The design of the SUV has slowly been altered to be more aerodynamic, but that is usually not the main focus for the designers. However, crossover models are being sold to serve as the middle ground between sedans and classic SUVs. The classic SUV has been disappearing in recent years and resembles smaller, softer line versions of their originals. For example, the Land Rover Discovery was first produced in the United Kingdom in 1989, but wasn't brought to the United States until 1994. There were very few changes in the SUV design over that time period. The vehicle was used for a variety of tasks like hauling and off-roading, as well as having a significant spacious design.

Figure 2. 1994 Land Rover Discovery

Figure 3. 2017 Land Rover Discovery

Figures 2[6] and 3[7] clearly show how the design of the Land Rover Discovery has changed over the years to become sleeker and more aerodynamic. It is common today for all car models, even some trucks, to incorporate more aerodynamic features, to improve fuel efficiency and, therefore, allow drivers to travel farther on the same tank of gasoline. However, there are other ways to keep improving fuel efficiency through aerodynamics.

Public Policy Issues

While reading through the U.S. National Highway Traffic Safety Administration (NHTSA) standards, specific regulations on aerodynamic additions such as front spoilers, undercar panels, fairings, etc. are not clearly mentioned. Most additions are legal in the United States, but it depends on the accessories added. Some features that are standard for vehicles in the U.S., cannot be removed like side view mirrors. For example, some car companies have come out with high-end vehicles that do not have side view mirrors (Figure 4)[8].

Figure 4. The Volkswagen XLI

The Volkswagen XLI is currently the most aerodynamic car in the world with a C_d of 0.19. It is a requirement of U.S. vehicles to have these mirrors, for safety reasons. However, other companies claim that the mirrors cause severe aerodynamic drag. If they were removed, the efficiency of the car would reduce drag by about 6%. Also, there is a new term, 'slippery,' that is being used to describe aerodynamic vehicles. The more 'slippery' the vehicle, the more fuel efficient it is. Many car designs today have incorporated a rear underside plastic bumper and exhaust system as pictured in Figure 5[9].


Figure 5. Underside plastic bumper and exhaust system

There are grooves on this panel which allows the air to flow more easily, creating less drag and a more 'slippery' vehicle. Most of these features are occasionally utilized in the United States, as well as in Europe, although European vehicle regulations are slightly more lenient, meaning companies have more flexibility with vehicle designs. Due to the strict U.S. safety standards that are in place, it is quite difficult for car makers to adjust designs for better aerodynamics and fuel efficiency. The biggest issue would probably have to be the weight of the vehicle. In the U.S., vehicles must be heavy, to be considered safe and crash test worthy[10]. Heavier cars, however, are less efficient. Therefore, until there is a compromise on that issue, most U.S. car makers have taken other routes to improve efficiency, while still adhering to U.S. vehicle standards.

Stakeholders

There are multiple levels of stakeholders when it comes to SUV aerodynamics. The consumer is probably the main stakeholder since they choose what vehicles to buy. They are the critics, the observers, and the testers. If the consumer likes the vehicle, it sells, but if they do not, then the vehicle does not sell and companies lose profits. Therefore, all the parts associated with an SUV, its design, color, shape, and size, all matter during the purchasing process.

The other stakeholder is the SUV manufacturer. The companies making their SUV's are directly impacted by the selling of their vehicles. If the consumer does not buy the company's vehicle, then the company suffers. On the other hand, if the SUV does sell, then the company prospers. The company is a stakeholder because they thrive on the choices that consumers make.

The stakeholders can also be the engineers[11] and designers of the SUV's. These designers have the duty to create images that will become the next best vehicle. A design can lead to the manufacturing of a new SUV model. These engineers and designers have their jobs on the line when they are working for various companies. In the eyes of the companies, the vehicles need to sell. If an SUV is made from a design that an engineer created, and that SUV model does not sell, then someone may be blamed. Therefore, the engineers and designers are stakeholders, with their jobs on the line.

Cultural Dynamics

The most obvious cultural dynamic regarding the redesign of an SUV would have to be the public perceptions. It is not always common for people to take a risk when purchasing a vehicle, because they want to know that what they are getting is safe, affordable, economical, etc. Therefore, today we see that many SUV companies create similarly designed and shaped vehicles. Many companies do this because they know the style of vehicles that sell well. Some companies take design risks in small ways, but not in seriously different ways. Such risks could include a redesign of a vehicle to have better aerodynamics, but usually only high end SUV companies create these different designs. Due to the lack of variety in SUV designs these days, the idea to create an altered SUV design, will not be very different from what people already know. It is important to take into consideration what people might think of a car that has various new features, because if those features do not stand out very much, and the shape and structure of the vehicle stays the same, then people would probably still be inclined to purchase the vehicle.

Another cultural dynamic present in the SUV industry includes differing opinions between the SUV companies themselves and between those companies and the legislators and regulators. Since efficiency is important in the design of SUVs, most companies want to create vehicles with improved fuel efficiency, but most of the time, regulators shut down those designs. Due to the strict regulations on vehicles in the U.S., the SUV companies must find other areas to improve fuel efficiency, which can be in very small amounts. Many companies have taken risks in vehicle designs, which have sometimes paid off and have sometimes failed, such as the example in Figure 6.

Figure 6. 1959 Ford Edsel

The Ford Edsel[12] was launched in 1958 and is still remembered as one of the 50 worst cars of all time. This is because the Ford marketing team led the public to believe the car would be some kind of 'wondercar,' but ended up resembling a Mercury brand car[13]. Long-standing cultural history beliefs is also a cultural dynamic present. Many companies want to stay true to their brand and their history when creating a new design, but sometimes it is difficult to stay true to tradition. Now that technology has improved so much in the last 50 years, SUVs have also improved in various ways, and many times they improved in their exterior designs. Many SUVs today have better fuel efficiency, partly due to the aerodynamics of the vehicle. There are plenty of SUVs that have been improved in just 15 years, but they could still be enhanced. If people become inclined to purchase a vehicle that has minor improvements, may look different from what they know, but in the end, is more fuel efficient, they will end up saving money down the road.

When consumers are looking at buying a new car, they usually want the luxury of the SUV and overlook the fuel efficiency and may not always use their vehicles for hauling, towing, off-roading, or carrying multiple passengers. Consumers tend to drive their SUV's on highways or for long distances, without utilizing any typical SUV functions. Sedans can travel farther than SUVs, due to the miles per gallon availability of both types of vehicles. In many states across the United States, people living in rural areas are more likely to own SUVs. They typically utilize SUVs for their true purpose, rather than urban drivers who mainly enjoy the use of greater passenger capabilities and aesthetics of the vehicle. It is common to see consumers purchase vehicles that look appealing, rather than using them for a specific function. For years now, the trend has been to live in suburbs outside cities, therefore, causing people to commute to work more often. Carpooling, metro, bus, and biking are still great alternatives for commuting, however, many people still drive to work, even with SUVs. Plenty of people commute long distances just to get to work every day. It is not uncommon to see people traveling over an hour to get to their workplace. Many people who enjoy the rural, country lifestyle, potentially work in areas far away from where they live. Though, due to where they live, they drive SUVs in order to haul materials and/or manage the rough terrain. Therefore, some families might have SUVs instead of sedans, causing them to drive to work with a less economical vehicle.

Aerodynamic Features

In order to potentially reduce air pollution from vehicles emissions, the addition of underside parts, such as air dams (or spoilers) and/or full underside coverage with flat horizontal paneling, could reduce drag on SUVs, therefore, improving fuel efficiency and lowering vehicle emissions. The underside paneling would minimize the open area under the car, meaning it would reduce the amount of air moving underneath the vehicle and creating lift, which can also reduce the stability of the SUV[14]. The lower the amount of lift for a car, the closer the vehicle is to the ground, therefore, allowing air to move over the car in a less resistive way. The addition of panels that extend from the back of the SUV, called fairings, would streamline the air flow over the SUV and minimize the vortexes (rotational flow) in the wake of the vehicle. Today, many 18-wheeler trucks have fairings attached to the back to make the flow over the truck more streamlined and to minimize drag[15]. These trucks also have vertical underside paneling, like air dams, which lowers the amount of air resistance created by the truck, and can improve fuel efficiency (Figure 7)[16].

Figure 7. 18-Wheeler truck fairings and side air dams

Wheel covers are also a possible option as they would reduce the amount of air that gets trapped between the openings in tire rims. All features could be added to an SUV design in an aesthetically pleasing way, in order to improve fuel efficiency.

Background on Drag

The drag coefficient, C_d, is the dimensionless number used to compare drag between the model SUV and the actual SUV with and without the added features. Drag is created when a fluid is exerted onto an object in the flow direction[17]. In this case, the fluid is air and the object is the model SUV. Drag is usually an undesirable effect that occurs with every object moving through a fluid. Therefore, sedans have a drag coefficient just like SUVs, but due to the small size of the sedan, its C_d is lower than an SUVs. A typical sedan, like a Toyota Camry has a C_d of 0.31, but a typical SUV, like a Ford Explorer has a C_d of 0.43[18]. This shows that as the vehicle gets taller and more rectangular, the drag coefficient increases. The air flow moves around an object and comes to the region behind the object, the wake, where vortices can be formed in the case of an SUV. Since flow separation is common with SUVs, circulating fluid chunks can move over the vehicle and shed in the wake of the vehicle. Flow visualization is a great tool used to observe the separation point in the air flow, along with the wake region. This can be done by using a smoke flow visualization, or thin threads attached to the SUV, to see the streamlines of the air flow over the SUV. The turbulent boundary layer is the region above the object, where the fluid does not move at a constant rate. Usually, there is a transition from laminar to turbulent flow, however, with most SUVs, the flow jumps to turbulent flow almost instantaneously.

There have been numerous papers written on drag reduction and aerodynamics, however, this paper emphasizes techniques that can be utilized on a variety of SUVs. The Journal of Wind Engineering and Industrial Aerodynamics published a paper that discussed a modified cab-roof fairing (CRF), which significantly changed the flow structure on a scaled model of a 15-tonne truck[19]. From the experiment, the CRF reduced the truck's drag by about 19%. An article cited by the paper discussed a vehicle addition that is also being tested in this thesis, the underbody coverage. The final results from the article mention that with the addition of a small underbody cover board, there was a drag reduction of about 2%[20]. The Journal of Visualization published a paper on "Drag-reducing underbody flow of a heavy vehicle with side skirts" which provided results of a 3.1% drag reduction for a straight-type side skirt, but with a flap-type side skirt the drag reduction was 6.1%[21]. According to these sources, it seems likely that the experimental testing conducted for this project could yield promising results.

Project Goal

The purpose of this project is to experimentally study the aerodynamics of an SUV, specifically associated with features that could reduce drag on a model SUV and, therefore, improve fuel efficiency. Features tested on the model SUV include fairings, wheel covers, full underbody coverage, and air dams. If the features provide significant drag reduction, they could be part of an aftermarket "eco" package, in which consumers could purchase any particular feature combination from their desired car company. The use of aftermarket additions could potentially help reduce vehicle emissions and minimize the environmental impact.

Methodology

Fuel efficiency has been overlooked by the automotive industry, with regard to SUVs. The burning of excess fossil fuels is detrimental to human and environmental health, therefore, simple aerodynamic additions could help reduce the vehicle emissions produced by SUVs. To test this hypothesis, a scale model SUV was used to measure drag, which is directly related to fuel efficiency. The higher the drag reduction, the more fuel the SUV can consume, therefore, the vehicle will use less gasoline and will release less air pollution.

Materials

Table 1 below, lists all the materials used throughout the duration of the project.

Table 1. Materials used for experimental testing

Materials		
1	Drawing Materials/ Devices	• Computer • Pencil • Eraser • Sketchpad
2	2006 Range Rover Sport 1/18 Diecast Model Car by Maisto	
3	Feature Materials	• Premo! Sculpey® Accents™ Oven Bake Clay • Air dry clay • Plastic roller for clay • ArtMinds™ Flexible Clay Cutter • Sculpey® Modeling Tools • Toaster Oven • Aleene's Instant Tacky • Mod Podge Water-base sealer, glue & finish • Sponge brush (x2) • Cardboard • Scissors • X-Acto Knife • Steel Utility Knife • Computer with the Solidworks (3D) software installed • 3D printer and filament

<table>
<tr><td>4</td><td>Windows for car</td><td>Plastic sheet (used originally, but broke)
About 1/16” thick Aluminum piece (final version)</td></tr>
<tr><td>5</td><td>Aluminum Custom Made Dynamometer SUV Holder</td><td>Rounded Head Thread-Forming Screws for Brittle Plastic, 410 Stainless Steel, Number 4 Size, ½” Long, packs of 100
Multipurpose 6061 Aluminum, Rectangular Bar, 3/8” x 2-1/2”, 2’ Long
Screwdriver</td></tr>
<tr><td>6</td><td colspan="2">Safety glasses</td></tr>
<tr><td>7</td><td>Wind Tunnel
(Located at the ATF lab)</td><td>Mesh Screen
Dynamometer
Calibration Materials
Range of weights in grams
Orange synthetic rope (4 mm diameter)
Metal stand and clamps
2 small pulleys
Allen Wrench set
Two ½ inch screws
Power source and circuit boards
Red and black banana plugs
Multimeter set to DC Voltage
Oscilloscope set to show average Voltage
Plug for test section window
1’ x 1’, 2” thick Acrylic block
Pitot-Static Tube (1/8th Diameter)
Plastic tubing
Handheld Digital Pressure Meter
Dwyer 1227 Dual Range U-Inclined Manometer, 0-16” W.C.</td></tr>
<tr><td>8</td><td>Flow Visualization Materials</td><td>Orange synthetic rope (4 mm diameter)
Scotch tape
Smoke generator
High speed camera (Model: 60K M1)</td></tr>
</table>

Methods

<u>Background</u>

To properly begin the project, academic literature was studied for multiple topics associated with aerodynamic principles, as well as various SUVs. The *National Committee for Fluid Mechanics Films*[22] videos and reading materials, including the *Engineering Fluid Mechanics*' Textbook Chapter 8 were provided as a resource by Dr. Karim Altaii, to begin preliminary study on my own regarding drag reduction, flow visualization, fluid dynamics, dimensional analysis, and boundary layers. Other reading materials were obtained through the JMU library in book and electronic article format.

Online study of SUVs was conducted to determine which vehicle could appropriately represent the aerodynamic deficiencies in the automotive industry. An SUV with a box-like shape seemed to be the best type of vehicle to use to observe how aerodynamic additions could reduce drag, and therefore improve fuel efficiency. Since it takes more fuel for an SUV to move through the same air as a sedan, the boxy shape acts as an appropriate representation for a typical SUV seen throughout the years.

Ideally, a sponsorship from a car company would have been helpful in obtaining an appropriate replica of their vehicle which could be used for experimental testing. The various car companies that were contacted include Ford Motor Company, Land Rover, General Motors, Chrysler, and Jeep. Since these companies were unable to provide a proper replica, other means were taken in order to conduct testing, which will be explained in the Model and Feature Design section.

Preliminary Calculations

Once the aerodynamic principles were understood, Reynolds Number (1) calculations were completed to find the appropriate speed for wind tunnel testing that is equivalent to a highway speed of 60 mph for the actual SUV.

$$Re = \frac{\rho V L}{\mu} \tag{1}$$

Re = the Reynolds Number, (dimensionless quantity)

ρ = density of air, (1.205 kg/m^3) – at standard atmospheric pressure and temperature

V = velocity of fluid (air), (m/s)

L = characteristic length, (m) – in this case, the length of the SUV

μ = dynamic viscosity, (1.983 x 10^{-5} kg/m.s) – at standard atmospheric pressure and temperature

The Reynolds Number equation (1) is used to relate a model and actual object by density, velocity, characteristic length, and dynamic viscosity. The Reynolds Number, a dimensionless number, is used to determine dynamic similarity. The number should be the same for both the actual and model SUV. Originally, the 2010 Range Rover Sport HSE was chosen to be 3D printed at a length of about 9 inches, using a drawing file found online that was compatible with Solidworks, the 3D software we were using. However, when the Reynolds Number was calculated using the actual SUV's length at the speed of 60 mph, the result was larger than expected. The result just obtained was then used to find the equivalent velocity that could be tested with model SUV. After completing the calculation, the velocity equivalence was 561.5 m/s or 1,256 mph, which is a supersonic speed. From these findings, it is not possible to test the model SUV at a size of approximately 9 inches at the equivalent speed of a full-sized SUV moving at highway speed. The equivalent speed would be well over the capability of the JMU wind tunnel, which is a subsonic wind tunnel. This was an issue mentioned in the paper "Effects of rear spoilers on ground vehicle aerodynamic drag." Also, the book, "The Illustrated Guide to Aerodynamics," has a section on scale effect under Wind tunnel testing problems, stating that "running the tunnel faster might not be possible, and even if it were, we would probably have to go so fast that we would encounter Mach effects, again invalidating our test data." This excerpt from the book, clearly mentions the same issue that occurs with scaling methods just mentioned. One possible solution was to pressurize "the wind tunnel as NACA", or NASA today, "did in its variable-density tunnel; however, this is a complicated and expensive proposition"[23]. This technique was also mentioned in two other books, *A history of aerodynamics and its impact on flying machines*[24] and *Low-speed wind tunnel testing*[25]. Since this problem has arisen, academic literature was used to find information that supports the testing of a model at various speeds. Some papers that have tested models at various speeds include, "Investigating the Drag Coefficient Of Scaled Model Car By Using Wind Tunnel"[26], *In Depth Cd/Fuel Economy Study Comparing SAE Type II Results with Scale Model Rolling Road and Non-Rolling Road Wind Tunnel Results*[27], and *Experimental Investigations on Aerodynamic Characteristics of a Hatchback Model Car Using Base Bleed*, just to name a few. Therefore, the decision was made to test the model SUV with the available speed of the JMU wind tunnel, rather than the speed of dynamic similarity.

Model and Feature Designs

Once a 3D file for the 2010 Range Rover Sport HSE was obtained, it was evident very quickly that the file was unstable and would not produce an accurate 3D model. Therefore, a toy model SUV was purchased. The SUV purchased was the 2006 Range Rover Sport (Figure 8) at a 1/18 scale[28]. This was similar to the original model choice of the 2010 Range Rover Sport HSE.

Figure 8. 2006 Range Rover Sport 1/18 Diecast Model

Before the SUV was even chosen, four feature designs were developed on paper, then eventually made using oven bake clay. Jenna Altaii assisted in the clay feature construction, as well as demonstrating the use of the glaze to protect the clay pieces. The oven baked clay proved to be a suitable option for feature construction due to its durability and the smoothed surface created by the glaze, which was added after the baking process. The preliminary designs (Figure 9) were drawn before the 2010 or 2006 Range Rovers were chosen. The designs were used to help construct the features that would attach the model SUV.

Figure 9. Preliminary drawings for wheel covers, air dams, and fairings

The wheel covers, fairings, and side and back air dams were all made from clay. The grey fairings were constructed at first, but redesigned and thinned to make the pink ones in Figure 10. The side and back air dams, as well as wheel covers were constructed only once.

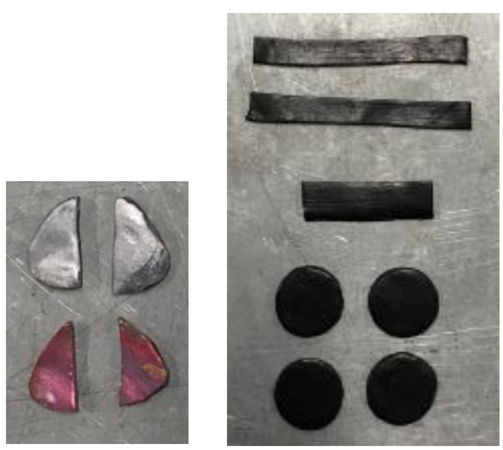

Figure 10. Fairings, side and back air dams, and wheel covers

The full underbody coverage and front air dam took a few trials to construct as well, with use of clay and ultimately 3D printed (Figure 11). They were designed using Solidworks software, then 3D printed, with the help of the James Madison University's Machine Shop and Engineering Department.

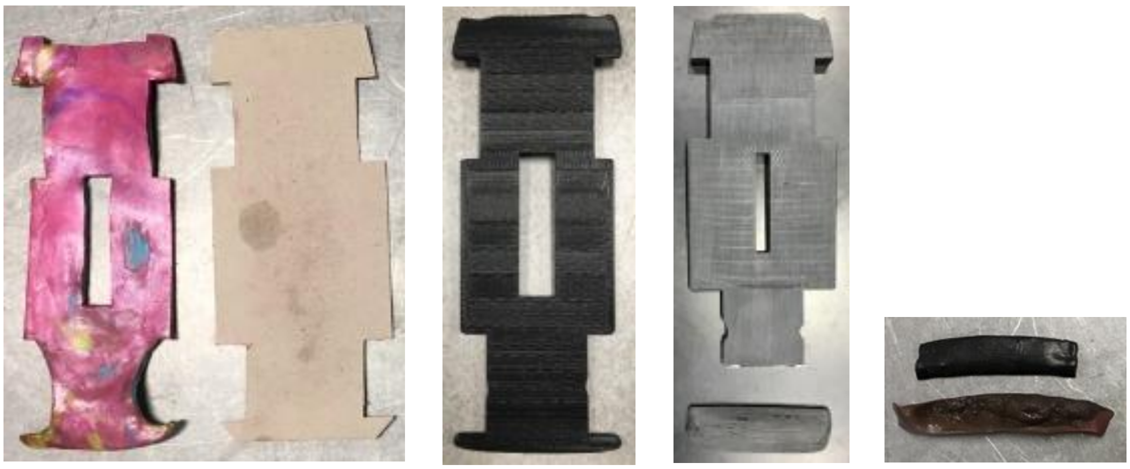

Figure 11. Full underbody coverage and front air dams

Makeshift aluminum windows were cut and shaped by the JMU Machine Shop, since the toy model SUV did not come with front windows (Figure 12). All features were attached using sticky tack.

Figure 12. Makeshift metal windows for model SUV

The experimental testing of the features on the model SUV was conducted in the wind tunnel (Figure 13) at the James Madison University (JMU) Advanced Thermo-Fluids Laboratory.

Figure 13. JMU Wind Tunnel

Dynamometer Calibration Testing

Calibration testing for the dynamometer (Figure 14) was conducted to find the relationship between the output voltage and the mass, which can be related to force.

Figure 14. Dynamometer

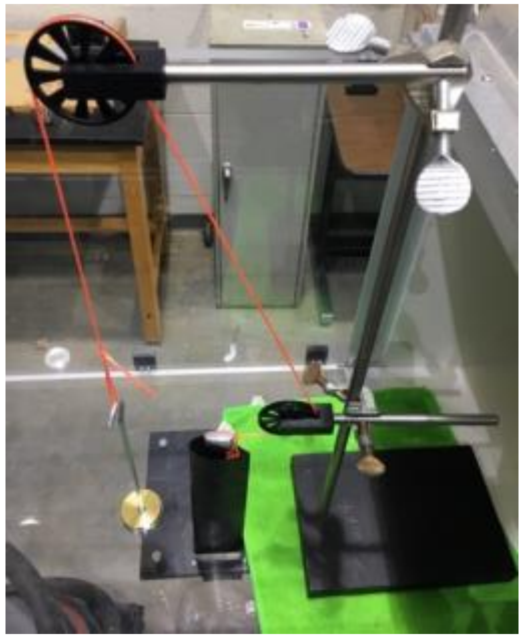

Figure 15. Dynamometer calibration setup

The calibration testing was conducted by using metal weights ranging from 0 to 900 grams and a multimeter set to measure DC Voltage. The mass in grams (g) was converted to kilograms (kg) and correlated to the corrected voltage values to show the linear relationship in the data, using Microsoft Excel. Corrected voltage was calculated by subtracting the first drag voltage reading from all subsequent drag voltage readings, since the dynamometer did not read 0 volts at the beginning of any of the trials. Three trials of calibration testing from 0g to 900g back to 0g was done two ways. The first consisted of hanging the weights vertically from the pulleys in the wind tunnel test section (Figure 15). The second method was conducted by laying the dynamometer on its side on a table and resting the weights on the metal mount attachment. As the downward force increases and decreases, the voltage output also increases and decreases, creating the linear relationship. From that relationship, a trendline (2) was obtained using Microsoft Excel, to convert drag voltage to drag force by using the slope from the calibration trendline (4). In equation 2, the y-variable represents the mass in kilograms and the x-variable represents the corrected voltage values. As mass increases, voltage increases, which creates a linear relationship. The force equation[29] (3) was restructured to incorporate the slope, voltage, and acceleration in order to cancel out the mass term, therefore, equation 4 incorporates equations 2 and 3 in order to obtain drag force.

$$y = 0.2134x - 0.0055 \tag{2}$$

$$F = ma \tag{3}$$

F = force, (N)

m = mass (kg)

a = acceleration due to gravity, (9.8 m/s^2)

$$F_D = 0.2134Va \tag{4}$$

F_D = drag force, (N)

V = corrected voltage, (V)

a = acceleration due to gravity, (9.8 m/s^2)

The second calibration method was conducted in order to observe a more precise linear relationship, however, the trendline from the first calibration method was used in the drag force equation 4. The drag coefficient could then be calculated by using equation 5 below.

$$F_D = \frac{1}{2}\rho v^2 C_d A \tag{5}$$

F_D = drag force, (N)

ρ = density, (kg/m^3) – calculated at test conditions

v = velocity of fluid (air), (m/s)

C_d = drag coefficient, (dimensionless quantity)

A = frontal area, (m^2)

The frontal area was calculated by taking a photo of the front of the model SUV with a ruler (Figure 16) and then uploaded to Solidworks to sketch the perimeter of the front of the car (Figure 17). The ruler was used to determine size, therefore, allowing the Solidworks program to calculate the frontal area in inches^2 and meters^2.

Figure 16. Photo used for frontal area calculation


Figure 17. Sketch of frontal area of the model SUV in Solidworks

Before the model SUV's drag coefficient was determined, the actual SUV's drag coefficient was obtained as a reference. The published C_d for the 2006 Range Rover Sport is 0.37[30], which is typical of most SUVs around the world. However, the C_d measured for the model SUV, 0.69, was used as the reference when comparing to the drag coefficient for the SUV with the features, in order to appropriately observe any drag reductions.

To confirm that the dynamometer was accurately calibrated, a smooth sphere was tested in the wind tunnel to compare the drag coefficient obtained from testing to the published smooth sphere's C_d of 0.5[31]. The calculated C_d for the sphere, 0.5, matched the published drag coefficient, therefore, showing that the dynamometer calibration was accurate.

A custom-made mount (Figure 18) for the dynamometer was made by the JMU Machine Shop to appropriately fit the model car in the wind tunnel test section on the dynamometer itself as denoted by the black arrow below.

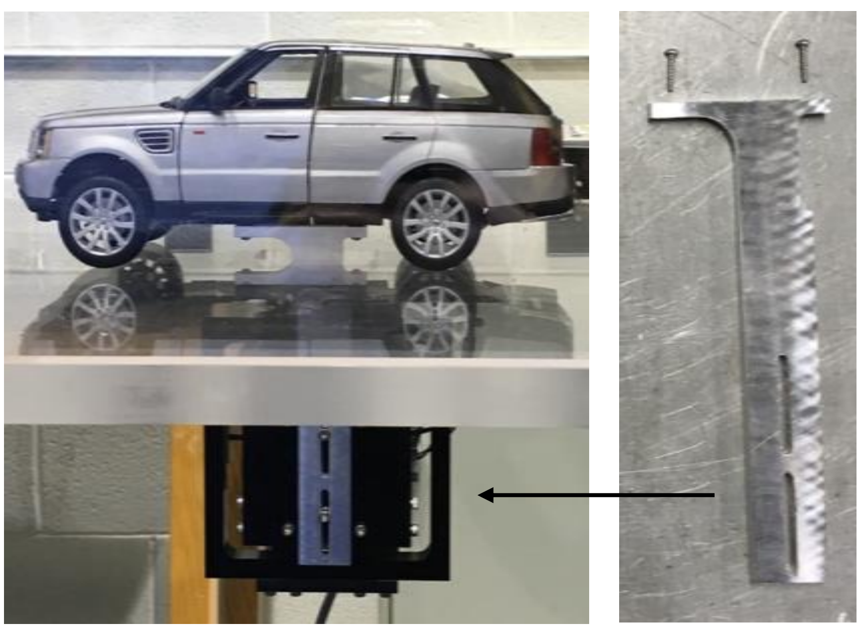

Figure 18. Custom made dynamometer mount with SUV in wind tunnel test section

Pitot-Static Tube Calibration Testing

The pitot-static tube (Figure 19) was also calibrated to be sure that the pressure difference output from the digital and U-Inclined manometers (Figure 20) was the same. The calibration test was also necessary in order to obtain the relationship between speed of the wind tunnel in Hertz (Hz) versus velocity in miles per hour (mph).

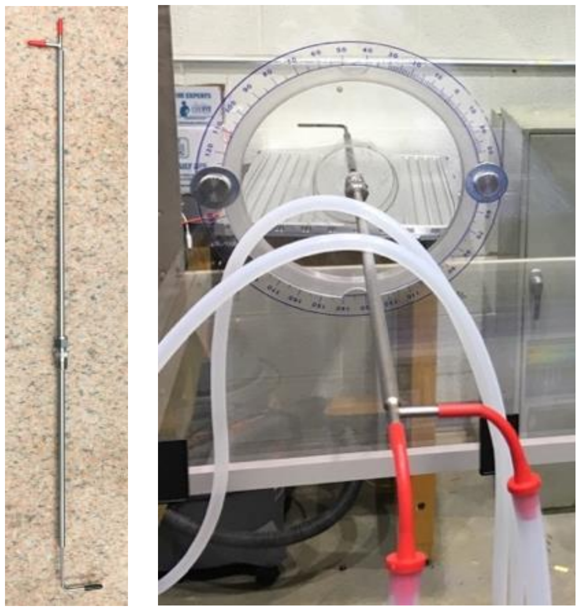

Figure 19. Pitot-static tube and custom made wind tunnel plug

Figure 20. U-Inclined and digital manometers

The JMU Machine Shop made a replica of the wind tunnel test section acrylic plug (Figure 19) with an opening for the pitot-static tube to allow for pressure readings while testing was conducted. The black arrow points to the digital manometer and the dashed black arrow points to the U-Inclined manometer (Figure 20). Before the calibration could be done, the density of the air in the wind tunnel test section had to be determined. Bernoulli's equation[32] (6) was reconfigured into two equations, which allowed for the calculation of density of air for the digital (7) and U-Inclined (9) manometers. However, the ideal gas law equation (8) was also used in density calculations.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho a h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho a h_2 \tag{6}$$

P = pressure, (N/m^2)

ρ = density of fluid (air), (kg/m^3)

v = velocity (m/s)

a = acceleration due to gravity, (9.8 m/s^2)

h = height of fluid, (meters of water)

$$P_d = \frac{1}{2}\rho v^2 \tag{7}$$

P_d = dynamic pressure, (N/m^2)

ρ = density of fluid (air), (kg/m^3) – calculated at test conditions

v = velocity (m/s)

$$P = \rho RT \tag{8}$$

P = absolute pressure, (N/m^2)

ρ = density of fluid (air), (kg/m^3) – calculated at test conditions

R = individual gas constant, (J/kg)

T = temperature (^{o}C)

The dynamic pressure[33] equation (7) is used to calculate density of air using the digital manometer pressure difference output. The digital output is measured in kilopascals (kPa); therefore, conversions were done to find Pascal's (Pa). In order to have the correct units for the dynamic pressure equation, Pa were converted to N/m^2, which is a 1:1 ratio.

$$\Delta P = \rho a \Delta h \tag{9}$$

ΔP = pressure difference, (N/m^2)

ρ = density of fluid (air), (kg/m^3) – calculated at test conditions

a = acceleration due to gravity, (9.8 m/s^2)

Δh = depth of fluid, (meters of water)

The fluid pressure calculation[34] (9) was used to calculate the pressure difference from the change in the inches of water, which was converted to meters of water. Since both equations are derived from Bernoulli's equation, they can equal each other. Both the digital and U-Inclined manometers measure the same variable; therefore, the pressure difference should be relatively the same. The pressure from both devices was used to find the air velocity in m/s and in mph.

Figure 21. Wind tunnel speed adjuster

The speed measured in hertz (Figure 21), used by the wind tunnel, was converted to air speed, velocity in miles per hour. Therefore, the pressure difference measurements were used to calculate velocity in m/s then converted to mph. After all the calculations were conducted, the pitot-static tube calibration could be completed to confirm that there is a linear relationship between the wind tunnel speed in hertz and velocity in mph for both the digital and U-Inclined manometers. The testing ranged from 0 mph to approximately 71 mph and back down to 0 mph, with a mesh screen inside the wind tunnel test section, with and without the SUV model. The mesh screen prevented any features or parts of the model SUV from coming off and getting stuck in the wind tunnel. Due to the pressure diffidence calibration testing, the digital manometer was used for the remainder of the experimental testing.

The density had to be recalculated for each of the three trials for each experimental test. This process consisted of recording barometric pressure and air temperature. Those values were obtained by a small weather system located in the Advanced Thermo-Fluids Laboratory, near the entrance of the wind tunnel to obtain the most accurate readings. The atmospheric barometric pressure output was given in inches of mercury (in Hg), but needed to be converted to hectopascals (hPa)[35] in order to properly calculate density in (kg/m^3)[36]. The ideal gas law (equation 8) was used in a Microsoft Excel spreadsheet to calculate and convert the necessary variables. Testing was conducted for the car with the metal windows, but with no features.

Experimental Testing of Features

The features were then attached to the model SUV and tested three times; each time pressure from the digital manometer was recorded, along with drag voltage from the multimeter (Figure 22).

Figure 22. Multimeter and Oscilloscope

An Oscilloscope (Figure 22) was used to observe the noise in the drag voltage readings, therefore, providing a second source of reliable data for drag voltage. The four main features tested include fairings, wheel covers, air dams, and full underbody coverage.

The features and combinations were tested in the following order:

1. Wheel Covers only
2. Fairings only
3. Wheel Covers and Fairings
4. Side Air Dams
5. Back Air Dam
6. Front Air Dam
7. All Air Dams
8. Wheel Covers and All Air Dams
9. Fairings and All Air Dams
10. Full Underbody Coverage
11. Wheel Covers and Full Underbody Coverage
12. Fairings and Full Underbody Coverage
13. Front and Side Air Dams
14. All Features
15. All Features and No Windows
16. No Windows

It is important to note that the full underbody coverage feature was 3D printed to incorporate the front air dam and the coverage of the underside of the vehicle. The front and side air dams were tested towards the end of the experimental testing process, since the front and side air dams showed promising results as separate features. Therefore, they were tested together to observe any significant changes in drag. All features refer to the addition of the wheel covers, fairings, and full underbody coverage. The testing of no windows was meant to see how much drag is increased when the windows are down while driving this particular model SUV. Drag reduction was then calculated by using equation 10.

$$\frac{Model\ Drag\ Coefficient - Feature\ and\ Model\ Drag\ Coefficient}{Model\ Drag\ Coefficient}$$
$$= Difference\ in\ Drag\ Coefficient \times 100 = Percent\ Drag\ Reduction \tag{10}$$

<u>Mileage Improvement and Fuel Savings</u>

Once the percent drag reduction was obtained, for the best feature combination, this reduction was used to calculate the total highway MPG (miles per gallon) improvement (11) for the actual SUV[37].

$$Highway\ MPG \times Percent\ Drag\ Reduction = MPG\ Improvement + Highway\ MPG$$
$$= Total\ Highway\ MPG\ Improvement \tag{11}$$

Fuel savings calculations were completed to see the amount of money saved yearly if the best feature combination was used[38].

$$\frac{Miles\ Driven\ per\ Year}{MPG} \approx Gallons \tag{12}$$

$$Gas\ Price\ per\ Gallon * Gallons = Annual\ Fuel\ cost \tag{13}$$

$$Annual\ Fuel\ Cost_1 - Annual\ Fuel\ Cost_2 = Annual\ Savings \tag{14}$$

Flow Visualization and Additional Testing

Flow visualization was the last step in the testing process, which aimed to show how the air moves over the model SUV in the wind tunnel, which produced a visual representation in order to observe any irregular flow patterns at a particular speed. A high-speed camera filmed 1.361 seconds of smoke moving over the model SUV in the wind tunnel. That is about 1000 frames per second, but the video was converted and viewed at about 30 frames per second. Due to a surprising drag voltage spike around 10 mph for all trials, flow visualization was the best way to observe any patterns that could account for the irregularity in the data. The custom made mount was tested alone and with a metal boat shaped block (Figure 23) in the wind tunnel in order to see if the sudden spike in the experimental testing trials still occurred.

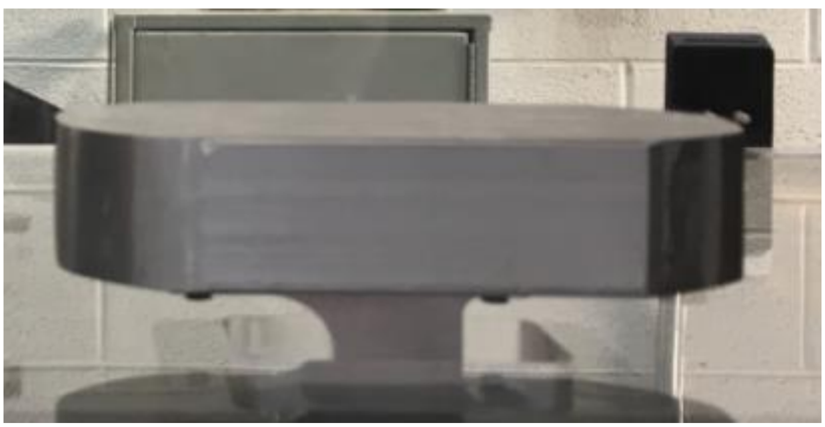

Figure 23. Metal block on custom made mount

Results

Environmental awareness is increasingly important nowadays, which makes the use of aerodynamic features seem useful and helpful in reducing vehicle emissions by reducing drag and improving fuel efficiency. The toy model SUV proved to be a successful purchase throughout the experimental testing process. All four features including fairings, wheel covers, air dams, and full underbody coverage, and combinations showed promising drag reductions.

Dynamometer Calibration

The dynamometer calibration results showed a linear relationship between mass in kilograms (kg) and drag voltage in volts (V). The two calibration methods were used due to the lack of precision from the first calibration test. The first method consisted of hanging the metal weights on the pulleys connected to the dynamometer in the wind tunnel test section. The second method had the dynamometer on laid on its side, outside the wind tunnel, with the metal weights placed on top of the dynamometer. Three trials were completed for both calibration methods and trendlines were created, however, the trendline for the first calibration test was used throughout the remainder of experimental testing, since both trendline slopes were extremely close (Figure 24).

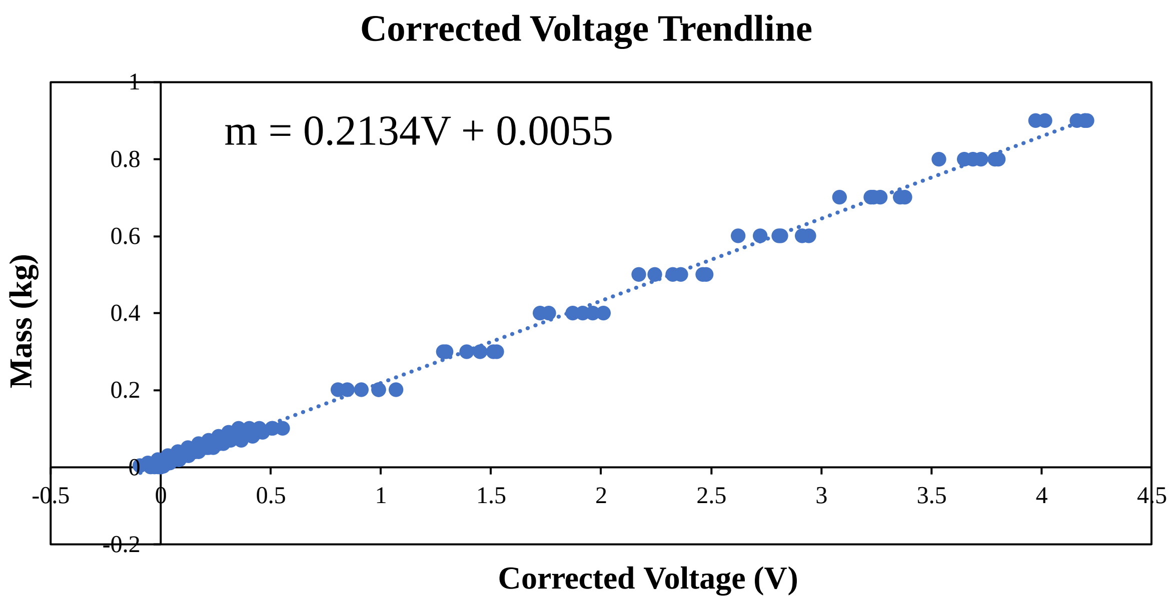

Figure 24. First dynamometer calibration test

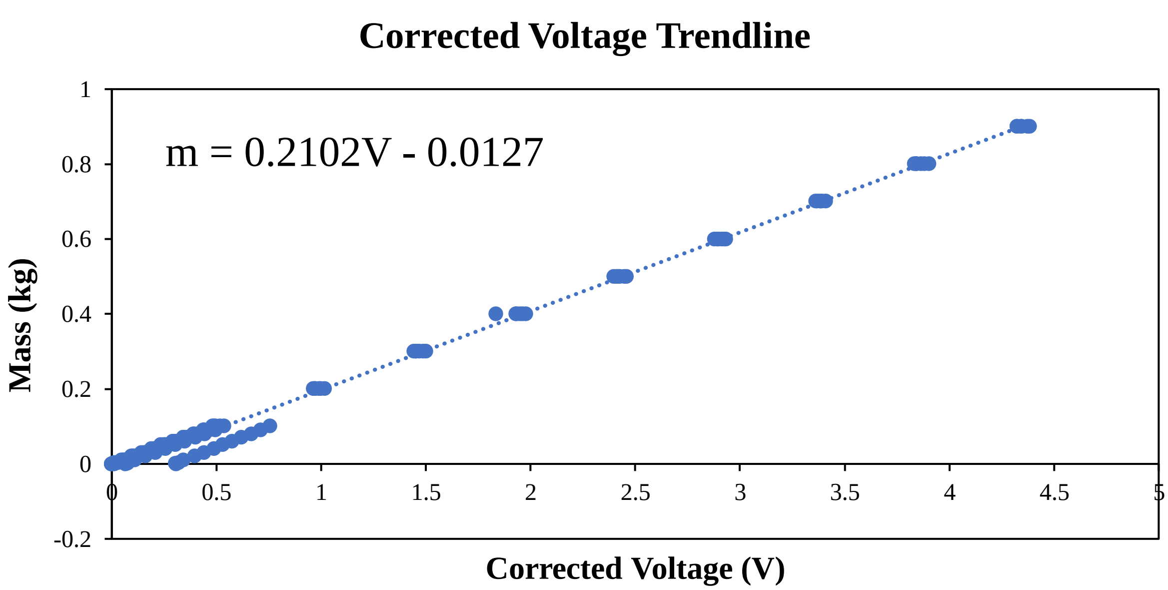

Figure 25. Second dynamometer calibration test

A smoothed sphere was used to prove that the dynamometer calibration was accurate, therefore, providing appropriate drag voltage readings for experimental testing. It became apparent very quickly that the drag coefficient for the smooth sphere matched the published value of 0.5. Therefore, this proves that the dynamometer drag voltage readings were accurate and not the reason that the model SUV's C_d is 0.69 instead of the actual SUV's published C_d of 0.37. There were readings that did not reach zero volts as the weights decreased, however, it can be assumed that there was some error with the second method (Figure 25) of calibrating. In order to obtain the drag voltage readings as accurate as possible, the dynamometer was manually held against the table surface to observe less fluctuation in the drag voltage readings. That very well could be the source of error in the second calibration graph.

Pitot-Static Tube Calibration

The Pitot-static tube calibration was completed to show the relationship between pressure and speed of the wind in the wind tunnel. The digital and U-Inclined manometers were compared to establish a trend between both devices' pressure readings.

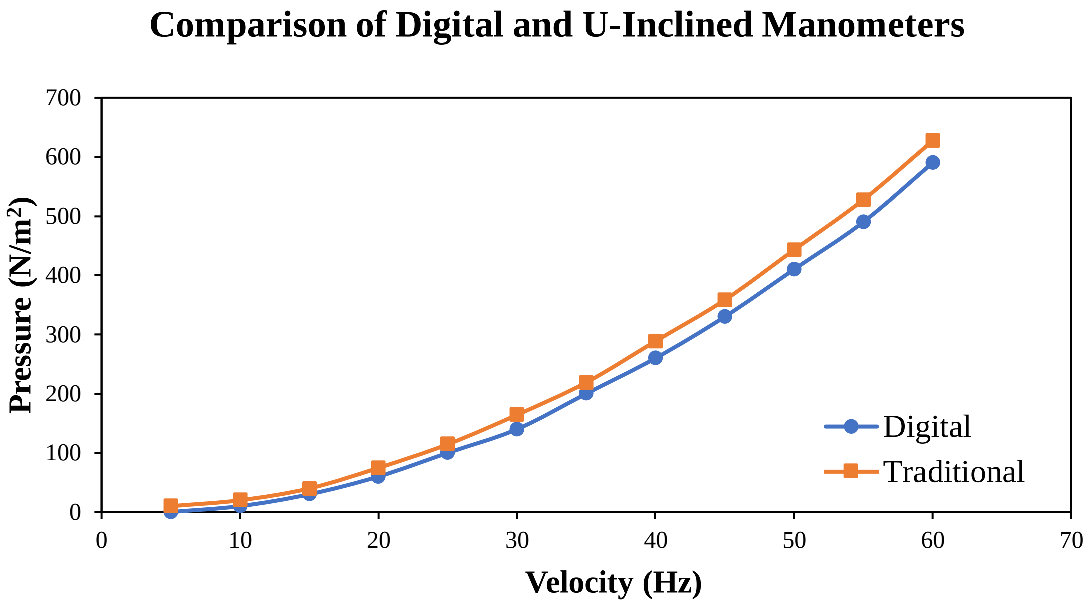

Figure 26. Pressure difference comparison between U-Inclined and digital manometers

From Figure 26, it seems that the pressure readings for the two manometers is very close, but not exactly the same. The U-Inclined manometer showed pressure readings slightly above the digital manometer, even after three trials. Since the trial results showed close agreement, the digital manometer was chosen to conduct the remaining experimental tests, because it was easier to handle and read the pressure output than the U-Inclined manometer.

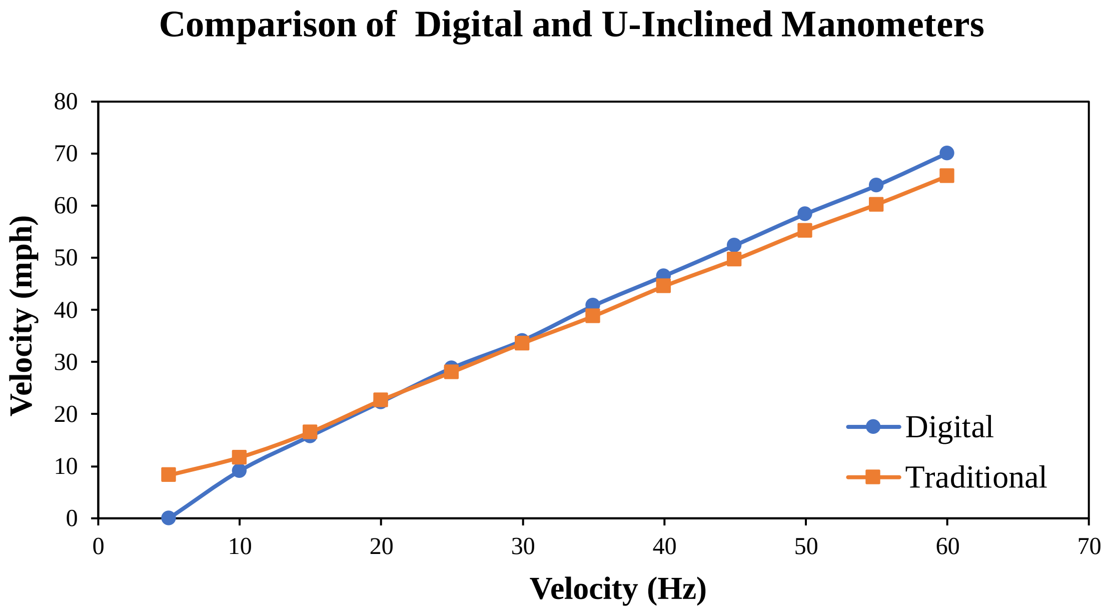

Figure 27. Velocity comparison between U-Inclined and digital manometers

The velocity comparison, using Bernoulli's equation, of the two manometers showed that the U-Inclined manometer started off at a higher velocity (mph), but ended up being slightly below the digital manometer velocity (mph) as the wind tunnel speed (Hz) was increased. Figure 27 shows a very close linear relationship between the two devices, after three trials as well. When the pitot-static tube was calibrated with and without the model SUV, the relationship between the two manometers stayed fairly constant.

Preliminary Data for the SUV

Table 2. The relationship between velocity and drag coefficient

Car Only Trial 1	
Velocity (mph)	**Drag Coefficient, C_d**
0.000	-
9.081	1.113
24.025	0.699
37.441	0.664
49.737	0.693
62.254	0.690
72.076	0.679
60.234	0.700
48.050	0.715
36.323	0.742
24.025	0.837
9.081	2.059
0.000	-

Throughout experimental testing, there seemed to be an irregular trend in drag voltage for all the trials, but more prominent in the first trial. As velocity decreased, the drag voltage readings did not come back down to zero mph. The drag voltage was used to find the drag coefficient, therefore, in Figure 28 and Table 2, it is clear that the drag coefficient spikes for the first trial around 10 mph on the way down to 0 mph.

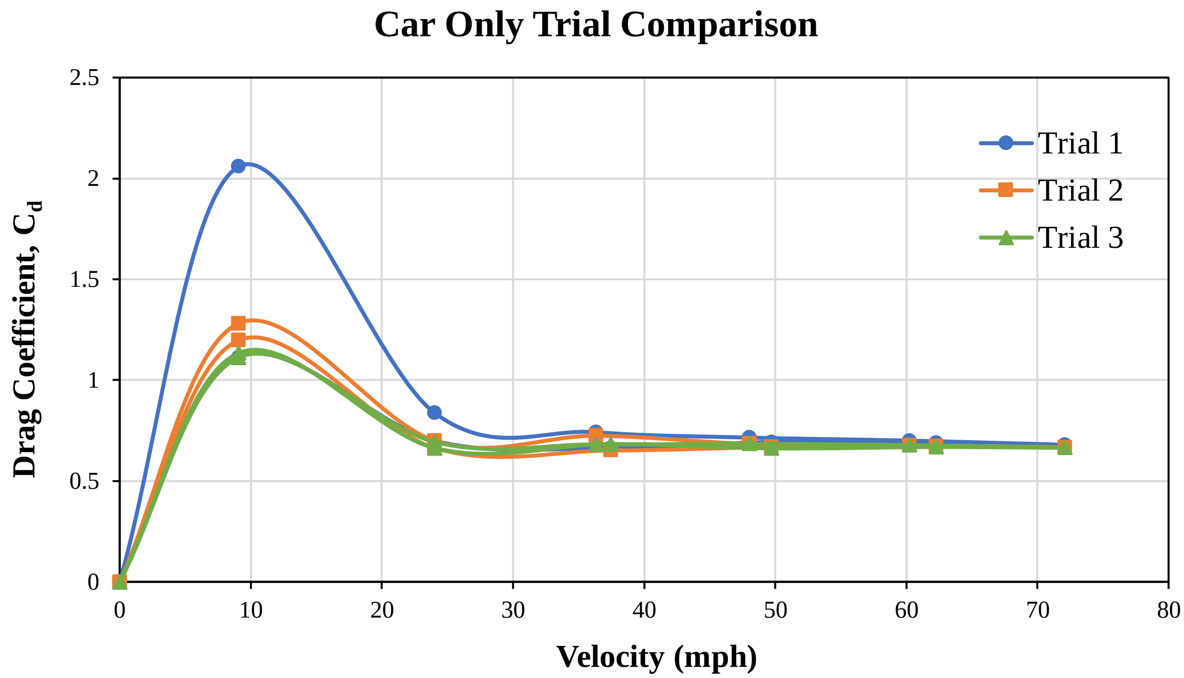

Figure 28. Model SUV drag coefficient compared to air velocity for three trials

This phenomenon seemed odd since conditions were fairly constant for testing and density was recalculated for each trial of each test. However, the irregular occurrence could be due to the laboratory room temperature not being at the appropriate temperature for testing. This could have happened when the large garage door was closed right before testing took place and there was not enough time taken to allow for the room temperature to settle. Flow visualization was done in order to observe the model SUV under low speeds and help determine what was the source of the irregular measurement trend.

Flow Visualization and Additional Testing

The smoke flow visualization technique did not show any significant patterns of inconsistencies with the streamline air flow over the model SUV (Figure 29).

Figure 29. Smoke flow visualization

A smoke flow visualization was used to conduct flow visualization for the model SUV. Figure 29 shows the smoke streamline moving over the model SUV at 5 Hz or 0 mph, no flow. The inconsistencies in data ranged from 0 to about 23 mph, but when viewing video footage of the streamlines for speeds 0 mph, 9 mph, 15 mph, 23 mph, and 28 mph, there were no irregular patterns observed. Therefore, this prompted the investigation of other sources that may have caused the spike as seen in Figure 28.

One final test was conducted to see if the dynamometer custom made mount was the source of the drag voltage reading spikes.

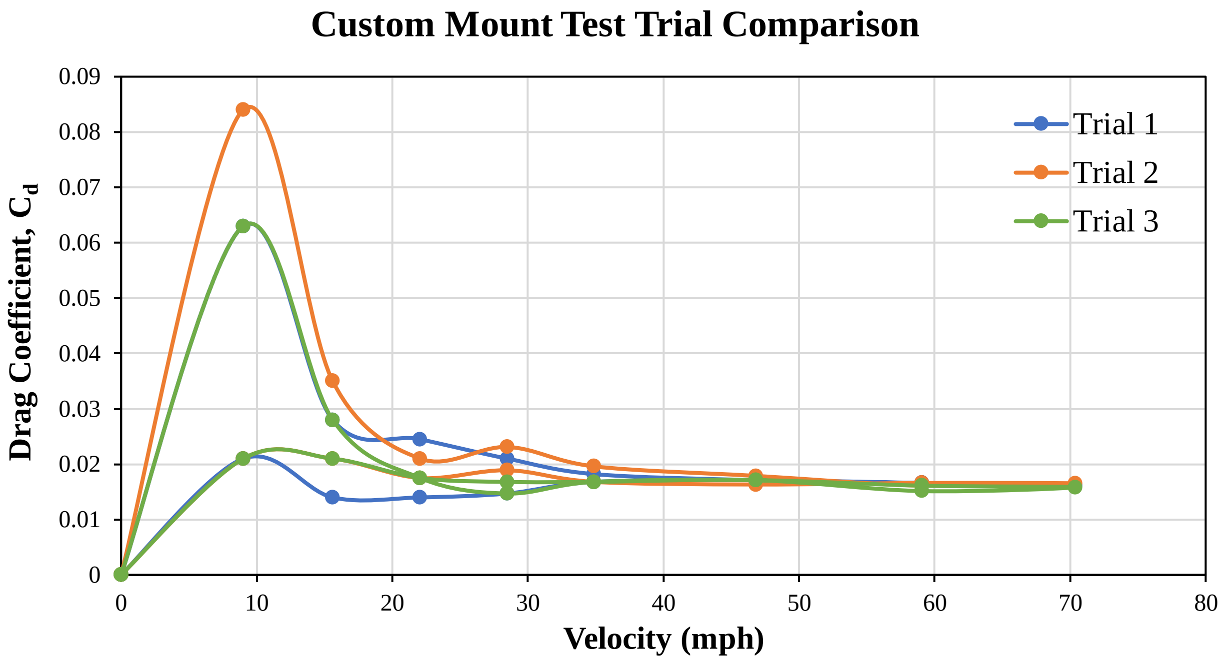

Figure 30. Custom made mount without SUV in wind tunnel

Figure 30 shows that the irregular trend still occurs when nothing is attached to the mount in the wind tunnel. Even when a boat shaped metal block was tested, instead of the model SUV, the results still showed the same irregular pattern around 10 mph.

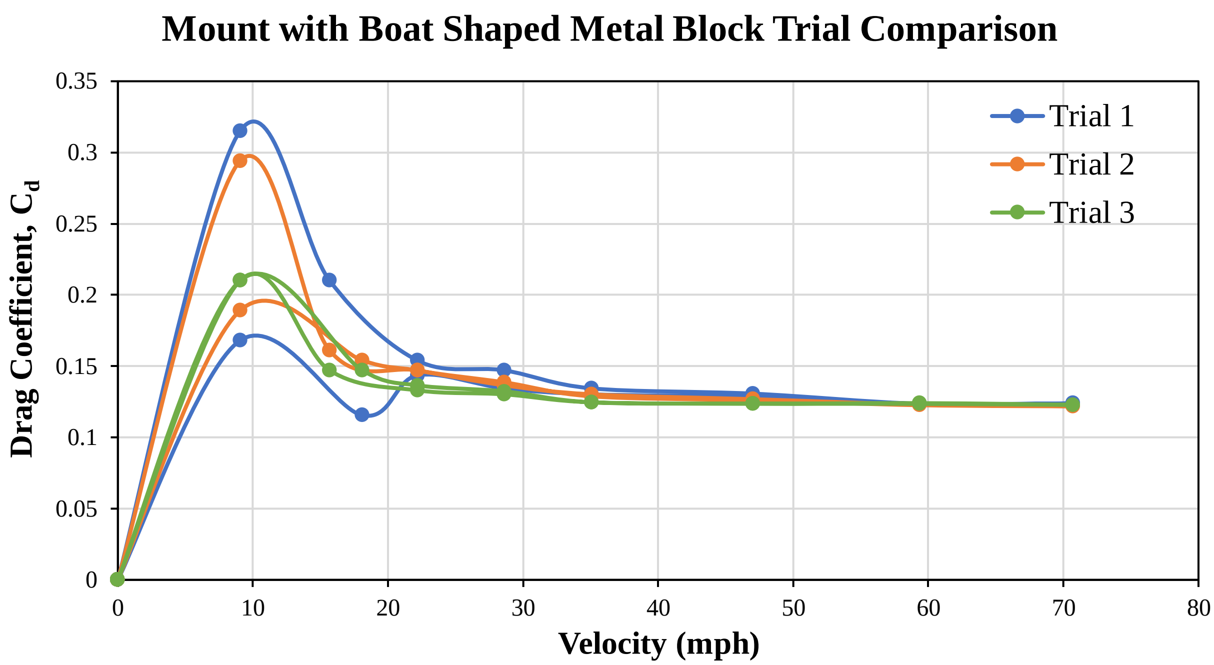

Figure 31. Custom made mount with metal block in the wind tunnel

It is clear from Figure 31, that the trend occurs regardless of what is attached to the custom made mount. Therefore, it is clear that there must be an issue with the drag voltage readings caused by the dynamometer and/or the custom mount around 10 mph. It was decided that the average drag coefficient readings, from the experimental test comparisons, would exclude the spike in the data that occurred in all trials from 0 mph to about 23 mph.

Drag Reduction

The final comparisons of the all the features showed a reduction in drag. Table 3 shows the complete list of features tested on the model SUV in the wind tunnel. The colored rows correspond to Figure 32 to show the top three features/ feature combinations that reduced drag the most from the model SUV's C_d of 0.69.

Table 3. Feature combinations with their corresponding drag coefficients and drag reductions

Final Drag Comparisons			
Test Number	**Features**	**Drag Coefficient, C_d**	**Drag Reduction, %**
1	Car Only	0.6890	-
2	Wheel Covers Only	0.6566	4.70%
3	Fairings Only	0.6732	2.29%
4	Wheel Covers & Fairings	0.6583	4.45%
5	Back Air Dam Only	0.6822	0.99%
6	Side Air Dams Only	0.6594	4.30%
7	Front Air Dam Only	0.5889	14.53%
8	Front & Side Air Dams	0.5567	19.21%
9	All Air Dams	0.5561	19.29%
10	Wheel Covers & Air Dams	0.5779	16.12%
11	Fairings & Air Dams	0.5790	15.96%
12	Full Underbody Coverage	0.5666	17.77%
13	Wheel Covers & Underbody	0.5645	18.07%
14	Fairings & Underbody	0.5865	14.88%
15	All Features	0.6100	11.46%
16	All Features & No Windows	0.6533	5.19%
17	No Windows	0.7233	-4.97%

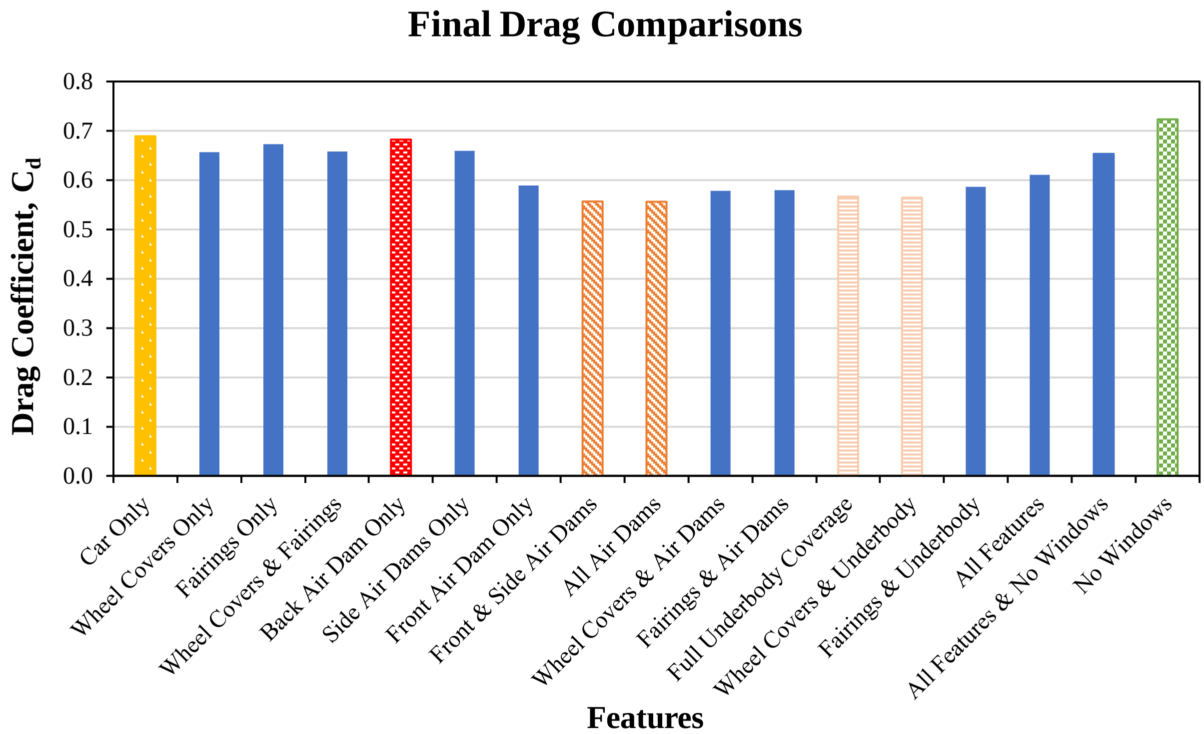

Figure 32. Final drag comparisons of all feature combinations

The green highlighted row (test numbers 17) represent the testing of no windows on the model SUV (Table 3). This represents the scenario of someone driving with the windows down in the 2006 Range Rover Sport. The first (yellow) bar shows the model SUV's drag coefficient, therefore, any bar below the black line shows a reduction in drag. From Figure 32 it is clear that all the features and feature combinations reduced drag of the SUV, which results in improved fuel efficiency. The dark orange diagonal lined bars show the most significant reduction in drag among all combinations tested. All air dams proved to be the best combination, with a 19.3% relative reduction in drag. However, the front and side air dams had a relative drag reduction of 19.2%. The calculation for percent drag reduction for the all air dams is shown below, using equation 10 listed in the methods section.

$$0.6890 - 0.5561 = \frac{0.1329}{0.6890} = 0.1929 \times 100 = 19.28\% \approx 19.3\%$$

The light orange vertical lined bars represent the next feature combinations that reduced the most drag. The wheel covers and full underbody coverage had a slightly higher drag reduction at 18.1%, rather than the full underbody coverage by itself at a 17.8%. In Table 3, test number 5, represents the feature with the lowest reduction of drag, with only a 1% reduction for the back air dam.

Individual Feature Comparisons

The original four features are compared in Table 4 in order to show the feature that reduced the most drag.

Table 4. Comparisons of the four original features

Individual Feature Comparisons			
Test Number	**Features**	**Drag Coefficient, C_d**	**Drag Reduction, %**
1	Car Only	0.6890	-
2	Fairings Only	0.6732	2.29%
3	Wheel Covers Only	0.6566	4.70%
4	Full Underbody Coverage	0.5666	17.77%
5	All Air Dams	0.5561	19.29%

In Table 4, test number 5, and in Figure 33, the diagonal lined orange bar, shows that the all air dams feature proved to be the best reducer of drag among the four, with a reduction of about 19.3%. However, the full underbody coverage feature was extremely close, at a reduction of 17.8%.

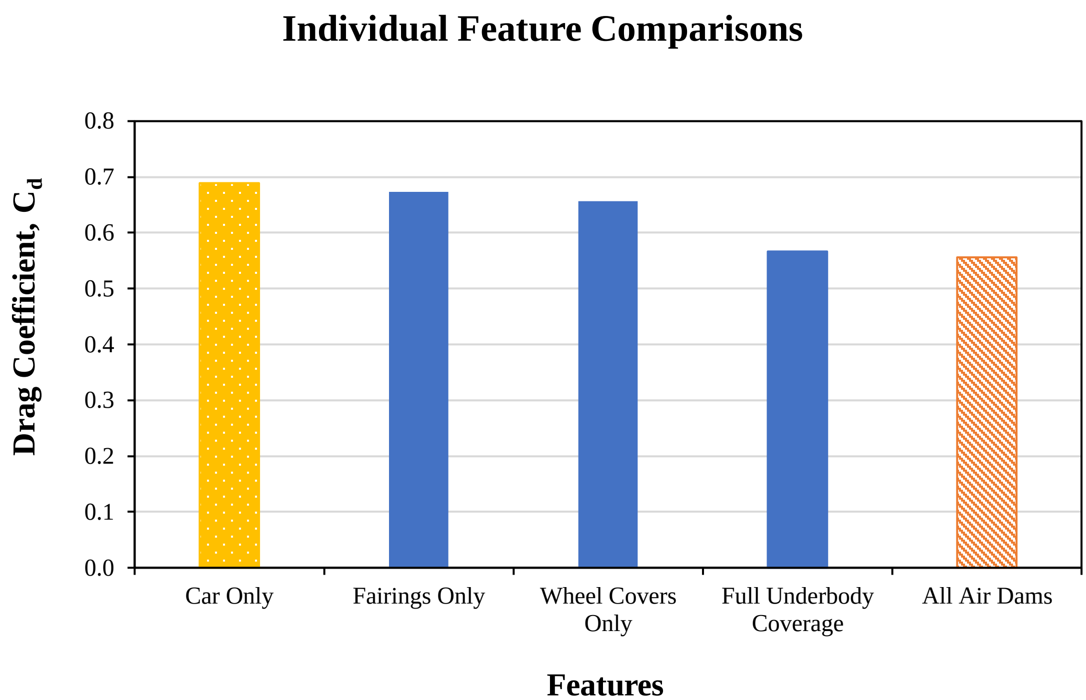

Figure 33. Individual comparisons of the original four features

It is clear from Figure 33 that all air dams and full underbody coverage are very close in their reduction amounts, but surprisingly the air dams proved to be the overall best feature. The air dams were all made of clay except for the front air dam, which was 3D printed and molded to the front of the model SUV with air dry clay.

Air Dam Comparisons

To better understand the drag reduction comparisons of the air dams, Table 5 and Figure 34 were constructed.

Table 5. Comparisons of air dam drag coefficients

Air Dam Comparisons			
Test Number	**Features**	**Drag Coefficient, C_d**	**Drag Reduction, %**
1	Car Only	0.6890	-
2	Back Air Dam Only	0.6822	0.99%
3	Side Air Dams Only	0.6594	4.30%
4	Front Air Dam Only	0.5889	14.53%
5	Full Underbody Coverage	0.5666	17.77%
6	Front & Side Air Dams	0.5561	19.21%
7	All Air Dams	0.5567	19.29%

When looking at the front, back, and side air dams separately, the front air dam reduced drag the most, by 15%. However, when combining the front and side air dams, the combination was even better than the front air dam alone, with a reduction of about 19.2%, but the combination of all air dams also showed a drag reduction of about 19.3%, as mentioned earlier. The full underbody coverage has a drag reduction of 17.8%, therefore, these results show that if consumers can only afford to buy one feature to add to their SUV, full underside coverage would be the best option. However, a front air dam could be cheaper than full underbody coverage paneling and would still provide a drag reduction of 15%. Otherwise, the combination of all air dams or just front and side air dams would be even better. Surprisingly, all air dams performed better than the full underbody coverage, but the front and side air dams did just as well as the all air dams. This suggests that adding the back air dam is not necessarily needed if someone wants to reduce drag and improve their fuel efficiency.

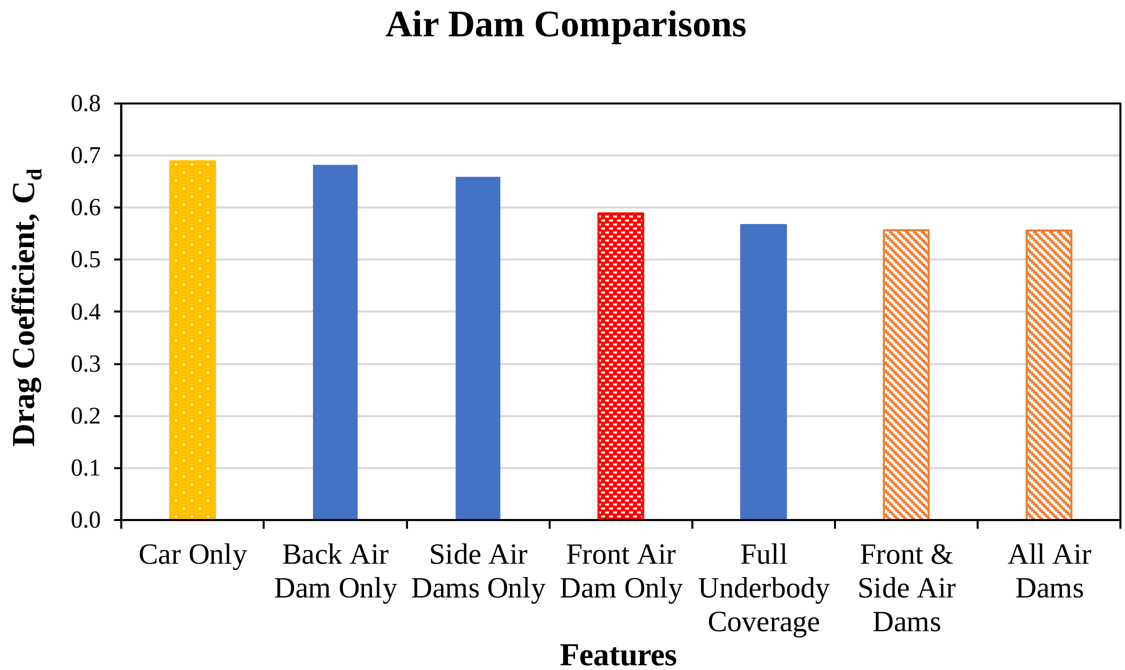

Figure 34. Air dam comparisons

Full Underbody Coverage Comparisons

Table 6 and Figure 35 show the drag coefficient comparisons between the full underbody coverage combinations with the other features.

Table 6. Comparisons of full underbody coverage drag coefficients

Full Underbody Coverage Comparisons			
Test Number	**Features**	**Drag Coefficient, C_d**	**Drag Reduction, %**
1	Car Only	0.6890	-
2	Fairings & Underbody	0.5865	14.88%
3	Full Underbody Coverage	0.5666	17.77%
4	Wheel Covers & Underbody	0.5645	18.07%

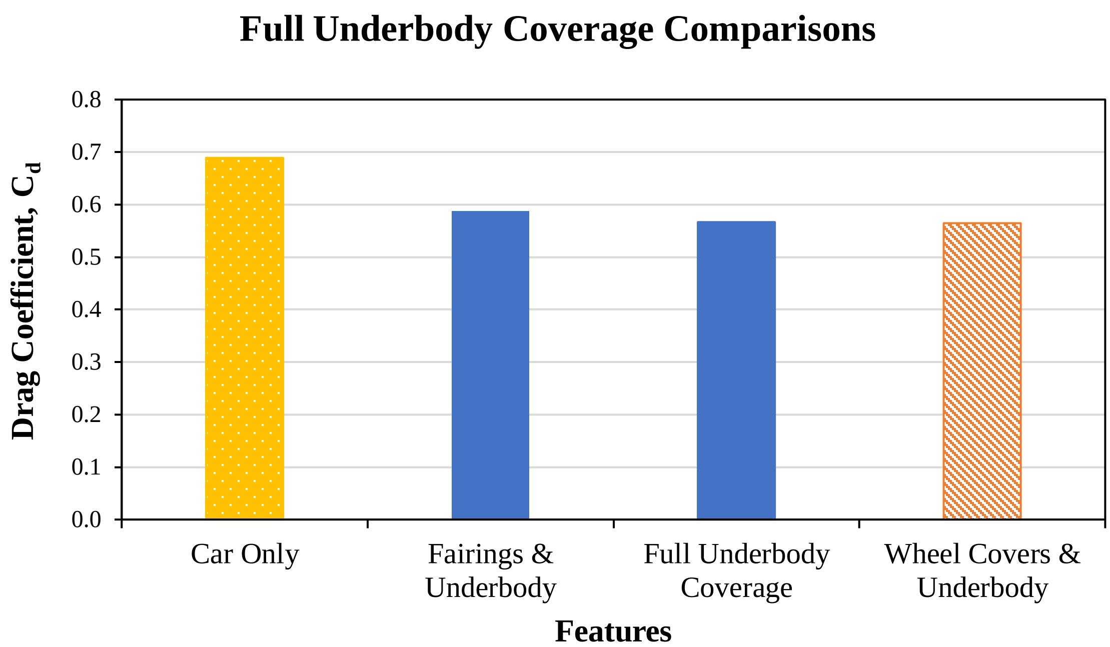

Figure 35. Comparisons of full underbody coverage combinations

When wheel covers and full underbody coverage are combined, the drag reduction is 18.1%. However, the full underbody coverage alone is 17.8%, which shows that the addition of wheel covers could slightly improve fuel efficiency. However, fairings and full underbody coverage was a close third place at about 15% drag reduction. Therefore, if someone can afford to purchase full underbody coverage paneling, they should try to also invest in wheel covers to add to the improvement in fuel efficiency.

<u>No Windows Comparison</u>

The experimental test for the no windows scenario is displayed in Table 7 and Figure 36.

Table 7. The comparison of having windows down, while driving

No Windows Comparison			
Test Number	**Features**	**Drag Coefficient, C_d**	**Drag Reduction, %**
1	Car Only	0.6871	-
2	No Windows	0.7258	-4.97%

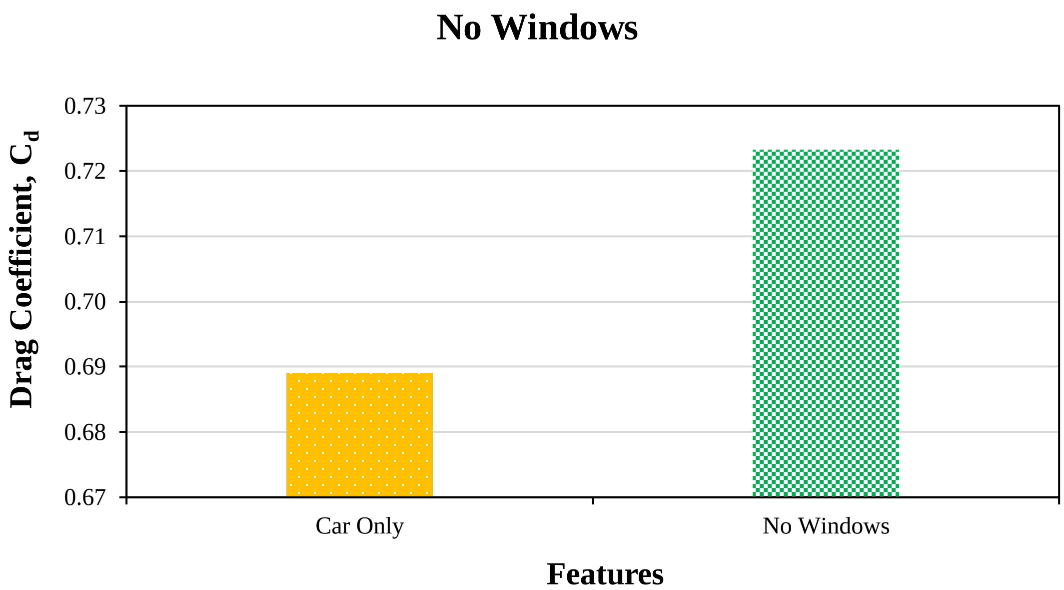

Figure 36. Graphical representation of having windows down, while driving

This experimental test provides evidence to prove that when someone drives with their windows down at high speeds, there is a decrease in fuel efficiency and the drag increases by about 5%, for the 2006 Range Rover Sport.

Mileage Improvement and Fuel Savings

Fuel savings can also be calculated in order to show how much money one could save annually when driving the 2006 Range Rover Sport. However, the fuel savings calculations can be easily calculated for any vehicle. The highest percent drag reduction, of 19.3%, was used to calculate the highway miles per gallon (MPG) improvement for the actual SUV, using equation 11 listed in the methods section.

$$19\, mpg \times 0.193 = 3.667\, mpg + 19\, mpg = 22.7\, mpg$$

The highway MPG improved by 19.3% to 22.7 mpg, which allows for fuel savings calculations to be conducted, using equations 12 – 14 listed in the methods section.

$$\frac{12{,}000\, miles}{19\, mpg} = 631.58\, gallons$$

$$\$2.83 \times 631.58\, gallons = \$1{,}787.37$$

$$\frac{12{,}000\, miles}{22.7\, mpg} = 528.63\, gallons$$

$$\$2.83 \times 528.63\, gallons = \$1{,}496.04$$

$$\$1{,}787.37 - \$1{,}496.04 = \$291.33$$

The fuel savings calculation includes using the highway MPG for the 2006 Range Rover Sport of 19 mpg. The fuel savings from is about $291.33 annually, for the specific model tested. This is only in the case of driving approximately 12,000 miles yearly and purchasing premium gas in the U.S. at about $2.83 a gallon.

Discussion

Climate change will continue to occur and people can only try to minimize their effect on the environment. The experimental results show that the use of aerodynamic features reduces the drag on an SUV, which improves fuel efficiency.

According to the results from experimental testing, the most significant reducer of drag was all air dams as well as the combination of just the front and side air dams. The reduction of drag by about 19%, for both features, shows that the SUV can have improved fuel efficiency. Consumers are usually interested in saving money whenever possible; by either adding all air dams or just front and side air dams, consumers can drive more miles on the same tank of gasoline. However, depending on how much money a consumer is willing to spend, the feature combinations vary. Ideally, installing front and side air dams would provide the greatest return on investment, but the cheapest option would most likely be the front air dam alone. If someone is willing to spend a little more money, they could invest in full underside coverage instead of just the front air dam, since the full underside coverage is the higher reducer in drag. Since, someone driving the 2006 Range Rover Sport would get a 19.3% drag reduction, using all air dams, their highway MPG improves from 19 mpg to 22.7 mpg. This results in an annual savings of $291.33. Therefore, if the all air dams feature was valued at about $200, someone would still save about $91.33 in their first year since purchasing the feature additions and would save approximately $291.33 each subsequent year. One assumption was that SUV owners are interested in improving their fuel efficiency and saving money.

When the model SUV was tested, windows and no features, the C_d came out to be 0.69. The significant difference between the C_d, 0.37 vs. 0.69, could be due to a variety of issues. Possible reasons for the variance in drag coefficients could be related to how the model parts were assembled and may not be exactly like the actual SUV or the roughness of the material of the model SUV compared to the actual SUV. Also, both the model and actual SUV should be dynamically similar, meaning their Reynold's number and drag coefficient should match. However, the model SUV would have to be tested at supersonic speeds in order to obtain dynamic similarity. Due to the limitations of the JMU wind tunnel, the experimental model was tested at the speeds available, therefore, perhaps causing the difference in drag coefficient compared to the actual SUV.

It is not surprising that all features tested were successful in reducing drag. This is due to the use of feature designs already utilized in the automotive market. However, most aerodynamic features are not marketed by major car companies, but by smaller manufacturers or are even homemade using online tutorials. Not many companies invest in aerodynamic feature additions, except for spoilers on the back of sedans which enhance stability, rather than reducing drag.

The irregularity in the data from 0 to 23 mph for the first trial in all feature tests proves to be an issue. Future users should be aware of the problem associated with the dynamometer performance in this velocity range.

The test with no windows was conducted to show how at higher speeds, there is more aerodynamic drag when the windows are down[39]. However, at low speeds, using the air conditioner increases fuel consumption more than when driving with the windows down. The fuel consumption by using air conditioning over lowering the windows at low speeds can greatly affect the vehicle emissions. Therefore, at higher speeds, use air conditioning, and at low speeds, have your windows down, only if it is necessary[40]. It is important for the environment, that people try to minimize their carbon footprint, especially when it comes to their vehicles.

Conclusions and Future Work

The experimental testing of all features and combinations showed reductions in drag for the 2006 Range Rover Sport model. The most significant reducer was all air dams, however, the addition of just the front and side air dams proved to be just as significant, with both feature combinations reducing drag by approximately 19%. Therefore, the addition of the back air dam is not necessary considering the front and side air dams did just as well as all air dams. The environmental impact of the aerodynamic feature additions may not seem to be that significant, but the environment will benefit from any reduction in vehicle emissions.

More experiments can be performed to see if the results can be extended to other models of SUVs. If the project were to continue, more experimenting would need to be conducted to prove the results stated above can be applied to other SUVs. The testing of a different vehicle could be useful, in order to see if another SUV had similar results, or to show how a sedan or 18-wheeler truck vary from an SUV. Other features and combinations could be tested to see if there are more opportunities for drag reduction and improvement in fuel efficiency. Additional features such as an underside paneling without the air dams as well as more aerodynamic side view mirrors could be tested on the model SUV. Adjusting the surface roughness of features could be an interesting project. Therefore, variation in design and testing could be significantly reduced, creating more accurate results.

Some opportunities for an aftermarket "eco" package could include deployable side air dams, where the driver could press a button, before traveling at highway speeds. The side air dam could also double as a side foot step while the vehicle is parked. The fairings could be collapsible onto the SUV, while parked, then deployed when driving. The wheel covers could have designs on them, like the spare tire covers on Jeeps and older Land Rovers. The wheel covers would cover the rims of the tire, with small air pockets for airflow, but could be easily washable. Since, some consumers take an interest in buying specific rims or hub caps, the wheel covers serve as an alternative since they provide both an appealing atheistic and functional purpose. These marketing incentives are possible if carmakers decide to pursue mainstream selling and distribution of aerodynamic additions for their vehicles. There are long term benefits for the consumer, the carmaker, and the environment. The consumers get a more fuel efficient SUV, the carmaker can make more money, and the environment will hurt just a little bit less than it did before aerodynamic additions were introduced.

Appendix

Glossary

1. **Aerodynamics** – Is the science of how things move through air.
2. **Air Dam** – (Spoiler) A streamlining device below the front bumper of a vehicle, or around the underside of an entire vehicle.
3. **Boundary Layer** – The region surrounding the car where the air speed increases from zero to its free stream velocity[41].
4. **Dimensional Analysis** – physical quantities added to or equated with each other must be expressed in terms of the same fundamental quantities (such as mass, length, or time) for inferences to be made about the relations between them.
5. **Drag** – Air resistance; is the force that a moving body feels when the flow of air around it starts to become turbulent (or disrupted). The drag force is opposite to the direction of the object's motion.
6. **Dynamometer** – a two component instrument used to measure lift and drag forces. The device utilizes signal conditioning to obtain DC voltage.
7. **Fairings** – An external metal or plastic structure added to increase streamlining and reduce drag, especially on a high-performance car, motorcycle, boat, or aircraft.
8. **Flow visualization** – in fluid dynamics, it is used to make the flow patterns visible, in order to get qualitative or quantitative information on them.
9. **Laminar flow** – generally happens at low flow velocities. The flow of a fluid when each particle of the fluid follows a smooth path, paths which never interfere with one another. One result of laminar flow is that the velocity of the fluid is constant at any point in the fluid[42].

10. **Lift** – the raising of an object due to the force of air thrust upon the object.
11. **Pitot-Static Tube** – an open-ended right-angled tube pointing into the flow of a fluid and used to measure dynamic and static pressures.
12. **Reynolds Number –** is the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.
13. **Solidworks Software** – is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) computer program that runs on Microsoft Windows.
14. **Turbulent flow** - vortices, eddies and wakes make the flow unpredictable. Turbulent flow happens in general at high flow rates[43] and is considered to be irregular flow that is characterized by tiny whirlpool regions.
15. **Vortex** – A vortex can be made up of anything that flows, such as wind, water, or electricity. It takes place in the wake of the vehicle and is a rotational movement of fluids.
16. **Wake** – The region of air flow behind a vehicle.
17. **3D Printing** – A process for making a physical object from a three-dimensional digital model, typically by laying down many successive thin layers of a material (such as filament).

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