LOW MASS VEHICLE AND ITS AERODYNAMIC STUDY

Huayi Feng
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PROJECT

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SUMMER
2011
LOW MASS VEHICLE AND ITS AERODYNAMIC STUDY

A Project

by

Huayi Feng

Approved by:

______________________________, Committee Chair
Dongmei Zhou, Ph.D.

_____________________________________
Date
Student: Huayi Feng

I certify that this student has met the requirements for format contained in the University format manual, and that this project is suitable for shelving in the Library and credit is to be awarded for the project.

__________________________, Graduate Coordinator       _____________________________
Akihiko Kumagai, Ph.D.                                             Date

Department of Mechanical Engineering
Abstract

of

LOW MASS VEHICLE AND ITS AERODYNAMIC STUDY

by

Huayi Feng

Nowadays the fuel economy has become more and more important to both manufacturers and individual users. The main approach to achieve better fuel economy is to lower the vehicle and improve the aerodynamic performance. Lower vehicle’s mass is to reduce the mass by innovation design of vehicle’s structure, exterior, interior and apply with appropriate materials. To improve the aerodynamic performance mainly is to reduce drag, which is a major factor of highway fuel consumption. In order to maintain the vehicles capacity and comfort, the improvement of aerodynamics should not majorly affect the body shape.

The purpose of this research is to apply aerodynamic add-on devices to the Low Mass Vehicle to verify the aerodynamic performance while the vehicle body shape would remain untouched. The research approach is using computational fluid dynamics (CFD) technique. This project focuses on introducing the idea of Low Mass Vehicle and modern aerodynamic add-on devices and then applying the some of the devices like rear spoiler and vortex generator to the body to study its effects on both drag and lift. It was found that the rear spoiler reduces the drag by 10% and lift by 7%. However, the vortex generator does not affect drag and lift significantly. It was believed that there is potential
to improve the aerodynamic performance of the original LMV design. The approach of combination of lowering the mass and improving the aerodynamic is feasible.

_______________________, Committee Chair
Dongmei Zhou, Ph.D.

_______________________
Date
ACKNOWLEDGMENTS

I would like to thank my father, mother and my aunt to supporting me throughout my education and life. I would not go this far without their help.

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I would like to thanks all my teachers, school staff and friends for their help and support.

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SOFTWARE SPECIFICATIONS

Fluent Software version 6.3.26
Fluent software is a computational fluid dynamics (CFD) solver that runs on a personal computer. Through Fluent graphical user interface governing equations, physical properties, boundary conditions and initial conditions, etc. of these fluids, modified to solve unique complex mathematical problems. Models can be two-dimensional or three-dimensional and require pre-processing by Gambit software to generate the discretized computational domain. Fluent solves the complex model and provides post-processing capabilities for analyzing and displaying results.

Gambit Software version 2.4.6
Gambit is a computer software program used to create the physical model (geometry) used by Fluent CFD software. Gambit generates a mesh/grid by discretizing the computational domain to user specifications.

Solidworks 2010
Solidwork is a computer software program used to create the 3-D model (geometry). It could create 3-D model and save in different type of files. For this project save as .igs file and export into Gambit for meshing.

Fluent, Inc. and Ansys, Inc. make Fluent and Gambit
Chapter 1

INTRODUCTION

1.1 Introduction

With continuing increase and uncertain future of fuel price, the world has put more focus on alternative energy and saving it. Automobile industry, which consuming a decent percentage of fossil fuel, has been working on improving the fuel efficiency in past decades. Electronic vehicles, hybrid vehicles, and human powered vehicles were developed to pursue a high mileage per gallon in daily transportations. Besides finding alternative fuel for gasoline, engineers are also trying to improve vehicle gasoline efficiency by manipulating different parameters including engine parameters, aerodynamic drag, weight, and rolling resistance.

1.2 Factors Contributing to Fuel Usage

As we know, engine loss accounts for the majority of fuel loss. As showed in Figure 1.1, only about 15% of the energy from the fuel will be used in vehicle’s useful accessories, such as lights, air conditions and etc [2][1]. Engine parameters play a critical role in improving the performance of automobiles which includes variable valve timing and lift (VVT&L), Cylinder Deactivation, Turbo charging & Supercharging, Direct Fuel Injection (with Turbo charging /Supercharging) Integrated Starter/Generator (ISG). Manipulating those parameters has the potential to improve engine efficiency but the progress was slow because of technical or economical issues.
Besides engine losses, fuel energy is used to against the aerodynamic drags, rolling resistance, brake frictions as shown in Figure 1.2. In addition, energy will be used to acceleration against the inertia force. So, all the against force $f$ while driving is defined as

$$f = R_d + R_a + R_g + R_{ac}$$  \hspace{1cm} (1.1)
Where:

\[ f = \text{The Total Against Force} \]

\[ R_{rl} = \text{Rolling Resistance} \]

\[ R_a = \text{Aerodynamic Drag} \]

\[ R_g = \text{Gravity Force while Grading} \]

\[ R_{ae} = \text{Acceleration Resistance} \]

Figure 1.2 Forces and Resistances Act on a Vehicle [6]

Rolling Resistance

Rolling resistance, sometimes called rolling friction or rolling drag, is the resistance occurring when round object rolls on a flat surface which is mainly caused by
deformation of the object or and surface [4]. In our case, it is the tire deformation when rolling on road. The physical formula of Rolling Resistance ($R_r$) is calculated by

$$R_r = F_z (A_0 + A_1 F_z + A_2 / P)$$

(1.2)

Where:

$F_z = \text{load}$

$P = \text{inflation pressure}$

$A_0, A_1, A_2$ are constants

Grade Resistance

Grade resistance is a simple form of resistance and it caused by the gravitational force acting on vehicles, especially when vehicles are climbing on road with a slope. The Grade resistance ($R_g$) is calculated by

$$R_g = W \sin \theta_g$$

(1.3)
Where

\[ \theta_g = \text{Grade angle} \]

\[ W = \text{Vehicle weight} \]

Aerodynamic Force

![Aerodynamic Force Diagram](image)

Figure 1.4 Forces on an Aerofoil in Free Stream Flow [28]

Aerodynamic force is combination of two main forces, lift and drag as shown in Figure 1.4. Lift force is force acting on vehicle produced by different fluid speed flow over vehicles, and it is perpendicular to the flow direction. As Bernoulli’s principle states that for an inviscid fluid, with the increase in speed of fluid, the flow will result in decrease in pressure or fluid’s potential energy [9]. As vehicles running on road, the airflow at the different flow speed of up and down face of the vehicle generates the lift or upward force, which matters the vehicles stability and load. There is another popular explanation of lift, the Newton camp. Nevertheless, both of them are considered to be
correct. According to the Newton’s third law of motion, a turning action of the flow will result in a re-action (aerodynamic force) on the object [10]. The lift force could be calculated by:

\[ L = \frac{1}{2} \rho v^2 A C_L \]  

(1.4)

Where:

- \( L \) = lift force
- \( \rho \) = fluid density
- \( V \) = fluid speed
- \( A \) = Plan form area
- \( C_L \) = Lift Coefficient at Desired Angle of Attack, Mach Number, and Reynolds Number

Aerodynamic drag is the force acting on any moving object in a free stream flow, which is due to the pressure distribution over body surface \( (D_p) \) and surface frictions \( (D_f) \) [7]. Since the surface friction is due to viscosity, the friction drag is separated from pressure drag as shown in Figure 1.5.
Especially while in high-speed motion, the aerodynamic force is becoming much more significant. For modern vehicles, about 60% of the power is used to overcome aerodynamic effects while driven in highway speed [8]. Obviously, minimizing the drag will effectively improve the fuel efficiency. Furthermore, the aerodynamic force mainly depends on the body shape of the vehicle that makes the reducing drag the most effective way to improve the fuel economics. Drag force can be expressed as:

\[ F_d = \frac{1}{2} C_d \rho v^2 \]  \hspace{1cm} (1.5)

Where:

- \( F_d \) = Drag Force
- \( C_d \) = Drag Coefficient
- \( \rho \) = Density of Fluid
- \( v \) = Flow Velocity
A = Characteristic Frontal Area of the Body

1.3 Options of Improving Automobile Fuel Efficiency

As we have seen from above, rolling resistance, gravity force while grading, and acceleration resistance are concerning with the body weight and most of fuel is used to overcome aerodynamic forces. For a non-steady-state driving schedule, the energy consumption attribution of vehicle mass outweighs the energy needed to overcome aerodynamic drag. If the power used in acceleration and rolling resistance is included, about 80% of the energy expended during a city-driving schedule is mass related. Since the heavier the body weight the more fuel usage aerodynamic drag will result in more fuel usage, our main objective is to lower the weight and improve aerodynamic performance.

1.3.1 Weight Reduction

Research studies found that reducing vehicle weigh (mass) results in less tractive effort required accelerating the vehicle and less rolling resistance from the tires [11]. Drive cycles with more acceleration events showed greater fuel economy benefits from weight reduction than highway or steady state conditions [11]. And car of a 1.6L engine with valve timing and variable and variable lift technologies that reduce pumping losses shows the largest percentage fuel economy benefit with the baseline engine since it can operate at the reduced engine load points more effective[11].

Figure 1.6 shows the vehicle mileage performance at certain mass reduction by simulating derived 5-cycle regression equation for the 2008 model year. Since the tire loss has a greater percentage of total tractive effort at lower speed, reducing the vehicle
mass has a greater potential to improve vehicle’s MPG while it runs at lower speed (in city).

<table>
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<tr>
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<th>EPA Fuel Economy Benefit</th>
<th>European FE Benefit</th>
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<tr>
<td></td>
<td>City FTP/5</td>
<td>Highway HWFET</td>
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<tr>
<td>Baseline</td>
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<tr>
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<td>(mpg)</td>
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<td>44.7</td>
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<td>57.8</td>
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Figure 1.6 1.6L – 4V Gas Engine Vehicle Weight Reduction Contribute in Fuel Efficiency [11]

1.3.2 Improvement of Aerodynamic Performance

As it was discussed above, the aerodynamic force is combined by drag and lift. Aerodynamic force study is critically important for vehicle fuel efficiency at a high speed since the aerodynamic drag increases with the speed. Aerodynamic drag is the restraining force acting on moving vehicles in horizontal direction that matters the fuel economy. Lift is the force perpendicular to the oncoming flow direction and it could be considered as the force to affect the vehicle weight. It also might matter the vehicle’s fuel economy.
and stability in high speed. Compared to reducing mass improve vehicle MPG at lower speed, reducing aerodynamic drag could dramatically improve the vehicle MPG at high speed (high way).
Chapter 2

LOW MASS VEHICLES (LMVs)

2.1 Introduction to Low Mass Vehicles

In 1990’s, automobile fuel economy, emissions, and recycling had become important social concerns [13]. At the mean time, automotive industry competition has become more brutal and automotive companies began to put more effort on advanced vehicle design. Engineers believe that the automobile should be affordable, yet appealing, safe, and inexpensive to drive. Based on the situation, the Institute for Advanced Vehicle Systems (IAVS) under the leadership of Dr. Weber was founded to create new methods. The goal is to improve Vehicle performance in gasoline consumptions to make the vehicle inexpensive to drive [13]. The Low Mass Vehicles project was one of the methods developed by the Institute since the mass of vehicle is an important contributor to fuel consumption.

The LMV is intended to be an affordable but appealing vehicle similar to the Toyota Echo in price, features, space, and performance but with targeted 30% less mass [13]. The design goal is to reduce the weight while providing the customers expected space, feature, amenities and performance in that class. It is intended to be profitable in low volumes at low piece cost and low investment [13].

2.2 Design of LMV

The IAVS institute chooses to design a vehicle that is thirty percent lighter than a vehicle – the Toyota Echo that was already considered to be lightweight and it has the
same wheelbase as Ford Focus. The vehicle as shown in Figure 2.1 is able to provide acceptable space, feature, amenities and performance in the class while reducing the weight. The reason that IAVS choose Toyota Echo as a target of weight reduction is that, Echo has lightweight and IAVS does not have to break many rules to get weight out from a heavy vehicle. Choosing to target the wheelbase of Ford Focus is because it is agreed that Focus with long wheelbase than Echo provides a more smooth drive. The last important factor to put both vehicles under consideration is that both vehicles provide high fuel performance.

Figure 2.1 2005 Toyota Echo Sedan [14]

Toyota Echo as shown in Figure 2.1 is certainly small on the outside with 163.2 inches long and standing 59.1 inches tall. For the cargo capacity, Echo has a 49 cubic feet front interior volume and offering 39 cubic feet space in the rear. Echo has an affordable price that the four-door base model starts at $10,750. The Echo’s sophisticated 108 hp, 1.5 liter four-banger out-powers many of its competitors, and the Echo’s quick response
is enhanced by its low mass of 2128 pound. Echo has a top speed of 112 MPH and hits 60 mph in 8.5 seconds. Echo provides an inexpensive driving also. The EPA estimates fuel economy will run between 34 and 41 miles per gallon [15].

Compared to Toyota Echo, Ford Focus (see Figure 2.2) has a 56.8 inches width, 168.5 inches length, standing 56.8 inches height and 103 inches wheel base. For the cargo capacity, Focus has 40.2 cubic feet maximum cargo capacity and 18 cubic feet while all seats in place. The curb weight is estimated 2654 pounds and PEA interior volume is 112 cubic feet. EPA mileage estimated 22 mpg in city and 32 mpg in highway [16]. As we see, Focus is heavier in mass and has a lower fuel efficiency than Toyota Echo. However, it is more comfortable and smooth to drive Ford Focus than Toyota Echo.

![Figure 2.2 Ford Focus](image)

Figure 2.2 2005 Ford Focus

The exterior of the LMV was designed during a student competition held by the College of Engineering and Computer Science (CCS) in the University of Michigan – Dearborn, as shown in Figure 2.3. The design was chosen because it had the highest
potential of achieving the stringent weight, cost, and investment objectives without sacrificing occupant comfort.

![Student Designed Low Mass Vehicle](image)

**Figure 2.3 Student Designed Low Mass Vehicle [13]**

2.3 Benchmark of LMV

The LMV benchmark is designed with an ideal combination of dimensions from both Echo and Focus benchmarks. From the Figure 2.4, we can see LMV is shorter than both Echo and Focus but has a longer wheelbase. In addition, it has an in-between height and cargo volume, which makes LMV capacity acceptable and driving comfortable.
Figure 2.4 Benchmark of LMV Compare to Echo and Focus [13]

Figure 2.5 SAE Dimensions of LMV (Side) [13]
<table>
<thead>
<tr>
<th>SAE Code</th>
<th>Dimension</th>
<th>Value</th>
<th>SAE Code</th>
<th>Dimension</th>
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<td>H101</td>
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<tr>
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<tr>
<td>L104</td>
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<td>SgRP X</td>
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<td>2</td>
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<tr>
<td>L105</td>
<td>Rear Overhang</td>
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<td>W20</td>
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<td>H70</td>
<td>SgRP Z</td>
<td>568.081</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>H103-1</td>
<td>Front bumper to ground</td>
<td>230.6616</td>
<td>L8</td>
<td>AHP X</td>
<td>1113.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>H195</td>
<td>Lift over Height</td>
<td>556.3823</td>
<td>W8</td>
<td>AHP X</td>
<td>317.5</td>
</tr>
<tr>
<td>W101</td>
<td>Track Width</td>
<td>1423.25</td>
<td>H8</td>
<td>AHP Z</td>
<td>212.481</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>W103</td>
<td>Vehicle Width</td>
<td>1423.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 SAE Dimension Values (mm) [13]
Vehicle dimensions are specified from the figures and tables above. The occupant package is developed for meeting the requirements for occupants from 3 different countries; USA, China and India with a population that has different anthropometric characteristics [13]. Most important requirement is to achieve the smooth drive and decent cargo volume. However, as we said before, the institute breaks some rules to pursue the mass reduction. For example, exterior features using unibody structure instead of regular structure which is one third of the total vehicle weight, choosing to use slid doors and choosing better material for the unibody structure and space frame. Besides the exterior design, the interior design, which includes the climate control system and seats, chassis such as the suspension system and brake, electrical and electronics, is also being carefully designed to pursuit the target reduction of the mass.
2.4 Result of LMV Test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ford Focus</th>
<th>Toyota Echo</th>
<th>LMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy Highway (mpg)</td>
<td>36</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>0.32</td>
<td>0.31</td>
<td>0.474</td>
</tr>
<tr>
<td>Acceleration(s,0-60 mph)</td>
<td>9.0</td>
<td>9.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Top Speed(mph)</td>
<td>112</td>
<td>103</td>
<td>90</td>
</tr>
<tr>
<td>Stopping Distance(ft, 60-0mph)</td>
<td>124</td>
<td>136</td>
<td>132</td>
</tr>
<tr>
<td>Turning Radius (ft)</td>
<td>34.3</td>
<td>32.8</td>
<td>32.0</td>
</tr>
</tbody>
</table>

Table 2.3 Performance of LMV Compare to Focus and Echo [13]

From the provided in Table 2.3, the LMV has met the highway fuel economy requirement. However, we can see that the drag coefficient is 0.423 that certainly have a negative effect on highway fuel economy although the data table did not show the fuel economy for the city drive. The reason might be that the city driving is hard to be estimated and the highway fuel-efficient is more like the industry standard to estimate vehicle fuel economy. Since the LMV has a small engine size (1.1L), the acceleration and top speed are little worse than either the Toyota Echo or the Ford Focus. In addition, The LMV turning radius of 32 feet is very competitive even for vehicles in its class with much smaller wheelbase. Overall, the Low Mass Vehicle testing turned out pretty well and met its industrial design and packaging objectives. It is said that the LMV investment cost was not measured since the industry production is very different from the lab prototyping.
Not just for fuel economy, vehicle mass-reduction also affects the CO$_2$ emission. A research shows that for constant performance, every 20% mass-reduction will result in 12 to 16% CO$_2$ /mi decrease [17].

2.5 Mass Reduction in Vehicle Industry

<table>
<thead>
<tr>
<th>Company</th>
<th>Quote, statement, or commitment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford</td>
<td>• From 2011 to 2020: “Full implementation of known technology... weight reduction of 250-750 lbs”&lt;br&gt;• “The use of advanced materials such as magnesium, aluminum and ultra high-strength boron steel offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements”</td>
</tr>
<tr>
<td>Toyota</td>
<td>• 10-30% weight reduction for small to mid-size vehicles</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>• “Automotive light weight solutions are necessary more than ever to reduce CO$_2$ emissions”&lt;br&gt;• “Multi-Material Concepts promise cost effective light weight solutions”</td>
</tr>
<tr>
<td>GM</td>
<td>• “We... are likely to use more lightweight materials in the future”&lt;br&gt;• “One trend is clear - vehicles will consist of a more balanced use of many materials in the future, incorporating more lightweight materials such as nanocomposites and aluminum and magnesium.”</td>
</tr>
<tr>
<td>Mazda</td>
<td>• Reduce each model by 220 lb by 2015; another 220 lb by 2020</td>
</tr>
<tr>
<td>Nissan</td>
<td>• Average 15% weight reduction by 2015&lt;br&gt;• “We are... expanding the use of aluminum and other lightweight materials, and reducing vehicle weight by rationalizing vehicle body structure”</td>
</tr>
<tr>
<td>BMW</td>
<td>• “Lightweight construction is a core aspect for sustainable mobility improving both fuel consumption and CO$_2$ emissions”</td>
</tr>
<tr>
<td>Renault</td>
<td>• “To meet commitments on CO$_2$ emission levels, it is important that we stabilize vehicle weight as from now, and then start bringing it down.”</td>
</tr>
</tbody>
</table>

Figure 2.7 Automobile Maker’s Attitudes Regard on Mass Reduction [11]

With more concern of the fuel economy and environmental protection, more and more automobile makers has put more focus of reduce vehicle mass which could achieve both goals. As seen from the figure 2.4, automobile industry has put more concern on the mass reductions, and taken it as a competitive force. Not just these commitments, some automobile makers have started their steps to bring it to the industry.

The figure 2.5 is a Lotus Low Mass Vehicle Project, and Lotus engineers are making efforts on processes feasible in the 2017 time frame for 2020 MY production [24]. In addition, the target of mass reduction is 40%.
Another well-known automobile maker BMW is planning to bring the low mass vehicle to the world in 2013 too. The Figure 2.9 showed below is the BMW-I concept hybrid vehicle which is weighted 1250 kg and has a drag coefficient equal to 0.22. By combining with the hybrid system, it results in 62.56 MPH that is much higher than Toyota Pirus. It has two versions that the I8 is a sport car and the I3 is a crossover as shown in Figure 2.10.
Figure 2.10 BMW-I3 Low Mass Hybrid Concept Vehicle [25]
Chapter 3

VEHICLE AERODYNAMICS

3.1 Introduction to Vehicle Aerodynamics

Automotive aerodynamics is the study of the aerodynamics of road vehicles. The main concerns of automotive aerodynamics are reducing drag, reducing wind noise and preventing undesired lift forces. Investigation of the aerodynamics for vehicles helps to achieve better fuel economy, greater vehicle performance, reduced in wind noise level and improved road holding and stability for a vehicle on the move. Aerodynamic is insignificant at low speed but it become considerable with rising speed. As we have talked above, the Aerodynamics for vehicle is combined of drag and lift. Reducing drag is critically important to improve fuel economy and to reach the top speed for a certain given power. The aerodynamic problem of automobile is different from the aircraft since...
the vehicle is on ground and it has the interference with the airflow between the car underside and the ground [12]. In many cars, the engine compartment is open to the ground to help cool the engine. This kind of cavity may produce flow separation just behind the front bumper and create a high dynamic pressure region in front of the vehicle. This could create an additional aerodynamic lift force.

From the figure 3.1 above, we can see the air pass through both up and down side of the vehicle. In addition, a wake area is created behind the vehicle that generates the pressure difference between the front and back. This pressure difference generates a force against the motion of the objects that as we know called the aerodynamic pressure drag.

![Figure 3.2 “Longer Path” or “Equal Transit” Theory to Lift [6]](image)

Besides the aerodynamic drag, the lift is also a major concern of the vehicle aerodynamic forces that is perpendicular to the motion of object. As we introduced in previous chapter, there are several theories to explain the generation of lift. The figure 3.2 is “popular” explanation of the lift. The lift is concerned not just for fuel economy, but also because it matters the vehicle stability. Obviously, the vehicle stability is affected by a number of factors like wind speed, wind angle, vehicle mass and etc. To simplify the
question, sometimes we assume the condition is under low wind speed or no wind. As a research showed that under a certain wind speed, for a certain vehicle mass, there is a critical vehicle speed to assure the vehicle is stable. The figure 3.3 from the research study shows an estimated critical vehicle speed for a certain speed.

![Figure 3.3 Variation of Critical Vehicle Speed with Vehicle Mass for Various Wind Speeds at a Wind Angle of 90°](image)

**Figure 3.3 Variation of Critical Vehicle Speed with Vehicle Mass for Various Wind Speeds at a Wind Angle of 90° [18]**

### 3.2 Aerodynamic Devices

For concerned drag and lift, normally lowering the car to a certain ride height level as well as lowering frontal area will help to increase the desired downwards force requirements. However, an additional device like rear spoiler or vortex generator could
effectively improve the aerodynamic performance that is the aerodynamic devices. These aerodynamic devices are add-on mechanical parts to a vehicle to improve the vehicle aerodynamic performance by modifying drag or lift. As we know, Aerodynamic force depends on the body shape of the motion object in fluid. The benefit of this kind device is there is no need to change the original shape of the vehicle shape but modify it with additional parts to improve the aerodynamic performance. Since the vehicle aerodynamics has been studied as far as vehicle was land on road, so many vehicle devices have been developed to affect the air stream and improve the vehicle aerodynamic performance. There are some common used devices in both race and commercial vehicles for different purposes. In today’s vehicle body-kit market, most of the aerodynamic devices are just cosmetic. However, there are some body-kits are offering full aerodynamic functions.

3.2.1 Front Wing

The main function of a front wing is to create downward that enhances the grip of the front tires. This device’s could amount to up to 25-30% of total downforce and enhance the vehicle’s turning ability in sharp corners normally above 60 MPH [19]. This device is wildly used in F1 races to improve the vehicle stability while turning fast at sharp corners. The device’s function majorly is affected by the angle of attack and height of the wing. The design of the front wing is critical in controlling the flow of air over the rest of the vehicle. As shown in Figure 3.4 below, the basic design of a front wing is to design an airfoil suspended from the nose cone and with movable flaps incorporated in the design to adjust the angle of attack.
3.2.2 Canards

Canards are small wings attached to the front of the bumper to increase downforce and air flow dynamics. They can create vortices, which are normally seen on fighter jets wing tips like China new J-20. With installing canards at the front of vehicles, it could generate vortices, which run along the length of the vehicle, help in reducing drag and make for a more slipstream design. This device can be normally seen on high performance modified road cars or race series. They are not creating huge amounts of downwards force but improving the front to rear aerodynamics balance [19]. If strategically placed, they can also aid in clearing high drag areas on kit cars or open wheelers, or helping to increase aerodynamic efficiency on cars that is not specifically for
motorsport use. Canards are normally constructed of carbon fiber or reinforce plastics due to the high strength to weight ratio. Normally it is designed in a flat triangle shape with a curved edge to aid airflow direction as showed in figure 3.5.

Figure 3.5 Canards [19]

3.2.3 Front Splitter/Air Dam

The main function of the front splitter and air dam is to aid in optimization of the flow of air to the rest of the car to reduce drag, and it also create negative lift to aid the front tires to get more grip and reduce under steer tendencies. The front splitter is attached to the bottom of the air dam to increase the amount of downwards force at the front of the car. Airflow is brought to stagnation above the splitter by the air to dam create an area of high pressure. In addition, the air is accelerated and redirected away
from the stagnation point that causes the low pressure [19]. According to Bernoulli’s effect, this pressure difference creates the downwards force. This device can be made from fiberglass, carbon fiber and plastics.

![Vehicle’s Front Splitter and Air Dam](image)

**Figure 3.6** Vehicle’s Front Splitter and Air Dam [19]

### 3.2.4 Rear Diffuser

The function of the rear diffuser as shown in Figure 3.7 is to slow down the low-pressure fast-accelerated airflow from the chassis and underbody. This process is to match the high-pressure slow airflow at the back of the car, in order to reduce lift force, and minimize the drag. The rear diffuser is sensitive to air speed. It acts as an expansion chamber that the air get expand back the enough fast airflow under the car expanded back to the ambient pressure in the diffuser. It also could incorporate with the exhaust system. The exhaust gas energizes the airflow and raises the low-pressure air. In addition to reducing the drag, the rear diffuser also generates downwards force from the fast moving
underbody air and slow moving ambient air. Since it is so sensitive to the air speed that also could be considered to be the vehicle speed, it may cause handling issues while driver lifts off the throttle.

Figure 3.7 Rear Diffuser of Ferrari F430 [21]

The chassis and underbody aerodynamics could effectively generate downwards force and reduce the drag on vehicles. This chassis and underbody design combines the front splitter /air dam and rear diffuser to achieve better aerodynamic performance of the vehicle. The main principal works by the front of the car (splitter/ air dam) creating low pressure fast moving airflow to the underbody of the car. Then the rear diffuser creates an expansion area and accelerates the slowed airflow which generates additional downwards
force [19]. Furthermore, the diffuser also smoothes out the airflow at the back, reducing drag.

![Figure 3.8 Vehicle Underbody Aerodynamics [19]](image)

3.2.5 Vortex Generators

Vortex generators (VG), as shown in Figure 3.9, firstly were developed for aircrafts. Vortex generator is used to delay airflow separation in order to reduce the drag and lift. Airflow separation occurs when the airflow of an object detaches from the surface and creates eddies and vortexes. It will result in more drag and reduce the top speed and potentially downwards force because of the turbulent air entering other aerodynamic device (for example rear wing which generates the downwards force) and the wake of air behind the vehicle [19].
The figure 3.10 shows a Schematic of flow velocity profile on a vehicle’s centerline plane near the roof end without any vortex generator. As showed in the figure, the pressure gradient \( \frac{dp}{dx} \) has been changing along the boundary layer because of the air viscosity. The air separate at point B while the pressure gradient and momentum were balanced. At the point C, a pressure increase generates reverse force acting against the main flow and generates the reverse flow.

Figure 3.11 shows flows around the vortex generator, indicating that the separation point is shift further downstream. This enables the expanded airflow to persist proportionately longer, so that the air velocity at the separation point to become slower, and consequently the static pressure to become higher [22]. It increases the back pressure which functionally reduces the drag. Vortex is sensitive to the airflow velocity and
effective in speeds exceeding 60 MPH. However, the vortex generates stream wise vortices and brings in drag by itself. This results that the selection of shape and size of the vortex generators affect the device’s function.

Figure 3.10 Schematics of Velocity Profile around Rear End [22]

Figure 3.11 Schematics of Flow around Vortex Generator [22]
3.2.6 Rear Wing and Spoiler

Since the airflow at the rear of a vehicle has been affected by many factors, the rear wings could be less aerodynamically effective than the front wings. Figure 3.12 presents a rear wing factors. Typically, it has to generate more than twice as much downwards force as the front wings in order to maintain the handling to balance the car [19]. For vehicles with power delivered via the rear wheels, the rear wing will not only add acceleration and braking abilities, but also cornering grip [19]. Nevertheless, the main consideration is to achieve the top speed and create amount of downwards force needed. The function is affect by the aspect ratio or angle of attack.

![Figure 3.12 Rear Wing](image)

On normal vehicles, there is a confusing between the rear wings and spoiler. The difference between a rear wing and a rear spoiler is that spoilers are designed to reducing
lift and improve fuel economy instead of create downwards force. With flow of air at the rear of the vehicle becoming turbulent and a created low-pressure zone that increases the drag and instability, some synergy can be applied to spoilers and vortex generators to improve the vehicle aerodynamic performance. With a longer, gentler slop or angle of attack from the roof that was improved by other aerodynamic device, the spoiler helps delay flow separation of the fast moving air and increases the flow dynamics just as the vortex. This decreases drag, increases fuel economy, and helps keep the rear window clean.

Figure 3.13 Vehicle Spoiler
Chapter 4

CFD ANALYSIS OF LOW MASS VEHICLES

4.1 Introduction of CFD

CFD as an abbreviation of computational fluid dynamics is a branch of fluid mechanics that uses numerical methods and algorithm to solve and analyze problems that involve fluid flows [26]. It is the finite volume method (FVM) applied in fluid phenomenon. The FVM divides the problem geometry into small pieces and uses developed formula to approximate the solutions. As this kind method involves huge amount of calculations, The CFD requires computer to simulate and calculate the interactions of liquids or gases. Generally, the steps include creating the geometry, meshing the object and simulating with specific conditions. The calculated solution is not as accurate as the solution from real labs. However, it Greatly reduces the expense and inconvenience of using real labs. On the other hand, the solution is reasonably accurate to explain some flow phenomenon and to predict the results. In this project report, Solidworks is used to create the geometry of the LMV and it is meshed in the gambit. Then, the mesh file is imported to fluent and it is simulated with appropriate setups and assumptions.

4.2 Aerodynamic Analysis of LMV

As we discussed before, to achieve a better fuel economy, we have to reduce the vehicle mass and improve the aerodynamic performance. Since the low mass vehicles have been studied, we believe that the combination of low mass with high aerodynamic
performance vehicles is a potential solution of fuel economy for vehicle industry. At low speed (city drive), the lift and drag are insignificant and the vehicle stability is reliable. However, at a high speed (highway drive), the low mass of vehicle may result in instability and lacking of gripping ability. In this case, the main purpose of aerodynamic study is to achieve the best drag and lift for a certain low mass vehicles. As we have discussed in chapter 3, there are numbers of methods to improve the aerodynamics, including the add-on aerodynamic devices.

The following is a CFD simulation of the LMV without add-on aerodynamic devices. The geometry is created in solidworks according to the benchmark showed in the chapter two. The benchmark and photo of LMV defined general shape of vehicle and it is similar to modern crossover. The modeling is based on the general parameter but might not be as accurate as it was. In addition, missing of some parameters makes this model only able to introduce the basic outcomes of vehicles. On the other hand, the body design of low mass vehicle would not be unique but similar to crossover vehicles to maintain the cargo capacities.

The simulation is using air with the following properties: temperature of 293 K, density of 1.205 kg/m$^3$, kinematic viscosity of $1.511 \times 10^{-5}$ m$^2$/s. The airflow velocity is 30m/s, which equals to 67 MPH.

For the first case, we used the ground clearance equals to 0.2 m. As shown in Figure 4.1, the dynamic pressure is equivalent presentation of velocity. The red color indicates high dynamic pressure area that also presents the high-speed airflow. According to Bernolli’s effect, compared to the low velocity underneath of the vehicle, it generates
the lift. Figure 4.2 shows that the blue section represents the low pressure on the top of vehicle. The pressure difference between the top and underneath of the vehicle generates lift. As we have seen there is a wake area behind the vehicle and the pressure difference between front and back generates the drag.

From the simulation, it yields drag coefficient equal to 0.5 which is larger than 0.474 as expected. The lift coefficient is equal to -0.06 and it generates 262 N downward force at a speed of 67 MPH without any add-on devices. The geometry difference is possible factor to generate different lift forces since a minor add-on aerodynamic device could significantly increase the downward force. As we can see from Figure 4.3, the total pressure at the area in front of the windshield is high, which generates the drag and the downward force.

Figure 4.1 Dynamic Pressure of LMV without Add-on Devices
As results of lift coefficient and lift shown above, the lift force is negative. In this case, additional downward force is not required to maintain vehicle stability and handling ability. To verify this result, we use different meshes and ground clearance that equals to 0.3 m. The lift coefficient decreases to -0.063-N and generates 300-N downward force.
The drag deceases to 0.48 from 0.5. So based on the change in drag and downward force change, the fuel economy improvement is represented by increase of 0.4 mpg. By comparing Figure 4.4 with Figure 4.2, it is found that there is higher speed airflow passing underneath the vehicle that generates the lower pressure and create the downward force. Furthermore, the wake region in Figure 4.4 is slightly smaller than that in Figure 4.2, which reduces the drag. With different parameters and meshes, the simulation generates a reasonable result. Although the CFD simulation could not generates results as accurate as wind tunnel experiment, with reasonably simulated results, we could obtain the main idea of aerodynamic phenomenon and comparable data.

![Figure 4.4 Total Pressure of LMV with 0.3 m Ground Clearance](image)

From the Table 2.3 in Chapter 2, LMV has a 132 ft stopping distance (60 mph -0) and 32 ft turning radius, which is considered to be reliable in stability and handling. From the CFD simulation data, the vehicle generates downward force. It slightly enhances vehicles stability and handling. As shown in Figure 1.6, every 5% vehicle weight
reduction results in about 2% fuel economy. In addition, reducing drag coefficient by 0.01 will result in 0.2 mpg improvement [27]. Therefore, instead of achieving generating more downward force, the add-on device should focus on reducing the drag rather than significantly affect lift. Based on this situation, we select spoiler and vortex generator from the add-on devices introduced in chapter 3.

In order to indicate the relation between ground clearance and lift coefficient, another simulation with 0.1 m ground clearance is ran. The Figure 4.x shows the total pressure of LMV with 0.1 m Ground Clearance. While reducing the ground clearance the higher speed airflow pass underneath the vehicle generates the low-pressure region and increase the downwards force. From the simulation, the drag coefficient equals to 0.487 and the lift coefficient equals -0.1 that is a dramatic increase in downward force with decreasing the ground clearance.

Figure 4.5 Total Pressure of LMV with 0.1 m Ground Clearance
4.3 Aerodynamic Analysis of LMV with Add-on Spoiler

It is common in real world that a SUV or a crossover has a downward spoiler. Generally, for a SUV or a crossover, the angle of its rear spoiler will be downward at 1 - 30 degree. The best angle studied for a generic SUV is around 15 degree [28]. Therefore, the tested spoiler angle here is determined to be 15 degree to verify its typical performance. The dimension of the spoiler is 60mm in width, 18.5mm in thickness and the length matches the vehicle body as showed in Figure 4.5. The simulation results of velocity magnitude and total pressure are showed in Figure 4.6 and Figure 4.7 that the spoiler reduces the wake region which reduces the drag. While it is reducing the wake region, the LMV generates less lift at the same time because of slope of its hatchback that is also called lift-back. The simulation generates the results indicating that the drag coefficient is equal to 0.43 and that the lift coefficient is equal to -0.067. With this add-on device, both drag and lift are reduced. As we discussed in Chapter 3, the spoiler is different from the rear wing. The main function of a spoiler is to reduce drag but not aim to generate downward force. From data of the simulation, it shows that the spoiler successfully reduced the drag without significantly affecting the lift. With add-on spoiler, the vehicle maintains its stability and improves its fuel economy. With a reduction in drag coefficient of 0.044 and a reduction in lift coefficient of 0.007, which equals about to 6.6 pounds weigh increase, the fuel improvement is, estimated about 0.87 mpg.
Figure 4.6 LMV with Add-on Spoiler

Figure 4.7 Velocity Magnitude of LMV with Spoiler
4.4 Aerodynamic Analysis of LMV with Add-on Vortex Generator (VG)

In this simulation, we apply the vortex generator to LMV to verify its function for LMV. The VG is installed 100 mm in front of the rear end as shown in Figure 4.8. Figure 4.9 and Figure 4.10 present the pressure distributions of LMV with Vortex Generator installed. The CFD yields the drag coefficient of 0.504 and the lift coefficient of -0.056, indicating that it has no significant lift difference compared to the simulation results from LMV without any add-on devices. For this drag reduction, it is estimated about 0.65 mpg decrease in fuel economy. As we have reviewed in previous chapter that the vortex generator is sensitive to the flow velocity. In addition, the big size of the VG may generate drag by itself when air flow is passing over it. Inappropriate installation of VG might even result in more drags. As we have seen in the Figure 4.10, the absolute pressure value is higher in the front of the VG that is generating drag. However, the function of the VG is to delay the flow separation and this might reduce the same amount
of drag force as the VG generates itself. Better VG installation position and choice of its geometry might be able to improve its performance.
Since the VG could be in varying geometries, we simulate the LMV with added VG at different install positions and shapes as shown in Figure 4.11. Since the main function of VG is to delay the airflow separation, we install the VG 130 mm from the rear end, a little bit ahead of the previous one. The CFD simulation yields that a drag coefficient $C_d$ equals to 0.511 and a lift coefficient $C_l$ equals to -0.052. Fuel economy is estimated about 0.22 decreases. By comparing Figure 4.11 to Figure 4.2 that there is insignificant effect of wake region in the back. However, it generates a small wake region after the VG that produces drag and lift. From the simulation results, it indicates that the VG does not generate an aerodynamic improvement for this type of vehicles. For a regular sedan, it is common to see that a VG is installed before on the rear end. The reason that it does not work for SUV or crossover type vehicle might be that the flow separation of the SUV and crossover is at the rear end but there is not any body part like chunk of sedan to collaborate with the VG.
Figure 4.12 LMV with Revised VG

Figure 4.13 Total Pressure of LMV with Revised VG
4.5 LMV Handling Advantages

Handling and braking are the major components of a vehicle’s “active” safety [30]. LMV could advance several factors from regular SUV or crossover in handling.

Roll angular inertia

Roll angular inertia increases the time it takes to settle down and follow the steering [30]. With lowered mass, LMV takes shorter time to settle down and steering. With better aerodynamic performance, LMV could decrease the time to settle while not losing the gripping ability. In a uniform mass distribution, the roll angular inertia could be calculated by

\[ I = M \times \frac{(H + W)}{2} \]  
(4.1)

Where:

- \( I \) = Roll angular inertia
- \( M \) = Vehicle mass
- \( H \) = Vehicle height
- \( W \) = Vehicle Width

Unsprung weight

![Unsprung Weight Diagram](image)

Figure 4.13 Unsprung Weight [30]
As shown in Figure 4.13, unsprung weight is a mass which has its own inherent inertia separated from the rest of the vehicle [30]. When a wheel is pushed upwards by a bump in a road, the inertia of the wheel will cause it to be carried further upward above the height of the hump. If the force of the push is sufficiently large, the inertia of the wheel will cause the tire to be completely lifted off the road surface, resulting in a loss of traction and control [30]. In this case, lower mass reduces the risk of loss of control and traction. With the required downward force created by aerodynamic device, the LMV would maintain the handling on flat road and minimize the risk of loss traction on bump due to its low unsprung weight.
5.1 Conclusions

To achieve a better fuel economy there is no doubt that the combination of low mass and well aerodynamic performance vehicle could be one of the solutions. New materials and new body design method will be used to reduce the mass. However, in order to maintain the cargo volume at the same time, SUV or crossover is a better choice than regular sedan.

With reduced mass, the stability of vehicle has to be concerned in the mean time of reducing the drag. Therefore, the aerodynamic plays a significant role in the vehicle design. Without majorly modifying the vehicle geometry, right selection of add-on aerodynamic devices could effectively improve its aerodynamic performance. As the simulated results showed in CFD, the spoiler reduces the drag but it does not significantly increase the downward force. Compared to a regular SUV or crossover, LMV concerns more about the lift for its stability. With appropriate aerodynamic devices installed, the LMV is stable in normal road drive. However, in conditions like driving over a bump, LMV demonstrates a better handling ability than regular SUV.

CFD simulations showed that the VG generates drag and increases the lift when the flow is passing through it. VG is not as functional as the spoiler does. VG is used to delay the flow separation and to avoid turbulent airflow flowing into other aerodynamic devices that could affect its performance. According to the data from CFD simulations,
the VG does not reduce drag if it is installed alone. Unlike regular sedan with installed spoiler above the trunk and with the VG in the rear end, VG is not suitable for vehicles similar to shapes as tested LMV since the point of the flow separation in the rear end of vehicle.

Vehicle with low mass has a low rolling resistance, grading resistance and acceleration resistance and this could improve vehicle’s fuel economy. With certain shape being chosen to maintain the cargo capacity, aerodynamic devices are good choice to improve its aerodynamic performance. The installation and choice of aerodynamic devices are critical to improve the aerodynamic performance. As the LMV is combined with vortex generator, it generates more drag. This indicates that the size, angle of attack and installation position are not general to every vehicle. It has to be tested to certain body shape. Otherwise, it might not function as it is expected.

With appropriate selection aerodynamic device, LMV will have a better handling ability than regular SUV. For instance, instead of increasing uniformly distributed mass, aerodynamic device could create downward force at certain point to achieve better handling. Increasing downward force in steering tire will ease the steering effort. With the same amount of unsprung weight, LMV with appropriate add-on devices will be more stable on flat road to avoid loss of control when driving over bumps. Above all, LMV without good performance in aerodynamics could generate problems like loss of steering and traction if there is not enough force on the tire. However, LMV with good aerodynamics and with appropriate aerodynamic devices designed or installed could exceed the performance of regular SUV in both fuel economy and handling.
5.2 Future Work

This project is mainly to bring the idea of combining the low mass vehicle, which is introduced by Dr. Weber in University of Michigan, with aerodynamic devices to achieve its better stability and fuel economy. In the CFD simulation, only two add-on devices are simulated. Most of the aerodynamic devices are introduced in Chapter 3 and their combinations have not been simulated. In the simulation of LMV with add-on devices, they do not generate significant downward force for LMV to enhance its stability at high speed. Future work could focus on other aerodynamic devices or combine them to reduce the drag and generate required downward force at the same time.

Besides the work mentioned above, combination of the low mass vehicle, aerodynamic devices and new energy vehicle or hybrid vehicle has not been studied. At the end of Chapter 2, the BMW-I concept vehicle introduced its work on combining the low mass, good design of aerodynamic shape and hybrid system. In addition, as expected, it has a higher fuel economy with a 62.56 MPG. Therefore, the combination of different methods to improve the fuel economy could effectively improve the fuel economy and will appear in automobile industry in the near future. The further work should also focus on those combinations.
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