COMILLAS

UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Car-top Cargo Carrier Aerodynamics

Autor: Mateo Andrés Angelini Norkus

Director: Enrique S. Gutiérrez-Wing

Madrid

Julio de 2022

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Car-Top Cargo Carrier Aerodynamics

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2021/22 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

tomada de otros documentos está debidamente referenciada.

Fdo.: Mateo Andrés Angelini Norkus Fecha: 14/ 07/ 2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Enrique S. Gutiérrez-Wing Fecha: 14/ 07/ 2022

COMILLAS

UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Car-Top Cargo Carrier Aerodynamics

Autor: Mateo Andrés Angelini Norkus

Director: Enrique S. Gutiérrez-Wing

Madrid

Julio de 2022

Agradecimientos

I would like to take the opportunity to thank Boston University for giving us the possibility to work on this project, Professor Grace, Professor Geiger and Professor Gutierrez for all their help throughout the project, and ShuLan and Matthew for working with me on the project.

ESTUDIO AERODINÁMICO DE LOS PORTAEQUIPAJES

Autor: Angelini Norkus, Mateo Andrés.
Director: Gutierrez-Wing, Enrique S..
Entidad Colaboradora: Boston University.

RESUMEN DEL PROYECTO

Existe la suposición de que el portaequipajes produciría menos resistencia al aire si se colocara al revés. Este proyecto demuestra esta idea a través de simulaciones computacionales y pruebas en carretera reales para lograr resultados que sugieren que se puede lograr una reducción en el consumo de combustible de alrededor del 5% cuando se aplica esta idea.

Palabras clave: Portaequipaje, Orientación, Fuerzas de arrastre, Capa límite, Mecánica de fluidos computacional, Cuerpo Ahmed, Consumo de gasolina, emisiones de CO2.

1. **Introducción**

La reducción de emisiones de CO_2 ha sido uno de los temas de mayor relevancia durante los últimos años debido a su alto impacto en el cambio climático. Las emisiones de CO_2 tienen muchas fuentes, pero la principal es la combustión de combustibles fósiles en los vehículos utilizados en el transporte. La transición a los coches eléctricos ha comenzado, pero es difícil estimar cuándo terminará, por lo que es necesario mejorar la eficiencia del combustible para abordar el problema y reducir sus efectos lo antes posible.

El consumo de combustible de los automóviles depende en gran medida de las fuerzas de arrastre que experimentan. Estas fuerzas de arrastre varían según la forma del automóvil, la velocidad a la que viaja el vehículo, las condiciones ambientales o los accesorios que se les agregan, entre otras cosas.

Accesorios como los portaequipajes tienen efectos muy negativos en el consumo de combustible de un vehículo. Esto no se debe solo a que agregan peso, sino que también modifican su forma, haciéndolo menos aerodinámico y provocando mayores fuerzas de arrastre. Se ha informado que estos dispositivos aumentan el consumo de combustible en un 19 %[LINK20] con respecto al automóvil sin este componente.

Sin embargo, este aumento en el consumo de combustible podría reducirse si se invirtiera el portaequipajes. Esto se debe al hecho de que las fuerzas de arrastre también dependen de cómo y dónde se separa la capa límite del cuerpo (esto afecta al drag por presión).

Debido a su forma, la orientación invertida se parecería más a un perfil aerodinámico, donde el desprendimiento de la capa límite se produce más tarde en el flujo.

2. Definición del proyecto

Este proyecto pretende alcanzar tres objetivos principales:

- Demostrar si invertir la orientación de un portaequipajes reduce el coeficiente de arrastre para diferentes carrocerías (la investigación preliminar sugirió que no necesariamente esta idea podría funcionar en todas las carrocerías).

- Cuantificar el ahorro que podría suponer la reducción de la resistencia al avance en el consumo de combustible, aspectos ambientales y económicos

- Comprender y hacer una evaluación de los riesgos que conlleva la reorientación del portaequipajes

Con estos objetivos en mente, y con un presupuesto de 300$, financiado por Boston University, el proyecto se llevó a cabo a través de dos enfoques diferentes: Simulaciones computacionales y pruebas de carretera en la vida real. La primera parte ayudaría a decidir si los objetivos eran alcanzables mientras que la segunda parte estaría más enfocada en el segundo y tercer objetivo.

3. Descripción del modelo

3.1 Simulaciones Computacionales

Esta parte del proyecto se llevó a cabo a través de COMSOL. Estas simulaciones se llevaron a cabo en un entorno 2D gracias a la validación Ahmed Body [COMS22] (método para validar y relacionar simulaciones 2D con simulaciones 3D). Estas simulaciones estudiaron las variaciones en los coeficientes de arrastre debido a la orientación, así como debido al espacio entre el techo y el portaequipajes.

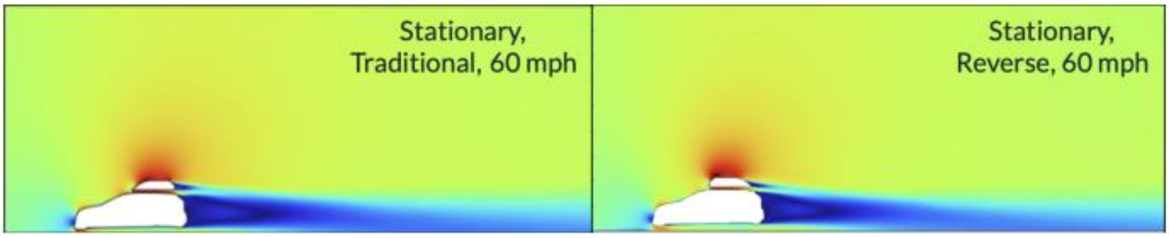

Figura 1: Campos de Velocidad, Tradicional vs Inverso

3.2 Pruebas en carretera

Esta segunda parte constaba de dos pruebas en carretera separadas, con dos coches diferentes pero el mismo portaequipajes. Usando las medidas registradas a través de un dispositivo OBD (diagnóstico a bordo) que se compró para garantizar lecturas más precisas, se compararon ambas orientaciones del portaequipajes en ambos vehículos.

Estas pruebas consistían en hacer viajes en una ruta (carretera) en ambos sentidos, con ambas orientaciones para poder comparar las configuraciones inversa y tradicional.

Figura 2: Prueba 1

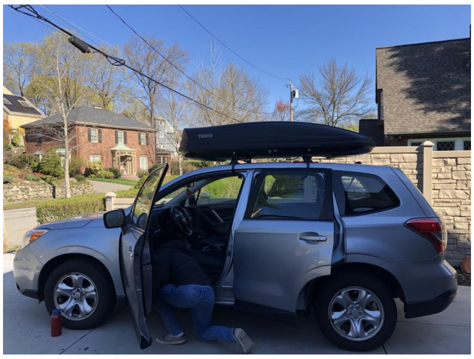

Figura 3: Prueba 2

4. Resultados

Computer Simulation	Drag	Equivalent % Fuel Consumption
% Difference	-9% to -16%	**-5%**

Road Test	Calix	Road Test 1	Road Test 2
% Fuel Consumption*	**-5%** to **-7%**	**-1%** to **-5%**	**-9%**

Figura 4: Resultados

Se encontró que tanto las simulaciones como las pruebas en carretera sugirieron resultados similares a los resultados expuestos por un fabricante de portaequipajes (CalixKlippan AB Group) que desarrolló un portaequipajes [SOLG21], [AUTO21] que incorporaba esta idea.

Además, el único riesgo asociado a esta reorientación fue la pérdida de la garantía por mala colocación.

5. Conclusiones

Los resultados de este proyecto junto con el informe del fabricante mencionado anteriormente, sugirieron que la idea que se intenta probar no es un fenómeno puntual, sino algo que es válido en varias ocasiones. Con esta idea en mente, se realizó una estimación de cuánto se podrían reducir las emisiones de CO_2, si la mitad de los vehículos utilizaran regularmente portaequipajes, y terminó dando como resultado una reducción del 0,3% a nivel mundial.

6. Referencias

[LINK20] Linkov, J., "How Rooftop Carriers Affect Fuel Economy for Cars and SUVs", https://www.consumerreports.org/fuel-economy-efficiency/how-rooftop-carriers-affect-fuel-economy/, 2020

[COMS22] COMSOL, "Airflow over an Ahmed Body", https://www.comsol.com/model/download/913121/models.cfd.ahmed_body.pdf, 2022

[SOLG21] Solgaard H., "New Aero Loader roof box that provides 7% better range", https://www-mynewsdesk-com.translate.goog/no/kgknorge/pressreleases/nye-aero-loader-takboksen-som-gir-7-procent-bedre-rekkevidde-3067278?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=wapp, 2021

[AUTO21] Autoform, "Test Report – Fuel/Power consumption", https://www.pebe.se/files/b3790aa99fd0a223458201fd86012ece.pdf, 2021

CAR-TOP CARGO CARRIER AERODYNAMICS

Author: Angelini Norkus, Mateo Andrés.
Supervisor: Gutiérrez-Wing, Enrique S..
Collaborating Entity: Boston University.

ABSTRACT

There is an assumption that car-top cargo carrier would produce less drag if they were placed the other way around. This project proves this idea through computational simulations and real-life road tests to achieve results that suggest that a reduction in fuel consumption of around 5% can be achieved when this idea is applied.

Keywords: Car-top cargo carrier, Orientation, Drag forces, Boundary layer, Computational Fluid Dynamics, Ahmed Body, Fuel consumption, CO2 emissions.

1. Introduction

CO_2 emissions reduction has been one of the topics with highest significance during the last few years due to its high impact on climate change. CO_2 emissions have many sources, but the main one is the combustion of fossil fuels in vehicles used in transportation. The transition to electric cars has started but it is difficult to estimate when it will end, therefore improving fuel efficiency is required to tackle the problem and reduce its effects as soon as possible.

Fuel consumption of cars depend highly on the drag forces they experience. These drag forces vary depending on the shape of the car, the speed at which the vehicle travels, the environmental conditions or the accessories added to them among other things.

Accessories such as Car-top luggage carriers have very negative effects on the fuel consumption of a vehicle. This isn't just because they add weight, but they also modify its shape, making it less aerodynamic, and causing higher drag forces. These devices have been reported to increase the fuel consumption by 19 % [LINK20] with respect to the car without this component.

However, this rise in fuel consumption could be reduced if the luggage carrier was to be reversed. This is due to the fact that drag forces also depend on how and where the boundary layer is detached from the body (this affects pressure drag). Due to its shape, the reversed orientation would resemble more closely an airfoil, where the detachment of the boundary layer is later in the flow.

2. Project Definition

This project aims to achieve three main objectives:

- Demonstrate whether reversing the orientation of a car-top luggage carrier reduces drag coefficient for different car bodies (preliminary research suggested that not necessarily this idea could work on every car body).

- Quantify the saving that the reduction of drag could imply in fuel consumption, and environmental and economic aspects

- Understand and do an assessment of the risks that come with the reorientation of the car-top luggage carrier

With these objectives in mind, and with a 300$ budget, funded by Boston University, the project was carried out through two different approaches: Computational simulations and real-life road tests. The first part would help to decide whether the objectives were achievable while the second part would be more focused on the second and third objectives.

3. Project design decisions and details

3.1 Computational Simulations

This part of the project was carried out through COMSOL. These simulations were carried out in a 2D environment thanks to the Ahmed Body validation [COMS22] (method to validate and relate 2D simulations to 3D simulations). These simulations studied the variations in drag coefficients due to the orientation, as well as, due to the gap between the roof and the luggage carrier.

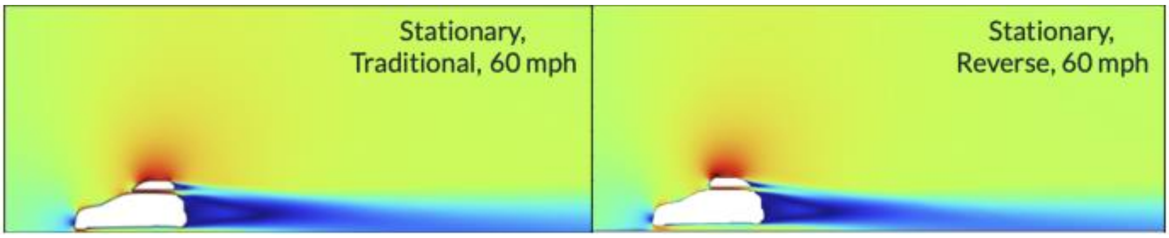

Figura 5: Velocity fields Traditional vs Reversed

3.2 Road Tests

This second part consisted of two separate road tests, with two different cars but the same luggage carrier. Using the measurements recorded through an OBD (On-Board Diagnostics) device that was purchased to ensure more precise readings, both orientations of the luggage carrier were compared on both cars.

These tests consisted of doing trips on a route (highway) in both directions, with both orientations to be able to compare the reverse and traditional configurations.

Figura 6: Road Test 1

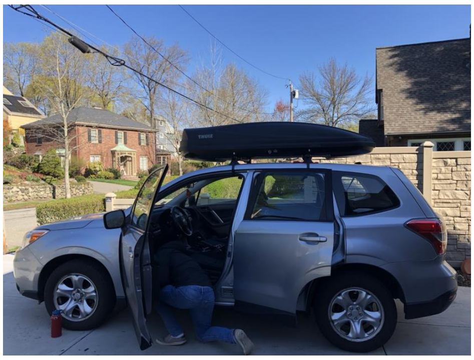

Figura 7: Road Test 2

4. Results

Computer Simulation	Drag	Equivalent % Fuel Consumption
% Difference	-9% to -16%	**-5%**

Road Test	Calix	Road Test 1	Road Test 2
% Fuel Consumption*	**-5%** to **-7%**	**-1%** to **-5%**	**-9%**

Figura 8: Results

It was found that both the simulations and the road tests, suggested similar results to the ones that a Car-top luggage manufacturer (CalixKlippan AB Group) that developed a carrier incorporating this idea reported [SOLG21], [AUTO21].

Furthermore, the only risk associated to this reorientation was the violation of the warranty for misplacement.

5. Conclusions

Results from this project paired with the report from the manufacturer mentioned before, suggested that the idea that is trying to be proven is not a punctual phenomenon, but rather something that is valid in various occasions. With this idea in mind, an estimation of how much the emissions of CO2 could be reduced, if half of the vehicles regularly used carriers, and ended giving a result of 0,3% reduction worldwide.

6. References

[LINK20] Linkov, J., "How Rooftop Carriers Affect Fuel Economy for Cars and SUVs", https://www.consumerreports.org/fuel-economy-efficiency/how-rooftop-carriers-affect-fuel-economy/, 2020

[COMS22] COMSOL, "Airflow over an Ahmed Body", https://www.comsol.com/model/download/913121/models.cfd.ahmed_body.pdf, 2022

[SOLG21] Solgaard H., "New Aero Loader roof box that provides 7% better range", https://www-mynewsdesk-com.translate.goog/no/kgknorge/pressreleases/nye-aero-loader-takboksen-som-gir-7-procent-bedre-rekkevidde-3067278?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=wapp, 2021

[AUTO21] Autoform, "Test Report – Fuel/Power consumption", https://www.pebe.se/files/b3790aa99fd0a223458201fd86012ece.pdf, 2021

INDEX

Figure Index

Table Index

1. INTRODUCTION

It has been estimated that there are currently 1.446 billion registered vehicles on Earth[HEDG22], and for the moment, the vast majority of these vehicles still run on fossil fuels. The combustion of these fossil fuels, that vehicles need to function, is one the main sources of Greenhouse Gas Emissions, accounting, for example, for 27% of the total national Greenhouse gas emissions in United States in 2020[EPA_22].

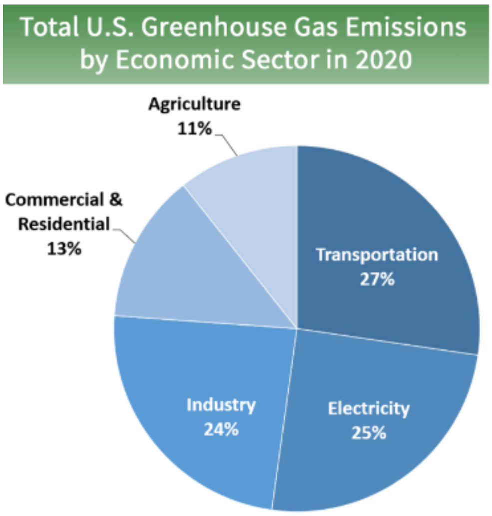

Figure 1:Percentage of Greenhouse Gas Emissions by Sector in US

This isn´t a new concern, and these emissions have been reduced through different ways, such as, the introduction of electric cars or the encouragement to use public transport to reduce the number of vehicles on the road. But these ideas are not effective enough by their own since electric cars still represent a very small percentage of the registered cars and the use of private vehicles is still the main form of transportation. Therefore, it is needed to discover methods to reduce fuel consumption.

The fuel consumption of a vehicle is determined, among other things, by the drag forces it experiences while it is moving, which depend on, the shape, environmental conditions or accessories added, and it is the last one that will be the subject of study in this project.

Accessories such as Car-top Luggage Carriers are devices that not only add weight to a conventional car, but also change the shape which is one of the most important parameters in drag force calculations. Car-top cargo carriers are determinant in the fuel consumptions of cars, it has been estimated that adding a luggage carrier to the top of a car can increase fuel consumption up to a 19% [LINK20].

However, this rise in fuel consumption could be reduced if the luggage carrier was to be reversed. This is due to the fact that drag forces also depend on how and where the boundary layer is detached from the body (this affects pressure drag). Due to its shape, the reversed orientation would resemble more closely an airfoil (Figure 2), where the detachment of the boundary layer is later in the flow.

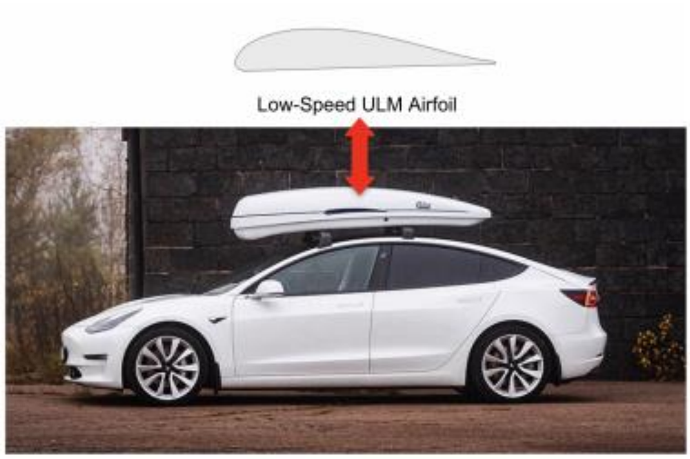

Figure 2: Car with luggage carrier reversed

1.1 MOTIVATION

During their senior year, students from Boston University are able to attend to a class called "Senior Design", where they are offered to work in groups, on different projects proposed by Professors from Boston University or other universities, as well as companies or customers for different purposes.

Professor Grace, from Boston University, proposed this project where the aerodynamics of car-top luggage carriers would be studied to firstly see if the reorientation of the roof box could reduce drag. This idea sourced from a discovery from a Professor at Clarkson University, Kenneth Visser, that was working with a device that would be attached to the end of the trucks to reduce drag [CLAR05].

The effect of the orientation of a nominal, hard roof-top carrier on vehicle drag was firstly intended to be studied through various methods, including 2D COMSOL simulations and road tests.

This project gives the opportunity to demonstrate this idea, and if it were to be true, the carbon footprint could be reduced, which is one of the main concerns worldwide nowadays, not only by reorienting but also by inspiring the redesign of other accessories to incorporate this idea. Furthermore, this improvement in fuel efficiency, would benefit its user economically as well since the expenses in fuel would be lower.

2. BENCHMARKING

Since 2011, discussions about how the design of Cargo carrier was far from optimal led to informal testing whose results could be found in non-academic forums, including EcoModder[ECOM11], AnandTech[ANAN15], Reddit[REDD21], and VWIDTalk[VWID21]. Most of these tests agreed that reversing the carrier achieved improvements in fuel efficiency. On the other hand, these tests also showcased that these effects were dependent on the combination of the luggage carrier and vehicle used, and that there is no assurance that this phenomenon is true for every combination.

Early in 2020 the Norwegian Technical Weekly Energy Magazine published an article [KVAM20] showcasing new findings from a professor from the University of Linköping, Peter Fritzon, who achieved 16% increased range of his Tesla once the luggage carrier was reversed[BLOM20].

This finding led to Autoform, as part of CalixKlippan AB Group, to carry out road tests with vehicles with roof-top carriers in different orientations. Those tests concluded that, as it was previously demonstrated by Peter Fritzon, having the tapered end facing forward is detrimental for the drag forces since the pressure drag (caused by separation of the flow) dominated the friction drag.

After it was ensured that Peter Fritzon's idea was right, CalixKlippan AB Group started developing a new roof box that incorporated this idea. And in January of 2021, the "Calix Aero Loader" was launched, a new roof box "developed with a focus on electric cars" and achieved the following results [AUTO21], [SOLG21] when comparing the range of the Aero Loader, to the range with other roof boxes with traditional designs from the same company.

	V60		Tesla		XC40	
Roof Box	AL	H22	AL	H22	AL	H18
Distance (km)	44,5	44,4	55,7	55,5	14,6	14,3
Average Speed (km/h)	110	110	100	100	110	110
Average consumption (l/100km, W/km)	5,82	6,15	207	221,5	7	7,5
AL vs H18/H22	-5%		-7%		-7%	

Table 1: Results from Autoform's test

In Table 1, it can be appreciated that this new car-top luggage carrier achieved increased ranges of at least 5% for all the vehicles tested, further information of the results can be found in Appendix I.

3. PROJECT DEFINITION

3.1 JUSTIFICATION

In the previous section, it was shown how the idea that is subject to this project, could have positive results. However, there are two reasons that make this project valuable:

3.1.1 VARIABILITY IN THE RESULTS DEPENDING ON THE CAR TYPE

Firstly, it was expressed in the non-official forums how there is a concern that reversing the orientation of the car-top luggage carrier may not be profitable for every car type.

In this project, the back part of the car was given high importance, since the detachment of the boundary layer not only depends on how the car-top luggage carriers is at the back of the car, but also how the car ends.

3.1.2 NON- EXISTING PRODUCTS FOR VEHICLES THAT RUN ON FOSSIL FUELS

The only product that is available nowadays, is designed to be paired with electric vehicles. This means, as it was stated earlier, that the vast majority of the vehicles that are on the road today and are the main originator of the Greenhouse Gases Emissions, are yet to be assessed in this aspect.

Finding higher range for electric cars benefit its users mostly, since it would mean fewer stops during a trip (it could also mean a small reduction in greenhouse gas emissions if the electricity were to be produced with fossil fuels, but it wouldn't be very meaningful nowadays and complicated to quantify).

However, finding improvements in fuel efficiency for gasoline and diesel vehicles could, not only be beneficial for the user in economic aspects, but also benefit the environmental development of the world.

Furthermore, this project's main purpose wasn't to create a new car-top cargo carrier that reduces fuel consumption, but to decide whether the user would find improvements in fuel efficiency from the reorientation of their traditional roof box, without needing to purchase a new one to get these improvements.

3.2 OBJECTIVES

The final objectives that were set with the customer and director to be accomplished, were the following:

1) Demonstrate that reversing the orientation of a car-top luggage carrier reduces drag coefficient for different car bodies:

   This was the first and most important objective that needed to be achieved. If it couldn't be demonstrated, the rest of objectives and the project itself would not be valuable.

2) Quantify the saving that the reduction of drag could imply:

   After proving that the drag is reduced, the next objective was to measure reduction in fuel consumption, economical expenditures and even carbon dioxide footprint reduction.

3) Understand and do an assessment of the risks that come with the reorientation of the car-top luggage carrier:

   There may be higher risks involved in the use of a car with a roof box placed backwards. Issues that are expected to appear could be related to noise, vibrations, problems to open the trunk of the car, inability to reorient due to either problems with the claw grips or the angle of the roof rack, increased lift forces depending on positioning or violation of warranty. The risk assessment was to be used to help understand if there were to be any reason to not take advantage of the reorientation of the roof box and its potential benefits.

3.3 METHODOLOGY AND PLANIFICATION

3.3.1 METHODOLOGY

To achieve the objectives described in the previous section the following steps were followed:

- As a first approach, 2D computational simulations were used to decide if the main goal of the project, that was to demonstrate the reduction of drag by the reorientation of the car top luggage carrier, is achievable, and to get some estimations of the numbers that should be expected in the other parts of the project. The simulations were firstly done in 2D with a general design of a roof box on top of a car with no gap in between them, and from that starting point both, models of the car and the car top luggage carrier, were developed. as well as adding gap between the car and the car-top luggage carrier, to end up achieving the closest to a real-life simulation as possible.

- In order to achieve the other objectives stated, road tests were carried out. The assembly car-luggage carrier was put together in one orientation, then the car was driven for a determined length, while measurements of fuel consumption were being taken, and then the car-top luggage carrier was reoriented for the car to be driven through the same route, with the same parameters being measured, to be later compared. These measurements were used to find the differences between the specifications that are not related to aerodynamics such as the financial savings or carbon dioxide emissions. These tests were also used for the risk assessment which could not be done through the computational simulations.
  Road tests were of highest importance; theoretical validation of the project hypothesis by simulation results are not as valuable as the actual validation by road test results. If the simulation results weren't to be supported by road tests, which was plausible given the idealizations made (explained in section 4.1.2) in 2D simulation, then there may be no meaningful real-world impact to these theoretical findings.

It is worth noting that when the project was first proposed, instead of carrying out road tests, alongside with computational simulations, wind tunnel tests were to be carried out in the wind tunnel available at Boston University. However, due to the expenses that involved the manufacturing of the model (car and roof box) and the modifications needed to be made to the wind tunnel (new floor needed to be manufactured), and the uncertainties related to the credibility of the results that were going to be found (it was going to be used a measurement system that hadn't been tested earlier), it was decided that changing this part of the project for the road tests would be more relevant. Information related to the work done for the wind tunnel simulation can be found in appendix II.

3.3.2 PLANIFICATION

The chart found in the following page, represents the development of the project during the first semester, and how the second semester was expected to progress after the wind tunnel tests were discarded. It can be appreciated a section of a chart that involves experimental simulation with fans. This was an idea that the director suggested before working with the wind tunnel. The idea was to have two cars side by side, attached by a string, each with luggage carrier with a different orientation, and then be subjected to the wind produced by a fan, and if there were to be differences in drag, the one with a higher drag coefficient would go backwards and the other one forwards. However, since the models were made out paper (it was a quick experiment and no added expenses were desired), and the fan available wasn't very powerful, the experiment didn't add much value, aside from a slight change in position, in favor of the reversed orientation model.

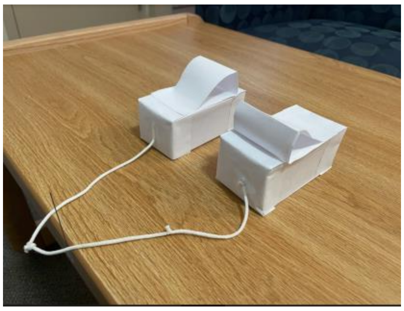

Figure 3: Configuration of fan test

Activity	Grade of Completion	October 4-17	October 18-31	November 1-14	November 15-30	December 1-15	January 10-25	Janury 26- February 10	February 10-28	March 1-15	March 10-31	April 1-15	April 15-30	May
Research	100%													
Making Decisions on models, softwares...	100%													
Creating the CAD Model for the Simulations	100%													
2D Simulations (learning+ Simulations)	100%													
Analysis of Results	100%													
Decisions for Wind Tunnel (Model, Manufacturing...)	100%													
First Experimental Tests (Fan+ both orientations	100%													
Manufacturing for the wind tunnel	0%													
Wind Tunnel Tests	0%													
Decisions for Road Tests	100%													
First Road Test	100%													
Analysis of Results	100%													
Second Road Test	100%													
Writing Reports	100%													

Table 2: Gantt chart of the project

3.4 DESCRIPTION OF TECHNOLOGIES AND COSTS

3.4.1 DESCRIPTION OF TECHNOLOGIES

Throughout the different parts of the project some tools are used that will be described in this section:

- In order to carry out the computer simulations, CFD (Computational Fluid Dynamics) was used. CFD is a tool available in various software used in Engineering that allow to carry out simulations and solve problems that involve the flow of fluids through grid convergence and numerical convergence (numerical analysis). Grid Convergence is related to the division of the volume desired to be studied in a mesh to then be solved through different governing equations that are modified to solve a finite difference problem. Numerical convergence refers to the idea of iterations until the values of the mesh do not change. COMSOL was chosen to be the software used for the project after suggestion of Professor Grace.

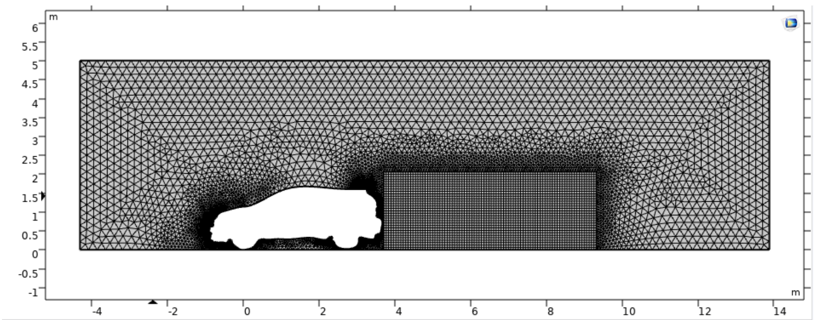

Figure 4: Example of Mesh

- For the road tests, an OBD (On-Board Diagnostics) device was purchased. OBD devices are computer systems that can be connected to vehicles to view and recollect further information about the performance of a car, than the car itself can show. This was decided taking into consideration the vehicles that would be subjected to these tests, since these vehicles were not too modern, it was expected its measurements could be not very precise.

Figure 5:BlueDriver's Pro OBD II

BlueDriver's Pro OBD II device was used to track and record all the measurements during the road tests of all the different parameters that were used in the graphs and discussions in the following sections. After comparison between different OBD devices, this one was chosen for its price, data exporting ability, and compatibility with a wide range of cars. The accuracies of this device are listed below in appendix III from Blue Driver's support page.

3.4.2 COSTS

Boston University funds the projects developed in the course explained in section 1.1. This project was given a budget of 300$ since it was being carried out by three members (100$ per member). However, the only expenses came from the road tests:

- A universal roof rack was purchased for 55$, in order to be able to mount the car-top luggage carrier in different cars.
- The BlueDriver's Pro OBD II explained in section 3.4.1 was purchased for 85$

It was not needed to purchase a car-top luggage carrier, due to the fact that the customer owned one. And the cars used to carry out the tests belonged to group members and relatives. Therefore, the total expenses for this project added to 140$ (without including the costs of gas).

4. PROJECT BREAKDOWN, AND DESIGN DECISIONS AND DETAILS

4.1 COMPUTATIONAL SIMULATIONS

4.1.1 OVERVIEW

Since the project started through this part, most of the research related to the parameters that affect drag to a car was studied here. From this research, between the most influential parameters for this project, one of them relate to the position of the carrier (both, whether it is center or displaced on top of the roof, and the gap between the roof box and the car). It was also confirmed that drag differences would appear between hatchback, notchback, and fastback-type cars [BRYA14].

After this research, and discussions with both the customer and the instructors, it was determined that the focus should be on just one car model for simulations. The Honda CR-V, 2013 model, was selected, as it was a reasonably popular family vehicle, and as it was not too recent, it had existing CAD models [MUHA14] and performance data available, estimating its drag coefficient between 0.37[ZAL_13] and 0.43[BILL11]

With the previous information, a 2D, turbulent, time dependent COMSOL CFD simulation was created. It gave reasonable drag values and showed a decrease in drag due to reorientation, furthermore the domination of pressure drag over friction drag made its appearance in these simulations. Later, the effect of the roof rack gap, or vertical offset, was also simulated from 0-12cm.

Afterwards two-dimensional outcomes were shown to be relevant through benchmark comparisons to three-dimensional Ahmed Body stationary simulations [COMS22]. This was used to justify reducing the problem from 3D to 2D, which was immensely helpful as it drastically reduced solving time. Then two-dimensional stationary simulations of a vehicle with a nominal rooftop carrier placed in its developers' recommended orientation as well as reversed were completed. The simulations at multiple speeds (55-80mph) show that the vehicle drag decreases when the carrier is placed opposite the recommended orientation.

4.1.2 SIMULATION DESIGN DECISIONS AND DETAILS

- Reynolds number was calculated to find whether it would be a laminar flow or turbulent, using the distance from the lowest flat surface of the car body to the top of the roof as characteristic length and a speed of 60 mph. To find Reynolds number of around a million, therefore it would be turbulent flow.

$$Re = \frac{\rho u L}{\mu}$$

- No-slip condition (speed of the fluid equal to zero) is imposed in every wall, however, to simulate open space simulation, top boundary is a moving boundary with the inlet speed.

- Inlet speed set to constant value (60 mph during the first semester and between 55 and 80 mph during the second semester). These ranges were chosen to emulate the different speeds at which a car would travel in a highway. fuel savings from reorientation are assumed to be most important to consider for long road trips where the majority takes place at highway speeds.

- Since the mach number of the flow is much lower than .3, incompressible flow is assumed

- One of the decisions that needed to be made was whether the 3D simulations would add valuable information to the project, or the 2D simulations could be valid. This is due to the fact that adding a new dimension increased exponentially the time a simulation needed to run until it converged. Therefore, the validation of the 2D simulations were done through the Ahmed body [COMS22].

This Ahmed body is a simplified version of car, that maintains the most important features of the vehicle, but allows for precise flow simulation.

Below, the tables will contain more values used for the simulations and the validations of the 2D simulations through the Ahmed body:

Parameter	**Value**	**Units**
μ	1.81×10^{-5}	$kg/m*s$
ρ	1.23	kg/m^3
P_{ref}	1.00	atm
T_{ref}	293.15	K
Ahmed Body Projected Area	0.11	m^2
Honda CRV 2013 Projected Area	3.47	m^2

Table 3: Project 2D Simulation Fluid Parameters

Parameter	**Value**	**Units**
ρ	1.20	kg/m^3
P_{ref}	1.00	atm
T_{ref}	293.15	K
Ahmed Body Projected Area	0.12	m^2

Table 4: COMSOL 3D Ahmed Body Fluid Parameters

The values for the 3D table correspond to the values used by COMSOL for this simulation, it can be appreciated how the density and the projected area differ from the 2D simulation from the project. The projected area increases in the 3D due to wheel posts(Figure 8) that cannot be in the 2D Ahmed body to allow the flow under the main body.

The following figures depict the designs used for the different simulations carried out:

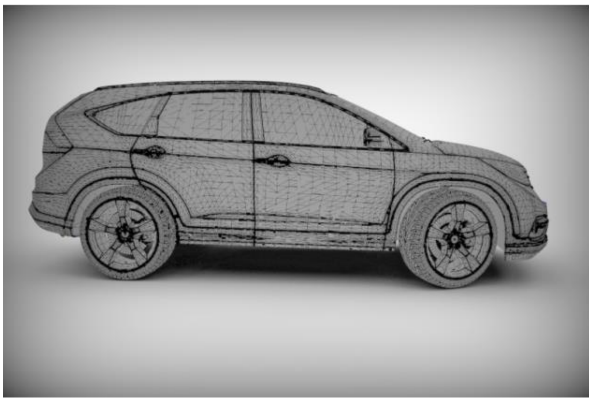

Figure 6: Honda CRV 2013 2D view

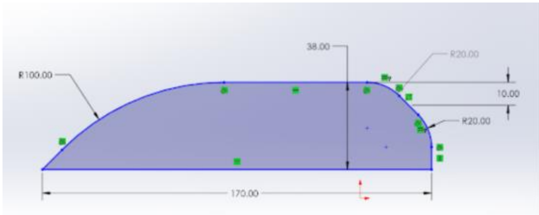

Figure 7: Original Luggage Carrier Mock-Up

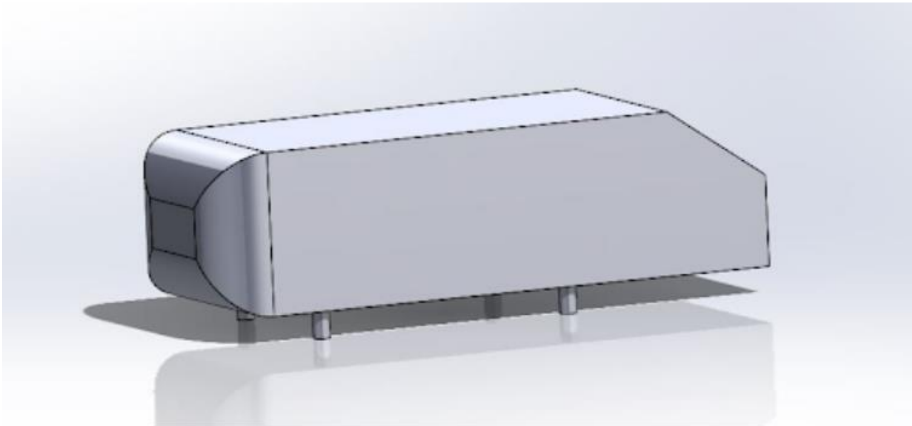

Figure 8:Ahmed Body

- During the course of the project, COMSOL introduced an update that enabled functions to better simulate the viscous sublayer therefore two different meshes were used during this project:

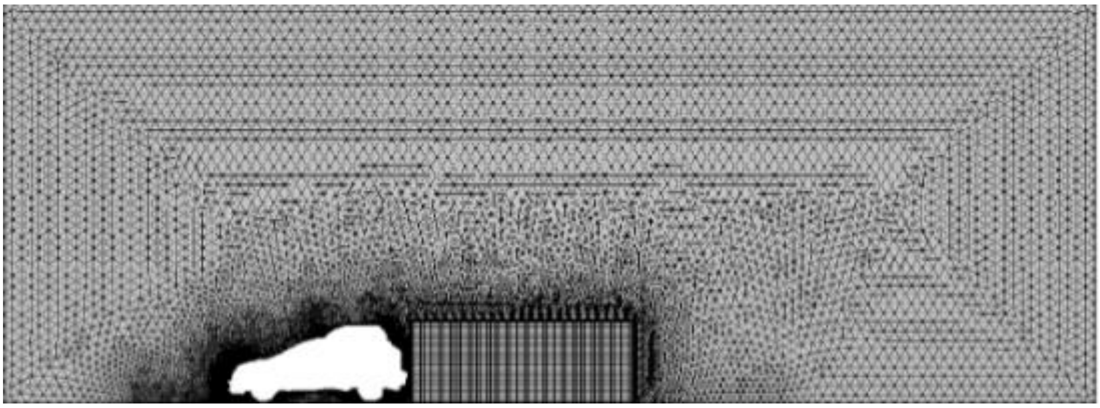

Figure 9: COMSOL 5.6 Car Mesh–Wheels

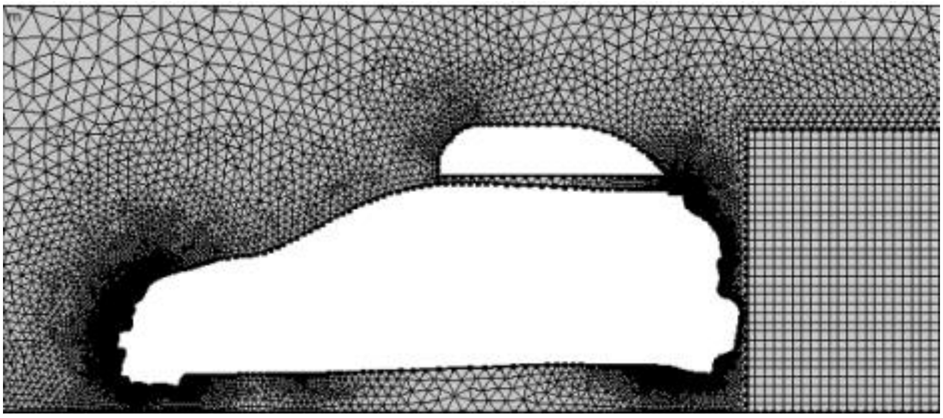

Figure 10: COMSOL 5.6 Car Mesh–No Wheels

During the first semester these meshes were used with COMSOL 5.6. The simulations firstly included the wheels, which needed to be removed, since it lowered the drag coefficient due to the fact that it stopped the flow of air underneath the car body (it acted as a car skirt), it was also added a 12 cm gap between the roof and the carrier.

After COMSOL 6.0 was released, boundary meshes were more important, and these were the ones used:

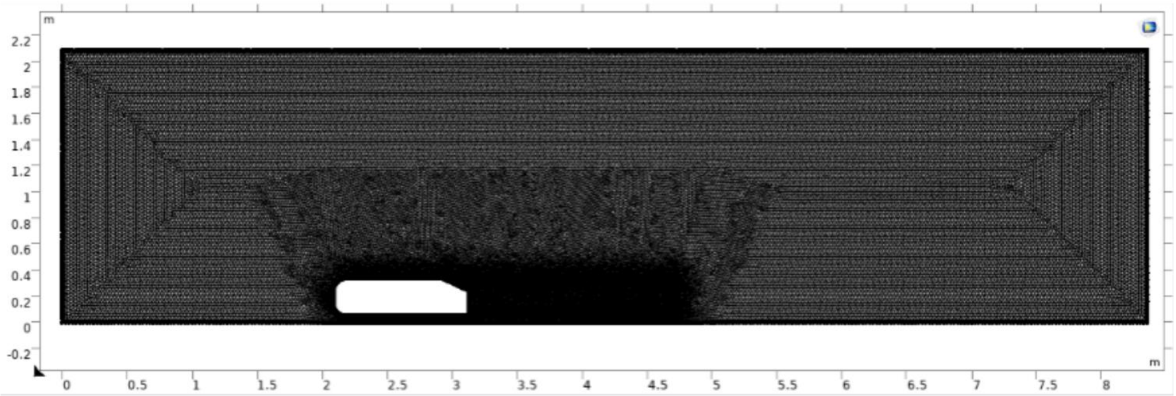

Figure 11: 2D Ahmed Body Mesh

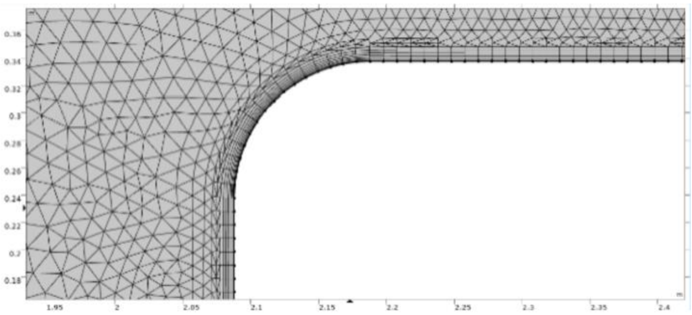

Figure 12: 2D Ahmed Body Boundary Layers

These meshes were also used for the with simulations for the Honda CR-V, but with more boundary layers.

Finally, the equation below was used to calculate the drag coefficients; substituting in the pressure forces or viscous forces into the equation yield what is called pressure drag and viscous drag in tables below.

$$Cd = \frac{2F}{\rho A_{PROJECTED} u^2}$$

4.2 ROAD TESTS

4.2.1 OVERVIEW

As it was explained in section 3.3, this part of the project was the most important since it would be the way that the results achieved in the simulations would be validated.

Road tests would also give the possibility to incorporate irregularities that are encountered in real-life situations and cannot be taken into consideration in simulations. For example, 2D simulations cannot include cross winds, road gradation or presence of other vehicles. Notably, tailgating can decrease drag substantially. Therefore, it was important to generate a procedure to try to minimize differences between runs.

As mentioned above, Autoform generated an official report for their road test experiments, but this did not include their procedure. While Autoform reports a 6-7% decrease in fuel consumption due to reorientation, since they only tested on fastback cars (Tesla Model 3, Volvo XC40 D2, and Volvo V60 D4), another reason was added to choose the Honda CRV 2013 for simulation.

Since the hatchback cars used for the road tests did not have the methods of logging their instantaneous fuel consumption, other methods of collecting data needed to be investigated. After research was made on this topic the following possible alternatives were considered: coast down testing, an industry standard way of measuring drag in which a car travelling at a certain speed was then put into neutral and was timed how long it took to come to a stop; throttle testing, in which the time it took for a car to reach a set speed from zero was recorded and related to drag; finally the OBD, explained in section 3.4, was discovered.

The latter method was chosen, since the OBD tool was most simple, and it was already a widely used tool amongst car mechanics. All vehicles manufactured past 1996 in the United States have a standard car diagnostic port, usually located on under the steering column.

Unfortunately, although the device had the capability to measure fuel consumption, both cars used in the road tests (2016 Honda Odyssey and 2015 Subaru Forester) were incompatible with this sensor. As an approximation, mass air flow rate (MAF) was used, with the understanding that a car travelling at fixed speed over flat terrain will have a constant air to fuel ratio, thus making MAF directly proportional to fuel consumption. For example, in the most optimal case in which all oxygen and fuel is burned, the air to fuel ratio can be calculated based on the physics and stoichiometry to be 14.7:1, and this is the ratio typically found for cars with warmed-up engines travelling at constant speed. When accelerating, going uphill, or carrying heavier than usual loads, this air to fuel ratio will decrease as more fuel is needed, and the engine is said to run" rich". When going downhill or decelerating, the air to fuel ratio will increase as less fuel is needed, and the engine is said to run" lean".

These results underscore the importance of conducting the road tests during low traffic times, since not only will other cars increase the possibility of including slipstreams in the tests, complicating the results, but also the presence of other cars may also make it difficult to keep a constant speed.

The procedure developed consisted in recording the desired parameters along a route with both orientations in both directions of the route. A more detailed procedure for the first road test can be found in the appendix section.

4.2.2 Road Test Decisions and Details

This part consisted of two separate road tests, with different cars, but using the same Car-top luggage carrier (Thule Pulse L) for both tests. This carrier's dimensions are the following: 76 inches long, 33 inches wide and 16.5 inches high and weighs 36 pounds. The procedure consisted in recording the desired parameters along a route with both orientations in both directions of the route. A more detailed procedure for the first road test can be found in appendix IV.

4.2.2.1 First Road Test

The first road test was conducted with a 2016 Honda Odyssey along a 3 mile stretch on route 2, located in Boston, Massachusetts. Some reference photos for the carrier placement on the Honda Odyssey are Figure 13 and Figure 14.

Figure 13: Traditional Orientation

Figure 14:Reverse Orientation

Since an empty luggage carrier was not realistic, and could have caused additional vibration issues, during the road test the luggage carrier was packed with 32 pounds worth of luggage. This weight was arbitrarily chosen.

As discussed earlier, it is known that the centering of the luggage carrier has a large impact on the aerodynamics of the car-carrier system [MIKO19], [BRYA14]. To keep the road test faithful to the 2D simulations, the luggage carrier was mounted as side-to-side symmetrically as possible.

Additionally, it was important to mount the luggage carrier onto the roof rack as horizontal as possible so that the reverse orientation would not have a different angle of attack from the traditional orientation, as that could impact the problem. Lastly, as noted in the road test overview, it was important to keep the luggage carrier in the same back-forward position, so white markers were stuck to the luggage carrier to keep the claw grips in the same position each time (see Figure 15 and Figure 16).

Figure 15:White Tape to Position Claw Grip

Figure 16:Estimating Side-Side Centering

Since both cars for the road test did not have roof racks, universal roof rack bars were purchased. Unfortunately, the ordered roof rack came with too short of straps to fit the Honda Odyssey, so they had to be lengthened with supplementary nylon straps (see image below).

Figure 17: Improvised Ratchet Strap Extensions

4.2.2.2 Second Road Test

The second road test was conducted with a 2015 Subaru Forester. A length of 6 miles, including the original 3-mile course, along Route 2 was chosen. However, since this test was conducted on a holiday, due to the small amount of time at the end of the year, the increased amount of traffic was another source of variability and error in the experiment. Additionally, the road test was performed at a lower constant speed than the first road test. Some reference photos for the carrier placement on the Subaru Forester are (Figure 18, Figure 19 and Figure 20).

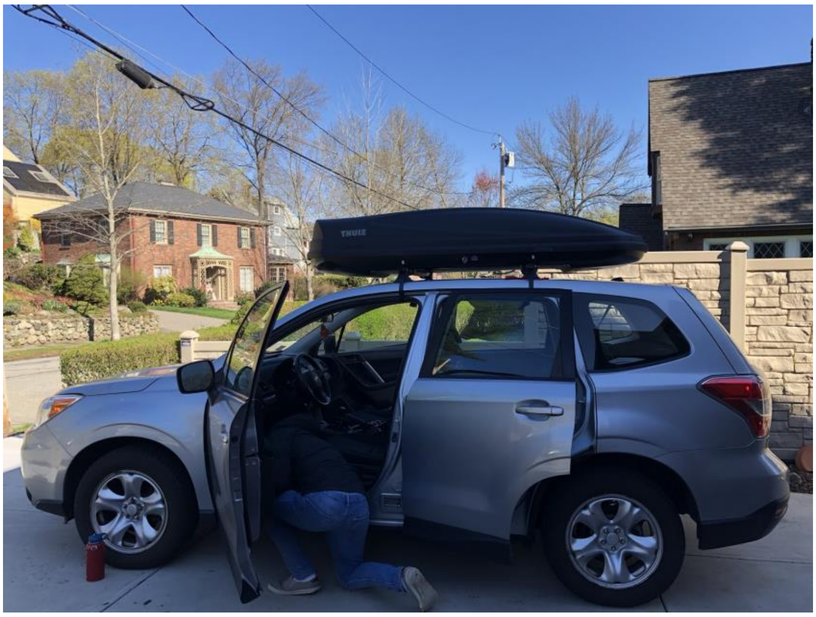

Figure 18: Reverse Orientation

Figure 19:Estimating Side-Side Centering

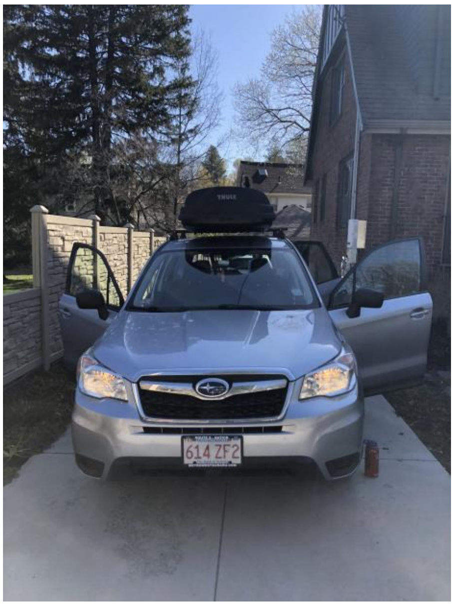

Figure 20: Estimating Side-Side Centering

5. RESULTS ANALYSIS

5.1 SIMULATION RESULTS

5.1.1 FIRST SEMESTER RESULTS (COMSOL 5.6)

With the parameters described in section 4.1.2, the mesh shown in Figure 10, and a time-dependent k-ϵ solver, the following results were found:

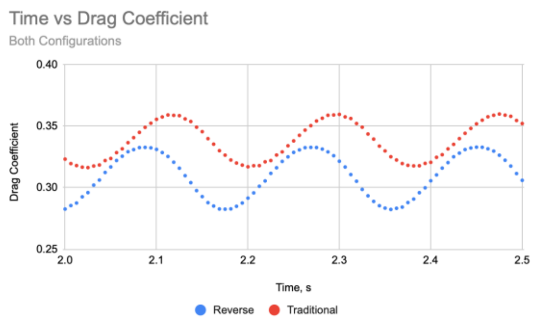

Figure 21: COMSOL 5.6 Drag vs Time

Orientation	Drag Coefficient, Averaged Over 3 cycles
Traditional	0,34
Reverse	0,31
%Difference	-9%

Table 5:COMSOL 5.6 Drag Results

After averaging the oscillating values of drag, the reverse configuration showed a 9% smaller drag coefficient than the traditional configuration. According to the Auto Research Center [AUTO22] a 10% decrease in drag would improve the fuel efficiency by 5%, meaning that this result would be in line with the results that were reported by Calix.

Literature search showed that not only does the luggage carrier placement matter, but also roof racks themselves could have a fuel consumption penalty of 1% [CHEN16]. With this idea in mind, and as an additional component, our customer also wished to test the effect of the roof rack gap on the drag. So, a series of simulations was run, with the traditional orientation. This was also run with a 60mph inlet speed. The graph below shows the full range of solved time for reference, but the drag values were only calculated (averaged) after the solution had reached steady state.

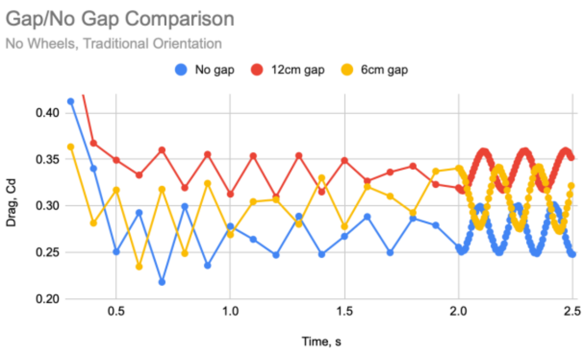

Figure 22:COMSOL 5.6 Drag vs Gap

Roof Rack Gap (cm)	Drag Coefficient, Averaged Over 3 cycles
0	0,27
6	0,31
12	0,34

Table 6:COMSOL 5.6 Roof Rack Gap Results

As anticipated, the roof rack gap had a significant effect on drag, with an increase of 20% in the drag coefficient when the gap was 12 cm with respect to the simulation where the carrier was touching the roof.

5.1.2 Second Semester Results (COMSOL 6.0)

As discussed in section 4.1.2, to validate the use of 2D simulations, a comparison benchmark to 3D simulations was required, and this was all done with the stationary solver. In this way, the Ahmed body could both be sued to justify moving the problem from three dimensions to two dimensions, and also indirectly for using the stationary turbulence solver. The velocity fields of the Ahmed body simulations are shown below.

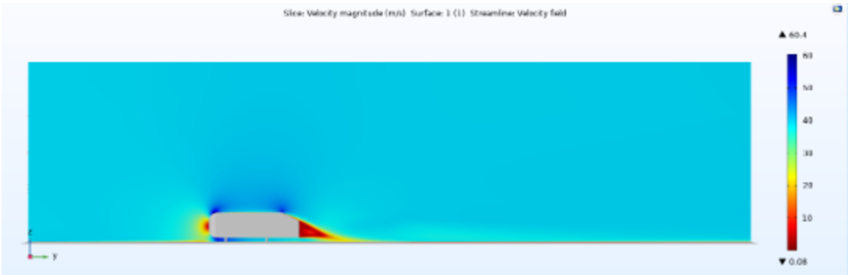

Figure 23: 3D Ahmed body Velocity Field

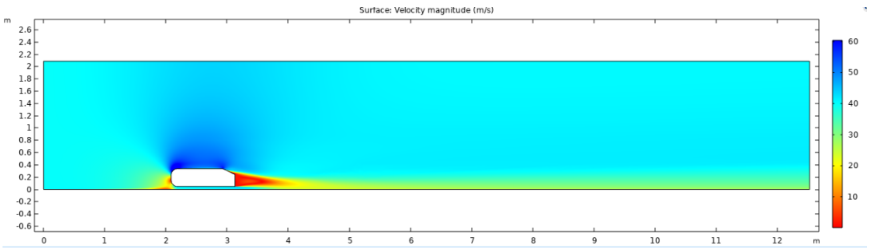

Figure 24: 2D Ahmed body velocity field

COMSOL has released commentary on their solutions for the Ahmed body simulation, because, while the shape of the wake and pressure force breakdown over the 3D body surfaces do not exactly match up with previously accepted values, the overall drag is accurate.

Similarly, while the size and shape of the wake is quite visibly different from 2D to 3D, the overall forces and drags are very similar. The 2D model represents the center line of the 3D simulation which is the maxima of the flow around the body, it would be expected that the pressure forces and therefore drag (since drag is dominated by pressure force) of the 2D simulation would be higher than for the 3D simulation, due to the fact that the pressure difference peaks in the center and drops off towards the sides of the car. The breakdown of the subsequently found drags can be found below; importantly, the drag coefficients were calculated using COMSOL's reference values as noted in Table 4.

	Drag Coefficient	Total Force (N)	Pressure Force (N)	Viscous Force (N)
3D	0,35	39	34	5,5
2D	0,36	41	37	4,4
%Difference	-3%	-5%	-9%	-20%

Table 7: 2D vs 3D Ahmed Body Drags

The comparison showed a 3% difference between both simulation in the drag coefficients, which was considered small enough to trust the values that would come from the 2D simulations. The viscous force showed the largest discrepancy, but friction forces make up a very small percent of the total force, so it could be considered negligible. Since 2D also doesn't account for the sides of the car, the lower viscous force found from the 2D case makes sense.

With COMSOL version 6.0, the same mesh as the validated 2D Ahmed body, and a stationary k-ϵ turbulence solver these results were found:

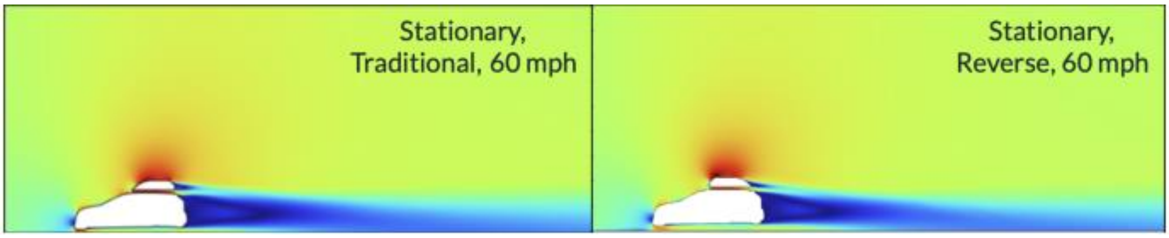

Figure 25:Comparing Traditional to Reverse Velocity Fields

It can be observed that the size of the reverse orientation wake is slightly smaller than that of traditional. Consequently, a decrease in the drag coefficients was also found. Here the drag was calculated using our reference values as noted in Table 3.

Speed (mph)	Drag Coefficient	Pressure Drag	Viscous Drag
55	0,453	0,424	0,0288
60	0,45	0,422	0,0284
70	0,446	0,418	0,028
80	0,442	0,414	0,0274

Table 8:Traditional Orientation

Speed (mph)	Drag Coefficient	Pressure Drag	Viscous Drag
55	0,383	0,356	0,027
60	0,38	0,354	0,0267
70	0,376	0,35	0,0264
80	0,373	0,347	0,0258
%Difference	-16%	-16%	-6%

Table 9:Reverse Orientation

While it may seem counter intuitive, it has been well documented that for bluff bodies increasing Reynolds number can cause a decrease in drag as turbulence delays flow separation. Correspondingly both traditional and reverse orientation see a decrease in drag with an increase in speed/Reynolds number.

The stationary (time-independent) problem finds a higher -16% drag difference when compared to the time dependent simulation, which would have some correspondingly higher percentage decrease in fuel consumption that may be more comparable to the results reported in the Technical Weekly Magazine [KVAM20]. However, when cruising down the highway, one can audibly hear the vibrations and oscillations of the wind around the car, so it is likely that the time-dependent problem, with lower fuel consumption savings associated with reorientation compared to the stationary problem, is a better match to reality.

5.2 ROAD TEST RESULTS

5.2.1 FIRST ROAD TEST RESULTS

It was suggested that the use of cruise control in the road tests could introduce spikes into the collected data. To determine whether this was true or not, an inbound and outbound run for the same orientation were graphed against each other, with one set of data reversed in time. This is shown in Figure 26:

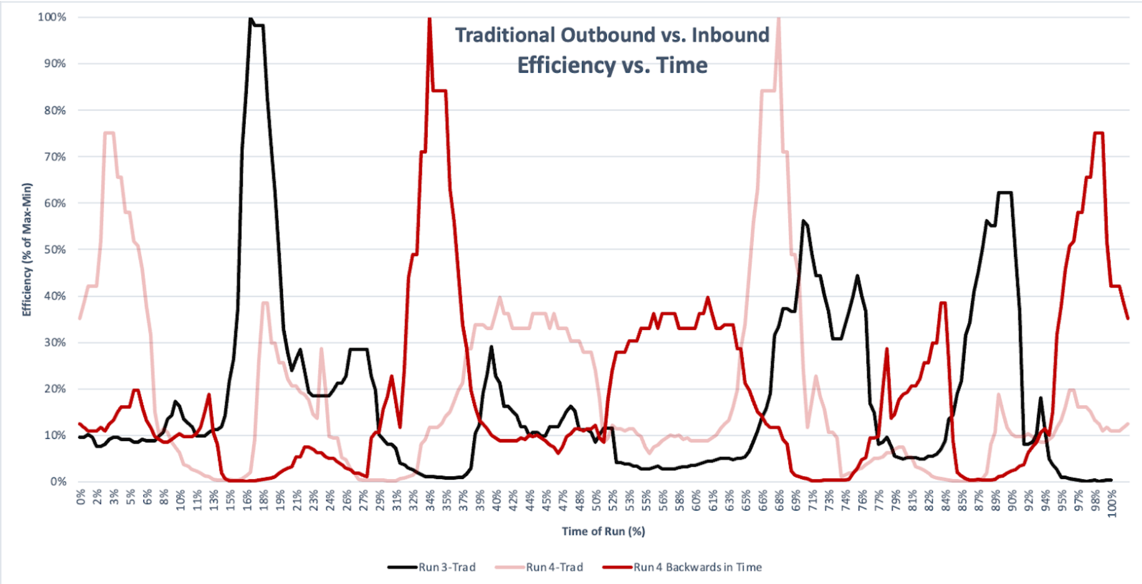

Figure 26:Traditional Inbound vs Outbound

The faint red line represents the original data, while the bold red line represents the same data reversed in time. Since the larger spikes intersect with minimums in the other data set (which is the opposite route direction), it seems that the larger variations are likely due to road gradation; that is, where the calculated engine load in an outbound run is high at some point in time, likely due to going uphill, the engine load is low at that same time for the time-reversed inbound run, as it corresponds to going downhill. This also serves as some measure of proof that the wind variations were minor between the studies, as these road effects are still discernible. After this was determined, outbound and inbound tests by traditional and reverse orientation were grouped separately to examine the overall variation of the experiment.

5.2.1.1 Inbound Route

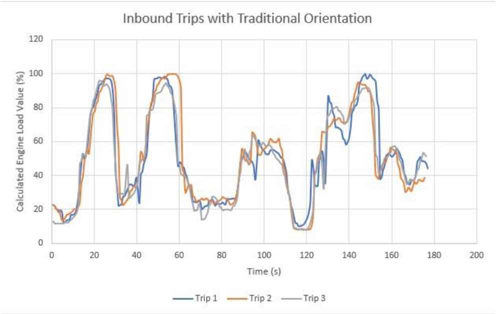

Figure 27: Traditional, Engine Load

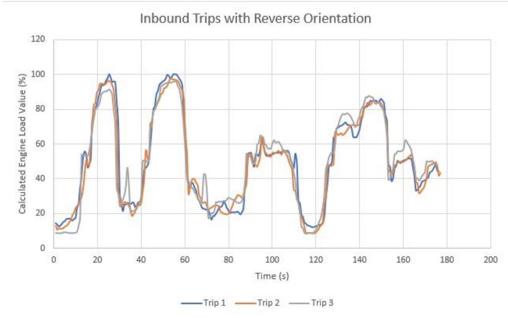

Figure 28: Reversed, Engine Load

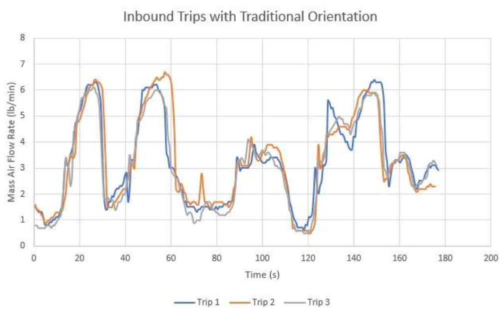

Figure 29: Traditonal, MAF

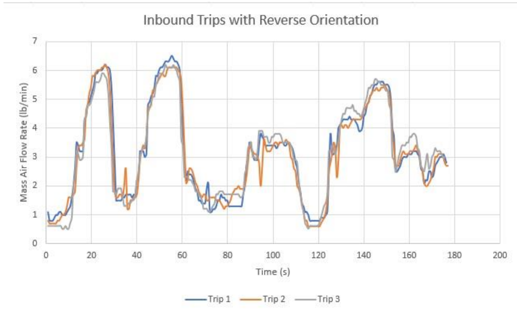

Figure 30: Reversed, MAF

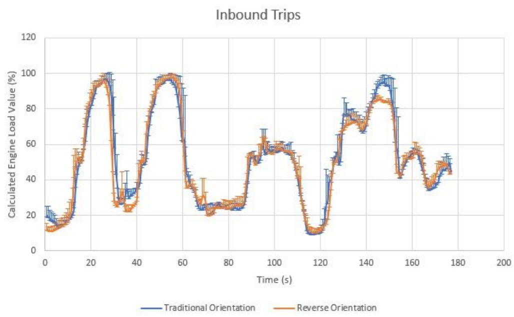

Figure 31: Traditional vs Reversed, Engine Load

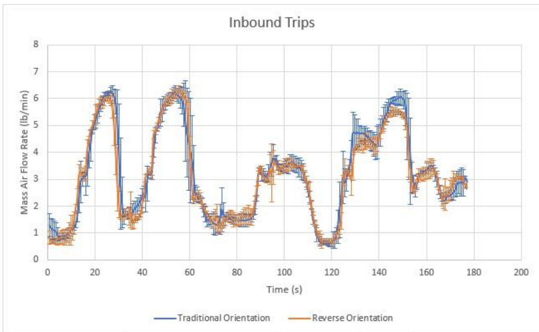

Figure 32: Traditional vs Reversed, MAF

	Calculated Engine Load (%)	MAF (lb/min)
Traditional Orientation	50,6	3,22
Reverse Orientation	50	3,14
Difference	-0,65	-0,08
%Difference	-2%	-3%

Table 10:Inbound Engine Load and MAF Difference

5.2.1.2 Outbound Route

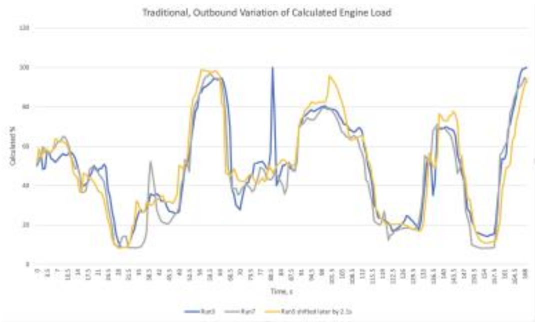

Figure 33:Traditional, Engine Load

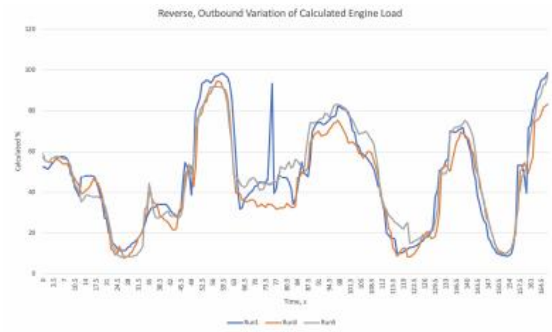

Figure 34: Reversed, Engine Load

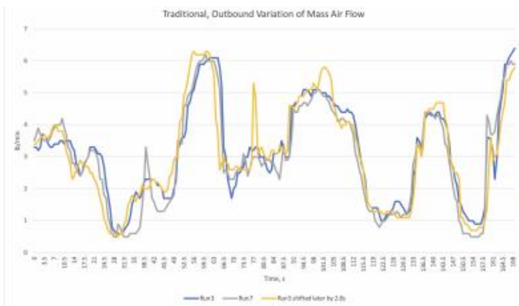

Figure 35:Traditonal, MAF

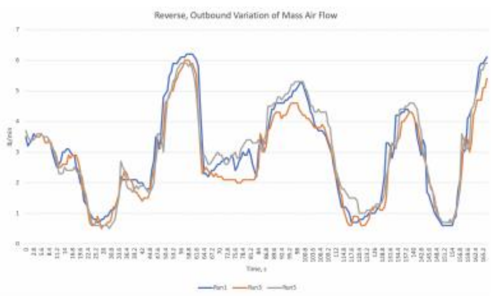

Figure 36:Reversed, MAF

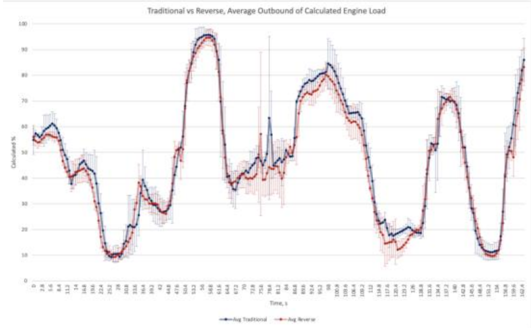

Figure 37:Traditional vs Reversed, Engine Load

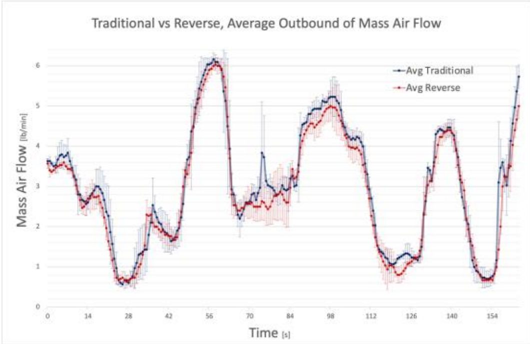

Figure 38: Traditional vs Reversed, MAF

	Calculated Engine Load (%)	MAF (lb/min)
Traditional Orientation	47,8	3,04
Reverse Orientation	45,5	2,87
Difference	-2,27	-0,165
%Difference	-5%	-5%

Table 11:Outbound Engine Load and MAF Differences

Some graphs were shifted slightly in time to align the peaks, but this was no more than 3 seconds at most. A time-averaged integration was used to calculate the difference between the traditional and reversed orientation, and the Riemann summation method was used to approximate the integral.

From Figure 27 to Figure 30 and Figure 33 to Figure 36 were meant to give a visual representation of how repeatable the experiment was, when sorted by route direction and luggage carrier orientation. No apparent differences in variation between orientation for a given route direction could be seen. At no time during road test 1 was it required to deviate from the set cruise control speed, there were a few occasions when it was necessary to change lanes to avoid drafting behind another car.

There are substantial differences comparing the inbound data to the outbound data: the percentage differences found for the outbound trips were higher than the ones for the inbound trips. This cause of this is also unknown; it could be due to human variability decreasing over time as the number of trials increased. Generally, it appears that the largest differences between traditional and reverse orientation can be seen on flatter regions, corresponding to flatter segments of the comparison graphs or Figure 31, 32, 37 and 38. Nevertheless, all cases of reorientation showed lower calculated engine load and MAF.

Assuming MAF is proportional to fuel consumption, a 1-5% decrease in MAF aligns with the lower end of Calix' results finding 5-7% decrease for a markedly different car-back type. This implies that a hatchback car may see an equal increase in fuel efficiency as a fastback due to reorientation, which may help in moving the discussion of reorientation from being highly specific to a certain car-carrier combination to being more of a general finding.

However, as discussed earlier, even though the speed was nearly constant, the graphs show that the road is not flat, so a constant air to fuel ratio cannot be assumed; even so, with identical changes in air to fuel ratio for the repeated course, the MAF is still a useable metric for percentage fuel consumption difference. The only implication this should have on our data is make us unable to use the direct equation to calculate exact fuel consumption from our current data.

5.2.2 SECOND ROAD TEST RESULTS

Following the same procedure as the one followed during Road Test 1, this test sought validation for longer driving periods. Taking advantage of cruise control, the test was conducted at an estimated constant speed of 55 mph. The same route was used in order to achieve the validation, using the BlueDriver OBDII to measure the Mass Air flow rate. Due to the test being conducted on a holiday, other sources of error and variability arose from greater traffic on the road. With the BlueDriver device set up along with the luggage carrier, a distance of around 6 miles was driven for each trip, going outbound and inbound. This produced 6 minutes of constant speed data that were used to analyze and compare results.

In this case, due to the increased traffic and some added problems with the cruise control, the inbound data didn't seem "clean" enough to be compared, and only the outbound trips are compared:

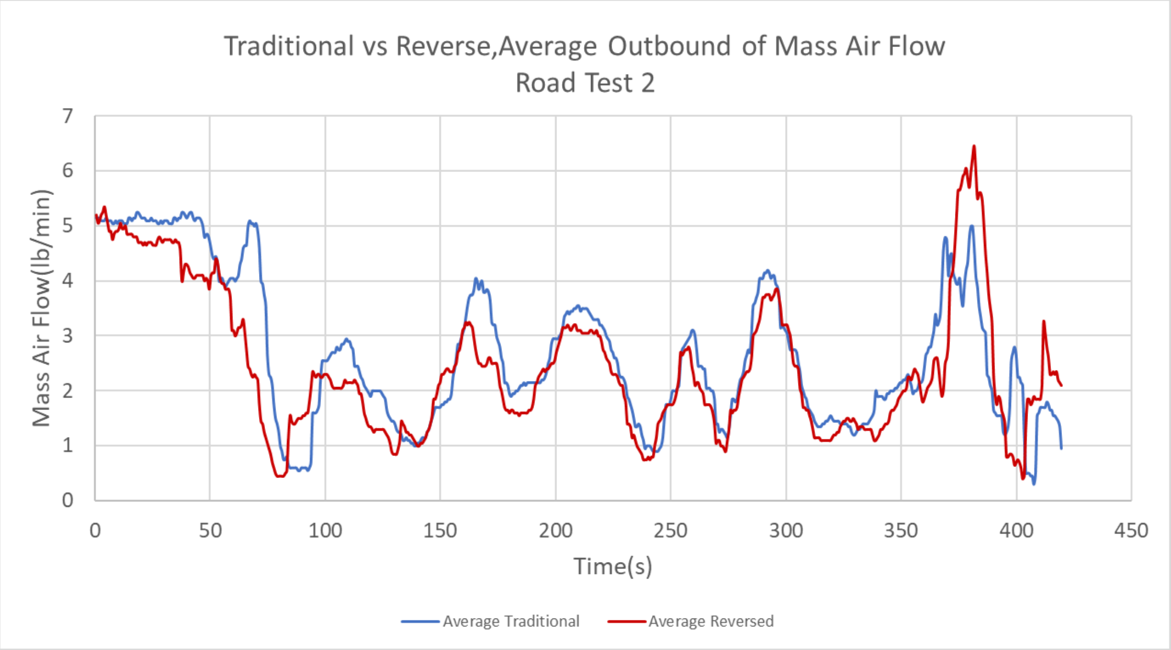

Figure 39: Average Traditional vs Reversed for MAF, Outbound

Following the same procedure as in the first road test, the trips with each configuration were averaged and then shifted to be plotted together as shown in the graph above.

And again, the same method was used to calculate the average for each Mass Air Flow rate for each configuration (time averaged integration through Riemman summation).

	MAF (lb/min)
Traditional Orientation	2,705
Reverse Orientation	2,4618
Difference	-0,244
%Difference	-9%

Table 12:Outbound MAF Differences

In this case, a 9% difference appears between both orientations, which does not differ highly from the other results, however this increased difference could be caused by tailgating during the test caused by the added traffic.

During both tests, all the risks that could appear, mentioned in section 3.2, were carefully looked into to see if any of them appeared:

- There were no added problems to mount the carrier in the reverse orientation since the claws worked exactly the same for both orientations, and the trunk could still be opened.
- The possible lift forces were not noticeable since the carrier was carefully mounted, using the white stickers that can be seen in Figure 15, to achieve the most horizontal mounting possible.
- Neither vibrations, nor extra noises were felt during either of the tests.

Reverse orientation was both possible and also did not impact the accessibility of the trunk. However, these concerns are still valid for other untested car and cargo combinations, and the issue of the warranty and overall safety is remains unaddressed.

6. CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

With the results from the data in this project, trends that show about 5% reduction in fuel consumption for multiple car (fastback and hatchback) and carrier combinations can be appreciated. Seeing these results, one would naturally wonder why people are not already changing the orientation of their carrier. Since this problem is not widely discussed in a formal academic setting, much information had to be gleaned from informal blogs and forums, and the consensus there was that there is a lack of awareness in the general public, and a lack of intuition for aerodynamic shapes, since generally the car has a pointed part in front, the carrier should match this design [KVAM20].

But further than this, we have identified two actual key risks that could cause a driver to hesitate before adopting the reversing solution, that being warranty and safety issues. As Calix mentions, current car carriers have been designed and crash tested with the traditional orientation in mind. Additionally, users void the warranty if they incur damages while not installing the product in the method specified by the manufacturer, and the user instructions that were found show the carrier installed in the traditional orientation. So, in the end, it is up to the consumer to be convinced by the trends found in this project.

If one does decide to adopt the reversing solution, taking 5% reduction in fuel consumption as a fixed number, we can estimate the potential benefits:

Assuming the average person drives 14,000 miles annually, and assuming 70% of that time is being driven on a highway and that the average car gets 25mpg (miles per gallon), one could expect to save about 20 gallons (about 75 liters) per year, which nowadays would also mean saving up 150$ in Europe, yearly, furthermore, given that for every gallon of gasoline consumed, 20 pounds of CO2 are emitted, emissions would be reduced by 400 pounds of CO2 yearly per person. Extrapolating that to world, in the introduction it was stated that there are 1.446 billion vehicles, given that there are no numbers related to the number of luggage carriers that are in use, if it was assumed that 50 % of the vehicles use carriers, 289.2

billion pounds of CO2 would not be emitted. In total, 89.28 trillion pounds of CO2 were emitted worldwide in 2019. Then, if the number calculated earlier were to be trusted, the emissions would be reduced by a 0.3% worldwide.

6.2 SUSTAINABLE DEVELOPMENT GOALS ALIGNMENT

Regarding how this project cooperates with sustainable development could be explained through two different Sustainable Development Goals:

- Goal 13: Take urgent action to combat climate change and its impacts.
  It has been showed the biggest impact that this project could have, is the worldwide reduction of carbon dioxide emissions, helping reduce the Greenhouse Effect, and therefore helping to combat climate change.
- Goal 15: Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss.
  This goal is closely related to the previous one, since one of the causes of desertification, land degradation and biodiversity loss is climate change, therefore reducing the carbon dioxide emissions would also increase the chances of achieving this goal.

6.3 FUTURE WORK

One of the doubts that still persists after this project, since the fluid mechanics are different in the laminar regime, is that these trends may occur to a lesser extent or not all while travelling at urban or residential speeds.

It is the hope of this project that this research may inspire others to test their own car and carrier combination at home, to further prove what the results that were obtained in this project suggest, which is that this idea could be true for every combination of car and luggage carrier. Of course, the unknown potential safety risks of reorientation must be weighed individually by the user against how much time they anticipate travelling at highway speeds with a cargo carrier, which is proportional to how much they may monetarily benefit. In both road tests, the same amount of security was found for both orientations, and there were no issues with reorientation or with accessibility to the luggage carrier or the rest of the car (such as the trunk). This shouldn't cause extra efforts, due to the fact that, unlike Calix' Aero Loader, this solution does not introduce a new product into the world, which creates new waste streams both for the production of the new product, and for the consumers throwing out their old but still useable luggage carriers. Instead, our project works with what already exists, and finds a novel way that points towards significant reduction in emissions.

7. BIBLIOGRAPHY

[HEDG22] Hedges & Company," How many cars are in the world in 2022?", https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

[EPA_22] United States Environmental Protection Agency, "Sources of Greenhouse Emissions", https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions, 2022

[LINK20] Linkov, J., "How Rooftop Carriers Affect Fuel Economy for Cars and SUVs", https://www.consumerreports.org/fuel-economy-efficiency/how-rooftop-carriers-affect-fuel-economy/, 2020

[CLAR05] Clarkson University News & Events, "Experimental Device Reduces Drag On Tractor Trailers – Increases Fuel Efficiency By 10%", https://www.clarkson.edu/news/experimental-device-reduces-drag-tractor-trailers-increases-fuel-efficiency-10 , 2005

[ECOM11] EcoModder, "Most aerodynamic Cargo box", https://ecomodder.com/forum/showthread.php/most-aerodynamic-cargo-box-18000.html, 2011

[ANAN15] AnandTech, "Car roof cargo box", https://forums.anandtech.com/threads/car-roof-cargo-box.2443281/, 2015

[REDD21] Reddit, "Swede turned his roof box backwards, increased his range by 16%", https://www.reddit.com/r/electricvehicles/comments/fo6fxb/swede_turned_his_roof_box_backwards_increased_his/, 2021

[VWID21] VWIDTalk, "25% reduction in range with roof box", https://www.vwidtalk.com/threads/25-reduction-in-range-with-roof-box.2074/, 2021

[KVAM20] Kvamme P., "Turned roof box, increased range", https://www-tu-no.translate.goog/artikler/snudde-takboks-okte-rekkevidden/488322?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en-US , 2020

[BLOM20] Blomhäll T., "16% longer range with rear-facing roof box", https://teslaclubsweden-se.translate.goog/16-langre-rackvidd-med-bakatvand-takbox/?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en-US , 2020

[AUTO21] Autoform, "Test Report – Fuel/Power consumption", https://www.pebe.se/files/b3790aa99fd0a223458201fd86012ece.pdf, 2021

[SOLG21] Solgaard H., "New Aero Loader roof box that provides 7% better range", https://www-mynewsdesk-com.translate.goog/no/kgknorge/pressreleases/nye-aero-loader-takboksen-som-gir-7-procent-bedre-rekkevidde-3067278?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=wapp, 2021

[BRYA14] Bryant G., "Aerodynamic designing and position optimization of roof box", https://pureportal.coventry.ac.uk/en/studentTheses/aerodynamic-designing-and-position-optimization-of-roof-box, Master's Thesis, 2014

[MUHA14] Muhaemin A., "Honda CRV", https://grabcad.com/library/honda-crv-1, 2014

[ZAL_13] Zal P., "Honda CR-V EX-L AWD (aut. 5) (2013) full detailed specifications listing and photo gallery", https://www.automobile-catalog.com/auta_details1.php, 2013

[BILL11] Bill Bryan Subaru, "Subaru Forester Compared to Honda CRV", https://www.billbryansubaru.com/subaru-forester-comparison-honda-crv.htm, 2011

[COMS22] COMSOL, "Airflow over an Ahmed Body", https://www.comsol.com/model/download/913121/models.cfd.ahmed_body.pdf, 2022

[MIKO19] Mikolaj Janicki R., Piechna A., "Examining influence of a rooftop cargo carrier position on automobile aerodynamics", https://aip.scitation.org/doi/pdf/10.1063/1.5092076, 2019

[AUTO22] Auto Research Center, "The Effect of Aerodynamic Drag on Fuel Economy", http://www.arcindy.com/effect-of-aerodynamic-drag-on-fuel-economy, 2022

[CHEN16] Chen Y., Meier A., "Fuel consumption impacts of auto roof racks", https://www.researchgate.net/publication/298706724_Fuel_consumption_impacts_of_auto_roof_racks,2016

.

APPENDIX I

autoform TEST REPORT

Test Report – Fuel/Power consumption

Report Date: 2021-01-18

This report shows the difference in fuel/power consumption for different roof boxes mounted on different cars.

Tested Roof Boxes: Calix Aero Loader (AL), Calix H22, Calix H18

Test Vehicles: Volvo XC40 D2, Volvo V60 D4, Tesla Model 3

Figure 1 – Areo Loader mounted on Tesla Model 3

Table 1 – Test result overview*

	V60		Tesla		XC40	
Roof Box	AL	H22	AL	H22	AL	H18
Distance (km)	44,5	44,4	55,7	55,5	14,6	14,3
Average Speed (km/h)	110	110	100	100	110	110
Average consumption (l/100km, W/km)	5,82	6,15	207	221,5	7	7,5
AL vs H18/H22	-5%		-7%		-7%	

Test Results

Tests show that the fuel/power consumption is reduced (i.e. range extended) up to 7% with Aero Loader compared to H18/H22.

*All tests made on public roads. Test routes and dates chosen from a traffic flow situation and as low total elevation as possible.

Autoform | Box 155 | SE-782 24 Malung | SWEDEN
Tel. +46 (0)280 – 59 33 00 | Fax. +46 (0)280 – 13 30 5 | E-mail: info@autoform.se | Web: www.autoform.se
Corporate ID: 556320-3867 | Bank giro.: 5423-6211 | VAT No.: SE556320386701

Member of the CalixKlippan Group

APPENDIX II

Wind tunnel Work

These tests were intended be carried out with models manufactured at EPIC (facilities at Boston University) with the CNC milling machines. It was not intended to be used to find actual values for drag, but to see a difference in measurements enough to compare orientations. The basic idea for measurement was to balance the drag force with weights hanging outside the wind tunnel as shown in the figure below:

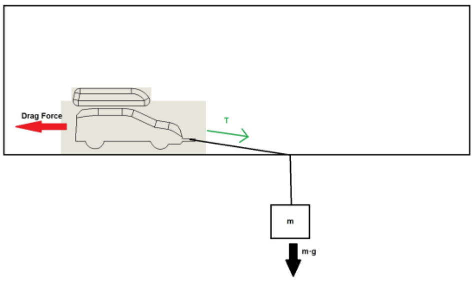

Figure 40:Scheme of the Wind tunnel procedure

The specifications for the model intended to be used for the wind tunnel were as follows: The car model had a length of 8.56 inches, a height of 2.91 inches, and a width of 3.59 inches. It had two tabs at the front of arbitrary dimensions that would have been used to attach string to car model. The tab had a hole with a length of 1.73 inches, a width of 2.59 inches and a depth of 2 inches. The holes that can be seen in the roof would be drilled afterwards depending on the screws that are being used. Fillets were added to make the model more similar to a car. The car-top luggage carrier had a length of 2.18 inches, a height of 0.5 inches, and a width of 1 inch. The fillets were arbitrary to try to make it look like a real-life product.

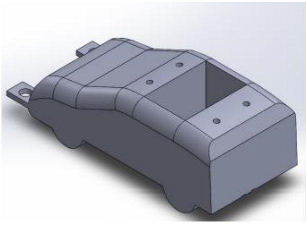

Figure 41:Car Model for Wind Tunnel

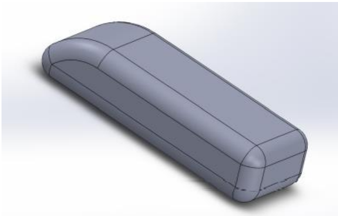

Figure 42: Carrier Model for Wind Tunnel

APPENDIX III

BlueDriver Support 3/23/22, 1:12 AM

Measurement Ranges & Accuracy

Modified on: Wed, 8 Jan, 2020 at 4:46 PM

Measurement	Range (up to)	Display Resolution	Accuracy
AC Voltage	600mV	0.1mV	2%
	6V	1mV	1.5%
	60V	10mV	1.5%
	600V	100mV	1.5%
	750V	1V	2%
DC Voltage	600mV	0.1mV	1.5%
	6V	1mV	1%
	60V	10mV	1%
	600V	100mV	1%
	1000V	1V	1.5%
AC Current	60mA	10µA	1.8%
	600mA	100µA	1.8%
	20A	10mA	3.0%
DC Current	60mA	10µA	1.5%
	600mA	100µA	1.5%
	20A	10mA	2.5%
Resistance	600Ω	0.1Ω	1.5%
	6kΩ	1Ω	1%
	60kΩ	10Ω	1%
	600kΩ	100Ω	1%
	6MΩ	1kΩ	1%
	60MΩ	10kΩ	2.5%
Capacitance	10nF	1pF	2.5%
	100nF	1pF	2.5%
	1µF	0.1nF	2.5%
	10µF	1nF	2.5%
	100µF	10nF	2.5%
	1mF	0.1µF	2.5%
	10mF	1µF	10%
	60mF	10mF	10%
	10Hz	0.001Hz	0.1%
	100Hz	0.01Hz	0.1%

https://support.bluedriver.com/support/solutions/articles/43000551864-measurement-ranges-accuracy Page 1 of 2

BlueDriver Support 3/23/22, 1:12 AM

Frequency	1kHz	0.1Hz	0.1%
	10kHz	1Hz	0.1%
	100kHz	10Hz	0.1%
	1MHz	100Hz	0.1%
	10MHz	1kHz	0.1%
RPM	Low (60-9,999rpm)	1 rpm	2.5%
	High (600-12,000rpm)	10 rpm	2.5%
Temperature	-20°C - 1000°C -4°F - 1832°F	0.1°	3%
Duty Cycle	1-99%	0.1%	2%
Pulse Width	0.1ms - 10ms	0.1ms	2%
Dwell Angle	4-8 cylinders	0.1°	2.5%

APPENDIX IV

- Pack ~31.5-32 pounds of linen luggage into cartop carrier
- Take picture of car top luggage carrier and car system with scale for reference, side, and front and back—white marks where claws grip bars
- Make sure can still open hatch up!
- Turn on car, then plug OBD device and check that the PIDS are available
- Let engine warm up ~20min (car has notification)
- Open app and initialize OBD device for new trip
  - I've set it up to measure fuel level, engine torque and load, engine rpm, MAF, barometric pressure, and vehicle speed
- Get on Route 2 outbound
- Set up camera to record journey and instantaneous mpg reading on car screen
- Start recording and getting live data from obd at roughly the same time
- Get on cruise control at ~63mph
- Make vocal notes of time start at ~132.2 mile marker and jot down obd time for the particular run (to correlate video with obd data which will only give time since trip start in seconds)
- Drive should be ~3 minutes. Make notes of miles and traffic if necessary
- Make vocal note of time end at ~129.2 mile marker and jot down obd time for the particular run (to correlate video with obd data which will only give time since trip start in seconds)
- Turn around and start new video for inbound
- Save data sheet/email/export to self and start new data sheet for new round trip
- Run round trip in same orientation 3x times (for a total of 6 different runs for one orientation) before driving back home.
- Flip cartop carrier around in driveway, being sure to line up claw grips with pre-existing white marks.
- Start new data sheet for new trip on obd.
- Drive along same route with reverse hard top case.
- Make same notes and export all final data, run 3x as before.

- Take measurements of dimensions and placement from photo! Used ruler for scale, and also measured key car landmark dimensions to get idea of size and placement from unruled photos.