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FINAL REPORT

Carbon Fiber Monocoque Chassis Redesign

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Project for: NIU Supermileage
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ABSTRACT
The NIU Supermileage Team develops ultra-energy efficient gas and electric vehicles. In the past, the team has created their vehicle using an aluminum tubing frame and carbon fiber shell. The carbon fiber shell is not load bearing and only acts as an aerodynamic shape for the vehicle, allowing it to slice through the air efficiently by minimizing drag due to air resistance and turbulence in the form of eddy currents. The primary goal is to develop a monocoque chassis for the Supermileage Team. A monocoque chassis is a body type in which the vehicle is composed of a singular, unibody structure. Rather than having an aluminum tubing frame as the structure and carbon fiber shell as the aerodynamic geometry, the carbon fiber composite structure functions as both the load bearing structure as well the aerodynamic structure. This allows for optimization in weight, aerodynamics, and rolling resistance. The Supermileage Team requires a carbon fiber monocoque vehicle redesign that improves overall energy efficiency.
1.0 INTRODUCTION

1.1 BACKGROUND

The SAE Supermileage and Shell Eco-Marathon competitions are ways for collegiate engineering teams to test their skills on the track against hundreds and even thousands of their peers from across the globe. The primary goal is the pursuit of the most energy-efficient vehicle. It is known that the primary contributors to energy loss after the powertrain in vehicles are rolling resistance and drag force. The carbon fiber monocoque redesign addresses both of these issues in-depth by focusing on the exterior shell of the car to address aerodynamic drag and sideload. Additionally, the large estimated weight reduction from designing a fully composite body is expected to greatly reduce rolling resistance. The project aims to expand upon the current knowledge of the NIU Supermileage Team and address many of the issues that have kept the team from reaching over 2,000 miles per gallon.

1.2 PURPOSE OF PROJECT

The carbon fiber monocoque redesign spans a wide range of mechanical engineering foci including CAD, parametric design studies using computational fluid dynamics and finite element analysis, sensor embedment in composite structures for strain sensing and predicted vehicle lifespan, and design for intricate yet feasible mold fabrication. The new vehicle design must maintain compatibility with Supermileage subsystems in addition to focus on reducing the overall size of the vehicle, decreasing the coefficient of drag, minimizing weight, increasing driver visibility, and maintaining a high degree of safety. Other items of consideration include vibrations, impacts, turning radius, field repairs, and general ease of maintenance (serviceability).

The team expects to achieve a reduction in weight of at least 10 pounds, which is significant considering the total vehicle weight is 100 pounds. In addition to weight reduction, the vehicle redesign reduces the coefficient of drag, optimizes the amount of negative lift, and minimizes the energy demand when driving forward or turning. This project also allows the team to integrate past design considerations that were not physically allowable in the old vehicle chassis, such as increased turning radius or wider tires and rims for reduced rolling resistance. Furthermore, monocoque design allows for futureproofing of the vehicle such that other subsystems can be implemented when needed. Overall, the carbon fiber monocoque chassis redesign provides the Supermileage team greater insight to the vehicle and allows them to implement changes that minimize energy losses for many subsystems.
1.3 PREVIOUS WORK COMPLETED

The NIU Supermileage Team was started as a senior capstone project by engineering technology students in the College of Engineering and Engineering Technology at Northern Illinois University (NIU) in 2009. In one year, they designed, fabricated, and competed with a highly fuel-efficient vehicle, placing in the top-3 positions at SAE Supermileage. Their success came from many components on the vehicle, namely the aerodynamic shell and the energy efficient engine.

Eleven years later, the NIU Supermileage Team is still using the same aerodynamic geometry that the original team used, all while modifying almost all of the internal components of the vehicle. While the first NIU Supermileage cohort propelled themselves to a top-3 finish, they achieved just over 1,200 miles per gallon. The current record held by NIU Supermileage, all while maintaining the same external shell geometry, is 1,888 miles per gallon. While it is clear that significant strides have been made in improving the internal functions of the vehicle, an improvement can be made in the vehicle's structure such that the energy efficiency can be increased even further through weight reduction and drag force minimization.

The current body is designed such that there is a structural frame made out of 1/16 inch and 1/32 inch thick aluminum tubing, and a carbon fiber composite shell that encapsulates the metal frame. While the vehicle is extremely reliable, resilient, and far exceeds the necessary load ratings of 250 lbs (F.O.S > 6), it is still heavy and due to the two-component structure, is much wider than necessary. Due to the drawbacks of the current vehicle design, a carbon fiber monocoque chassis will be developed, meaning that the aerodynamic geometry also serves as the load bearing chassis. This allows for a much more lightweight vehicle, all while allowing the vehicle to be slimmed down, and effectively reduce the drag force on the vehicle, as drag force is directly proportional to cross-sectional area.

1.3.1 PRODUCTS

While there are hundreds of teams across the world that develop Supermileage vehicles, there is only a small sample size of teams that have consistently performed well at competition. Most, if not all, of these vehicles share a commonality in body design. It is recognized that the work developed is not revolutionary but combining these efforts with the NIU Supermileage Team’s highly efficient engine is expected prove to lead a significant change in efficient vehicles.
From the current work found in industry that is accessible to customers, many manufacturers recognize the extreme difficulty in fabricating highly complex vehicles at scale [1]. Some of the only vehicle manufacturers that are beginning to address this sector of the market are Tesla Motors, Koenigsegg Automotive AB, Porsche, and other high-end vehicle manufacturers.

For example, Tesla holds 8 of the Top 10 “Fuel Sippers” spots as published by the Department of Energy [2] with the Tesla Model 3 Standard taking the first place with a combined efficiency of 141 miles per gallon (equivalent mpg for an All-electric vehicle). The only two spots not occupied by Tesla is the Hyundai Ioniq Electric in second and the Hyundai Kona Electric in tenth. One of the main reasons that the Tesla Model 3 has achieved such high efficiency is due to the shape having a lower drag coefficient than almost any other production car. The drag coefficient of the Model 3 is 0.23 [3] while the average drag coefficient of a vehicle is 0.3-0.4 [4].

1.3.2 PATENT SEARCH RESULTS AND LITERATURE SURVEY

The conclusion of a patent search resulted in limited applicability to the aerodynamic design of a monocoque chassis. Most patents relating to “aerodynamic vehicles” or “vehicle drag reduction” were for modifications for semi-truck trailers to help increase the fuel efficiency of the vehicles. While not directly applicable, these patents revealed portions of the chassis design that may have substantial impact on the drag force produced. For example, one patent described the use of structures hanging in front of trailer wheels to divert air out from under the trailer [5]. This movement prevents air from getting caught within the vortices of the rotating wheels. The different curvature of the structures has a significant impact on the effectiveness of drag reduction which could apply to the design of wheel covers within the monocoque chassis.

Some additional patents that could be beneficial to reference include some drag reduction systems patented by Toyota. These include devices such as a flap in the bed of pickup trucks which helps streamlines flow over the tailgate [6]. The flap is stored in the tailgate until it is deployed to effectively form a partial lid over the bed to catch the streamlines as they flow over the cabin. Ultimately, the patent may not be applicable to the project because the body design will be a continuous streamlined body without large obstructions such as a pickup truck’s uncovered bed. Toyota also patented a structure to provide an alternative tail design for a sedan [7]. Rather than an abrupt cutoff of the sedan, the tail-end flows smoothly into a cone shape which helps reduce
the aerodynamic drag once the air leaves the vehicle. This concept solidifies the current tail design of the body which flows smoothly to as point.

Due to the limited applicability of available patents to the project, an additional literature survey was conducted by referencing some design reports written by other universities’ Supermileage teams. One of these reports [8] was written by a team from the University of Laval, Quebec, about their iterative design process using parametric modeling and CFD simulations to maximize the aerodynamic efficiency. The team describes their in-depth analysis of different wind scenarios with varying wind yaw angle relative to the vehicle and the results of simulations on turbulent kinetic energy and pressure distributions. Their new body design is very similar to the PAC-Car II body, developed by ETH Zurich, which many Supermileage teams mimic due to its minimized drag coefficient [8]. After this iterative design process and in-depth simulation analysis, the team was able to increase their cross-sectional area by 25% (to allow for other modifications) with a reduction of 50% negative lift and drag coefficient reduction of 20%.

Another key report that could be applicable to the monocoque design is a master’s thesis from Brigham Young University by Sayan Dobronsky [9]. His thesis describes the process of improving the aerodynamic efficiency of the BYU Supermileage vehicle. While describing the parameters of the simulations, it was noted that the control volume involved 5 body lengths forward of the vehicle, 10 body lengths to the rear, and 5 body heights above the vehicle. This large volume was used to allow for the effect of the vehicle on the overall area to be analyzed, without cutting the volume too close to the vehicle. Also, similar to the simulations done by Laval, Dobronsky uses the k-ω turbulence model which allows for good convergence of both the drag and lift coefficients. This body redesign also used an iterative design process where many modifications were made after simulations to adjust for a better drag coefficient. Ultimately, this new body design created was able to reduce the drag coefficient of the vehicle by about 11% in fully turbulent flow.

1.4 BRIEF OVERVIEW of the REPORT

The report discusses the design methods used to create a Supermileage vehicle in CAD (computer aided design) in addition to the specific criteria addressed when designing and selecting the optimal geometries. These features include, but are not limited to, footprint and cross-sectional
area, weight, ground clearance, wheel fairing design, nose cone design, and tail design. Section 1.4.1 discusses the initial design methods and considerations for fabrication.

1.4.1 METHODS of DESIGN and FABRICATION CONSIDERATIONS

The initial stage of the project was to design and optimize the carbon fiber monocoque chassis using modeling and simulation software before the fabrication process can begin. Three iterations of the design are being produced to narrow down to an optimal design. 3D modeling tools including SolidWorks and OnShape are the primary CAD tools that are employed. The capability of this CAD software includes surface modeling features such as surface loft, surface extrusions, and boundary surface, which are heavily used in the design process. The design began with 2D sketches on both the top and right plane using profile photos of a previous Supermileage vehicle as a basis for dimensions. A step of the CAD design process is shown in Figure 1, above.

After initially sketching from a photo profile, a 3D scan of the previous Supermileage positive mold was attempted to further grasp specific dimensions. An Einscan Pro 3D scanner was used on the surface of the mold. Shown in Figure 2 below is an example of the profile being scanned.

Figure 1: Sketch and loft of preliminary body design

Figure 2: Profile scanned of previous Supermileage vehicle
Due to the organic nature of the mold and mostly featureless body, extruded tape features were added so that the 3D scanner could better pick up the geometry. The 3D scanner allowed for the tail end of the mold to be scanned and turned into a mesh model which is shown in Figure 3 below.

Figure 2: 3D scan of previous NIU Supermileage mold

Figure 3: 3D scan of tail
The 3D scanner continuously lost tracking throughout the process and did not allow for a complete 3D scan due to the lack of distinct features. This resulted in returning to the initial design idea of solely using sketch outlines and surface feature modeling (e.g., surface extrusions, boundary surfaces, etc.).

After the three iterations of body designing was complete, the process of evaluation to choose the optimal design for fabrication began. The dynamic tessellation software ANSYS, more specifically its fluid flow simulation capabilities of Fluent (a computational fluid dynamics analysis feature), was used to analyze the control volume surrounding the body. The literature review previously performed describes the control volume size and conditions that are necessary for streamline body simulations [9]. An example of a completed design using SolidWorks solid body modeling is shown below, **Figure 4** as well as surface modeling design in **Figure 5**.

**Figure 4:** Completed design with carbon fiber finish using solid body loft method

**Figure 5:** Surface modeling method of body design
Initially, an understanding of the ANSYS software and its abilities was gained through tutorials in addition to help from faculty and graduate students. The team began by simulating a similar object to that of the monocoque design such as a streamline body (e.g. tear drop shape). This allowed for testing and confirmation of correct boundary conditions on an object within air. Furthermore, the drag force was the main calculation factor when determining optimal design, with the overall goal being to minimizing drag while minimizing weight. This is further discussed in Section 2.1.4.

The fabrication process will begin in spring 2021 in partnership with Navistar International. The design chosen will be programmed by Navistar’s CAM program of choice and will cut the inverse of the vehicle shape into HDPE (high density polyethylene) foam. The negative mold will then be coated with layers of sealant, and once cured, the carbon fiber sheets will be laid into the mold to form the pattern of the vehicle and vacuum bagged to create the body.

The process will start by laying carbon fiber twill weave as an initial layer of the shell. Soric strengthening matrix and Nomex honeycomb core will be placed between layers of carbon fiber to provide rigidity and structural integrity. The soric matrix will be placed throughout to provide rigidity, but the Nomex honeycomb will be used in higher stress locations. The carbon fiber sandwich honeycomb panels will allow for higher loads and act as a floorboard along the length of the vehicle in addition to being used as a mounting point for steering, powertrain, and engine subassemblies. Having the honeycomb along the floorboard will allow for various mounting points to be placed and help to future proof the car in case of technical design rule changes. An aluminum honeycomb core was considered to be used as the rollbar and firewall that separates the driver from the engine compartment. Shown in Figure 6 below is an example of the aluminum honeycomb with paneling. Ultimately, it was decided to use aluminum tubing and plate for the firewall as it is lighter, stronger, and more affordable than the aluminum honeycomb.

![Figure 6: Aluminum honeycomb core](20)
After layers are placed throughout the mold, the resin and hardener are infused using a vacuum bagging technique to create the vehicle structure. The vacuum bagging will consist of a thin vacuum film laid and sealed along the sides of the mold. Tubing will be integrated with the resin and an air compressor. The film will create a vacuum allowing for resin to be guided under the film along the carbon fiber and matrix layers. Shown in Figure 7 below is an example of a carbon fiber monocoque vehicle from Duke University’s electric vehicle.

![Image of monocoque from Duke EV](image)

*Figure 7: Example of monocoque from Duke EV [21]*
2.0 PROJECT DESIGN

2.0.1 SUMMARY of DESIGNS

The designs selected for comparison of the carbon fiber monocoque chassis are detailed below. All designs had to follow a specific set of criteria set forth by the NIU Supermileage Team as well as the competitions attended, including SAE Supermileage and Shell Eco-Marathon. The Shell Eco-Marathon has a set of requirements that must be met in order to compete at the Shell Eco-Marathon Americas competition. The specifications are listed below in Table 1.

*Table 1: SEM vehicle dimension requirements [10]*

<table>
<thead>
<tr>
<th>Shell Eco-Marathon Vehicle Dimension Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. height: 1000 mm (39.37 in)</td>
</tr>
<tr>
<td>Min. track width: 500 mm (~20 in) [measured between tire midpoints of front wheels]</td>
</tr>
<tr>
<td>Min. wheelbase: 1000 mm (39.37 in) [front wheel axle to back wheel axle distance]</td>
</tr>
<tr>
<td>Height-to-track width ratio &lt; 1.25</td>
</tr>
<tr>
<td>Total width &lt; 1300 mm (51.18 in)</td>
</tr>
<tr>
<td>Max. length &lt; 3500 mm (~11.5 ft)</td>
</tr>
<tr>
<td>Max weight: 140 kg (~310 lbs)</td>
</tr>
</tbody>
</table>

Following the aforementioned requirements set by the Shell Eco-Marathon in Table 1, it was decided that three approaches should be used to design the vehicle. The first is a recreation of the vehicle geometry that the team has used since 2013 due to its previous success and ability to accommodate all of the current vehicle’s subsystems. The second is a design that is influenced by the PAC-Car II from ETH Zurich. This vehicle was considered the world’s most fuel-efficient vehicle until 2018, when Duke University’s electric vehicle outperformed ETH Zurich’s PAC-Car II [11]. The body design employed by ETH Zurich can be found as the basis for design of many vehicles at supermileage competitions due to its ability to perform very well [12]. Design 2 takes the general shapes of the PAC-Car II such as the side airfoil profile and the top profile. The primary modifications can be found in the critical areas of the vehicle that must be changed to accommodate the Supermileage Team’s current subsystems such as the engine, steering assembly, and wheels. The third design is a combination of the current Supermileage vehicle and the PAC-Car II geometries. Design 3 also takes the airfoil design used in the PAC-Car II but modifies it to allow for the subsystems to be placed within the vehicle. The same approach was taken with the top
profile, in which the body had to be elongated and widened to account for the engine and wheels. All three designs are found below in Figure 8.

<table>
<thead>
<tr>
<th>Current Supermileage Vehicle</th>
<th>PAC-Car II Influenced Design</th>
<th>Combination of Supermileage and PAC-Car II</th>
</tr>
</thead>
</table>

**Figure 8: Alternative vehicle designs overview**

All three designs are being analyzed using Ansys Fluent for Computational Fluid Dynamics (CFD) simulations to determine the aerodynamic properties of each design. This analysis method consists of importing the geometry into Ansys, processing the geometry into a mesh, and solving the computational problems constrained with boundary conditions to determine the fluid response as the car is moving.

After importing the geometry into Ansys, an enclosure is built around the vehicle to represent the fluid body such as shown in Figure 9. The enclosure walls are placed far enough away from the vehicle to not interfere with the analysis of the fluid flowing across the surface of the body.
This enclosure, along with the vehicle design inside it, are generated into a quadratic mesh with element sizes of between 2 - 3 cm, Figure 10. It was observed that the accuracy of the simulations improved with decreasing element size, but smaller element sizes require additional computational power. Using an element size of 1 cm exceeded the computational power of the computer used, but element sizes of 2 - 3 cm were able to be solved with enough precision for these preliminary analyses. This small element size led to meshes containing roughly 4 - 4.5 million cells each. Some additional mesh parameters include adaptive sizing and inflation boundaries to more closely represent the geometry of the vehicle body.

The simulations are modeled using the Shear Stress Transport k-ω (SST k-ω) model due to its popularity for use with aerospace applications [13]. This model combines the strengths of two traditional models, standard k-ω and k-ε, to better represent separation and reattachment between surfaces and walls. For the simulations, the inlet and outlet boundary conditions consist of fluid coming in at 25 mph and an outflow-based outlet. Each simulation was calculated for 250 iterations which all reached a convergence of $10^{-6}$.
2.0.2 ALTERNATIVE DESIGN #1

The current body is designed such that there is a structural frame made out of 1/16 inch and 1/32 inch thick aluminum tubing, and a carbon fiber composite shell that encapsulates the metal frame. While the vehicle is extremely reliable, resilient, and far exceeds the necessary load ratings of 250 lbs (F.O.S > 6), it is still heavy and due to the two-component structure, is much wider than necessary. Due to the drawbacks of the current vehicle design, a carbon fiber monocoque chassis is being designed, meaning that the aerodynamic geometry also serves as the load bearing chassis. This allows for a much more lightweight vehicle, all while allowing the vehicle to be slimmed down, and effectively reduce the drag force on the vehicle, as drag force is directly proportional to cross-sectional area. The design seen below in Figure 11 is the CAD for the current Supermileage vehicle design. This vehicle has proven to be very effective for the team, which is why it is being considered as part of the alternative design process. The current design can be converted from employing an aluminum internal frame to the desired monocoque design.

![Figure 11: Current Supermileage vehicle (Design 1)](image-url)
After running about 130 iterations for Design 1, the residuals steadily approached a convergence of $10^{-6}$ shown in Figure 12.

![Residual plot to verify convergence](image1)

**Figure 12:** Residual plot to verify convergence

**Figure 13** shows the pressure contour of the vehicle on the design surface, with high pressure at the front and lower pressure around the widest vehicle features. These pressure differences are logical because the air hitting the nose of the vehicle will slow and create higher pressure as it gets redirected but then the pressure is much lower around the hump due to the increased velocity around those features.

![Pressure contour of Design 1](image2)

**Figure 13:** Pressure contour of Design 1
The pressure contours of Design 1 from the top and side views are shown in Figure 14. It can be seen that the tail of the vehicle causes slightly higher pressure than most of the vehicle surface, which could cause unnecessary pressure drag. There is also reverse pressure underneath the body which is caused by the front wheel fairings that creates additional drag. Optimizing these areas could prove beneficial to further improve the aerodynamics of Design 1.

**Figure 14: Design 1 top view pressure contour (top) and side view pressure contour**

### 2.0.3 ALTERNATIVE DESIGN #2

The second alternative design is based upon the world leader for energy efficiency: the PAC-Car II vehicle design from ETH Zurich [11]. The same fabrication requirements exist from the first design, including the use of carbon fiber, honeycomb core, and Soric. Design 2’s dimensions were determined by using the design one dimensions of width, length, and height and applying it to the new and updated PAC-Car II cross sectional shape.

This design is more focused on being lightweight rather than the airfoil driven approach of Design 1. Design 2 can be found below in Figure 15.
As shown, the rightmost photo of the top view design does not take the shape of the airfoil but rather forms to different cross sections based on the set requirements. The widest part of the top profile is the track width (center-to-center distance of the front wheels) and incrementally decreases to a point at the back of the vehicle. This design follows similar geometric approaches as an airfoil, but is not as smooth when transitioning between the desired cross sections. This design choice may potentially cause more drag, but vehicle operating speeds would not cause a large enough impact to completely rule out this approach.

A side profile view of design two shows some striking differences from the first design. Instead of attempting to have the bottom half of the vehicle be close to the ground, this design focused on weight elimination and decreasing cross-sectional shape by raising the underside of the vehicle. The only extensions from the side profile are for the front and back wheels, while the rest is flush against the minimum firewall requirement. Design 1 could not do this as the steering system used is located underneath the driver, so much more vertical space is required. Design 2 is capable of raising the underside of the vehicle because the steering system can be reconfigured using a linkage system similar to what can be found in go-karts, in which the steering linkages can be in-plane with the driver rather than below. An example of a possible steering linkage can be seen below in Figure 16.
The track width of the design is approximately 20.5 inches, which meets the standard set by Shell with a small clearance of about ¾ inch. Furthermore, it also meets the required turning radius of the vehicle. The overall length of the vehicle is designed to be approximately 9.5 ft long, which is about 1 ft shorter than design one’s length. The maximum height is approximately 2.5 ft which is measured from the ground to the highest point of the body.

The driver compartment was evaluated to ensure that a driver with the height of 60-65 inches could properly fit and have optimal visibility. The driver compartment’s average diameter cross section was about 18 inches, which allowed for a minimal cross section in that area while also accounting for driver body size and shoulder width.

Some issues that need to be accounted for in future designs is that the PAC-Car II is based on an electric motor powered by a hydrogen fuel cell instead of the internal combustion engine (ICE) that NIU Supermileage uses [12]. This would require further space consideration in future designs, as well as strengthening placement of honeycomb to allow for the heavier engine placement on the back end of the vehicle.
The pressure contour on the surface of Design 3 is shown in **Figure 17** where it’s easily noticeable that the wheel fairings are a solid mass instead of cut down the middle. This causes a large increase of pressure for the air passing underneath the body as its only available path is to the side of the vehicle or through the 5 mm gap to the ground. It can also be observed in **Figure 18** how the reverse pressure to the sides of the widest feature is not as large as in Design 1 due to the smaller track width of Design 2. Some notes of concern are the pressure changes along the sides of the body from the ripple-like features.

![Figure 17: Design 2 pressure contour](image1)

![Figure 18: Design 2 top and side pressure contours](image2)
2.0.4 ALTERNATIVE DESIGN #3

The third design allowed for previous mistakes to be corrected in the final design process. A steering assembly was modeled along with the current engine assembly so that the new design could be accurately modeled from the interior components more closely. A GrabCAD model was provided of the PAC-Car II vehicle and used to understand the method of vehicle design in SolidWorks [14]. This design focused more on the surface method in SolidWorks compared to design two that employed the incremental loft method. Implementing the surface method allowed for the surface to be later knitted together and will prove to be much more effective in the optimization process when adjusting airfoil and vehicle profiles. The third design is shown in Figure 19 below.

![Figure 19: Combination of Supermileage and PAC-Car II (Design 3)](image)

It can be noted that the side profile (bottom left of Figure 19) of both Design 2 and Design 3 are similar as the wheel fairings extrude out of the main body to create a barrier for the wheels. It is also clear that the top profiles are very different between the two designs in that Design 3 removes the loft-based discontinuities in the body shape through the use of boundary surface modeling. Besides dimensional accuracy and method of approach, a big difference that Design 3 focused on was the wheel fairing geometry. Similarly, in the previous two designs, including the original Supermileage vehicle, the wheel fairings have a cross sectional shape similar to that of an ellipse. Using the PAC-Car II vehicle method, airfoil shapes were used as the cross section of all three wheel fairings. As discussed by ETH Zurich, the use of an asymmetric airfoil design for the
front wheel fairings guides the induced turbulence away from the back wheel fairing, which is a symmetric airfoil profile, in order to decrease aerodynamic drag.

Additional focus was also placed on planning and designing where the windows would be located. On the current Supermileage vehicle, this was an afterthought and only cut out after the carbon fiber was molded. To properly ensure driver visibility, Design 3 accounts for this and the windows are shaped and placed ahead of time as seen in Figure 19.

The track width of the design is approximately 22 inches, which exceeds the standard set by Shell. The track width increased by about 1.5 inches compared to Design 2, since a steering assembly with more accurate dimensions was used. The overall length of the vehicle is designed to be approximately 10 ft long, which is about 0.5 ft longer than Design 2’s dimensions.

Similar to Design 2, the driver compartment was evaluated to ensure that a driver with the height of 60-65 inches could properly fit and have optimal visibility. The driver compartment’s average diameter cross section was about 18 inches, which allowed for a minimal cross section in that area while also accounting for driver body size and shoulder width.

One of the largest differences between the pressure contours of Designs 1-3 is that the maximum pressure for Design 3 is roughly 50% that of the maximum pressures in Design 1 and 2, Figure 20. Another large difference is the large pressure in the wake of the tail for Design 3, with a magnitude similar to that on the nose, Figure 21. This pressure at the back of the vehicle is very different than that of Designs 1 and 2, and additional research is required to determine if this pressure is a benefit or a detriment.

![Figure 20: Design 3 pressure contour](image-url)
2.1 OPTIMAL DESIGN

2.1.1 OBJECTIVE

As previously stated, the project aims to develop the most aerodynamic vehicle possible while operating within the constraints of maintaining safety, increasing driver visibility, and installing all current Supermileage subsystems in the new design. The methodology of designing the vehicle is stated later in this document, but a large component includes performing an alternative design analysis of the current body design, the PAC-Car II by ETH Zurich, and a combination of the structures. Upon selection of the optimal design, a mold must be designed that accounts for all modes of mold failure, such as too small of radii, too small of features, or other limitations when implementing materials such as a honeycomb core. The mold is to be fabricated once it is decided which design is optimal. A novel method of sensor embedment will be attempted when fabricating the carbon fiber body by placing strain gauges or fiber optic FBG sensors for strain measurement in between layers of carbon fiber and honeycomb matrix core. Upon completion of body fabrication, all subsystems of the vehicle must be installed and tested.

Below in Figure 21 (same as Figure 19) is the selected optimal design (Design 3). The rest of Section 2.1 serves to justify this decision.
2.1.2 SUBUNITS
2.1.3 FOOTPRINT

The footprint of the vehicle is an important consideration as it is determined by the size of the CNC used to fabricate the molds, the internal components in the vehicle, as well as other vehicle specifications such as the wheelbase, track width, and driver height. Ensuring that the selected footprint is advantageous for energy efficiency is critical, so each design heavily considered overall footprint of the vehicle as a design factor.

In order to visually compare the vehicles, the figures below (23, 24, 25) show overlays of the designs to show the difference between each footprint. It is clear that the footprint was maintained at about the same length for each design since it is constrained by the height of the driver in addition to the internal components such as the engine, wheels, firewall, and steering.
Purely from visual analysis of the vehicles, the geometries of the side profile are starkly different. Design 2 and Design 3 are not as tall as Design 1 (current vehicle), have a much shallower nosecone, and employ a tail design that comes to a point rather than having a cutoff. The length of the current vehicle is 2.90 m (9.51 ft) while Design 2 and Design 3 have lengths of 2.89 m (9.48 ft) and 3.05 m (10.00 ft), respectively. While decreasing the length of the vehicle will inherently reduce the weight, it was also found that more weight reduction could be found from minimizing the height of the vehicles. As seen in Figures 4-6, the height of the main body (underbelly to top of vehicle) of Design 2 and Design 3 are much smaller when compared to Design 1. Design 1 has a height of 0.61 m (2.00 ft) while Design 2 and Design 3 have a height of 0.48 m (1.57 ft) and 0.46 m (1.51 ft), respectively. The reduction in height results in a large reduction in cross-sectional area, and therefore minimizes weight (further discussed in section 1.2.3).
From some of the further discussions in optimal design analysis, the importance of dimensions, nosecone, and tail design will be considered. For reference, the smaller the cross-sectional area of the vehicle, the smaller the drag coefficient is. When the area is reduced significantly, as seen in Design 2 and Design 3, the lower drag coefficient will result in less energy loss. In Equation 1, the drag coefficient equation is described in which $F_D$ is the drag force, $\rho$ is the density of the fluid (air), $v$ is the velocity of the object, $C_D$ is the drag coefficient, and $A$ is the cross-sectional area of the object.

$$F_D = \frac{1}{2} \rho v^2 C_D A$$

Equation 1 [15]

In order to show the importance of cross-sectional area on the drag force of the vehicle, each variable of Equation 1 will be set to a constant value, save for the area. The variables that remain constant are the fluid density, velocity, and drag coefficient.

$$\rho = 1.184 \ \text{kg/m}^3 \text{ (density of air at 25°C)}$$

$$v = 11.176 \ \text{m/s} \text{ (max competition speed)}$$

$$C_D = 0.074 \text{ [unitless]} \text{ (drag coefficient of Supermileage vehicle)}$$

While it is not realistic to use the cross-sectional area values from all three vehicle designs without considering the drag coefficients, the change in area will serve to provide an understanding of its role in minimizing drag force. Below, $A_1$ represents the area and $F_{D1}$ is the drag force of Design 1, $A_2$ is the area and $F_{D2}$ is the drag force of Design 2, and $A_3$ is the area and $F_{D3}$ is the drag force of Design 3. The cross-sectional areas of each design can be seen in Figure 26.

<table>
<thead>
<tr>
<th>Design</th>
<th>Area ($A$)</th>
<th>Drag Force ($F_D$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4 m²</td>
<td>2.189 N [kg⋅m/s²]</td>
</tr>
<tr>
<td>2</td>
<td>0.2 m²</td>
<td>1.094 N [kg⋅m/s²]</td>
</tr>
<tr>
<td>3</td>
<td>0.24 m²</td>
<td>1.313 N [kg⋅m/s²]</td>
</tr>
</tbody>
</table>
Decreasing the frontal area (and overall cross-sectional area) of the vehicle significantly reduces the drag force. In addition to the large reduction in drag force, a reduction in cross-sectional area leads to much less weight as well, which is the greatest factor on energy efficiency due to the impacts of rolling resistance.

2.1.4 WEIGHT

When trying to minimize rolling resistance to increase the vehicle’s efficiency, decreasing the weight of the vehicle can have a huge effect. Therefore, efforts should be taken to minimize the vehicle weight, which is a dominant reason for designing a carbon fiber monocoque body over the aluminum tubing frame and carbon fiber shell. To make sure the monocoque designs don’t weigh more than the current frame, the current body was weighed and weight estimates for the new designs were calculated. The current carbon fiber shell weighs about 14 lbs, found using a scale, and the aluminum tubing frame weighs an estimated 10 lbs. The weight of the carbon fiber shell includes patches of Soric material, in critical areas, and no windows adhered to the shell (but window slots were cut in the fiber shell).

In order to estimate the weight of the monocoque designs, the surface area of CAD model was evaluated using Solidworks and then multiplied by 1/32” to simulate two layers of carbon fiber all around the body. An estimated 7’ x 12” section of 0.5” thick Nomex honeycomb is used along the bottom of the body and approximately the same amount of Soric is used as the current body (about 7 lbs). The fabric density of the carbon fiber twill weave is 204 g/m² with a sheet thickness of 1/64”, resulting in a volumetric density of 0.51 g/cm³. However, since the twill weave
is infiltrated with resin during the vacuum bag process, and to add a factor of safety, the assumed
density of the material used in the calculations is $1.0 \text{ g/cm}^3$ ($0.036 \text{ lb/in}^3$). The estimated weights
of Design 1, $W_1$, and Design 3, $W_3$, are as follows:

$$W_1 = (SA \ast t \ast \rho) + 7 \text{ lbs} = 8,313 \text{ in}^2 \ast \frac{1}{32} \text{ in} \ast 0.036 \frac{\text{lb}}{\text{in}^3} + 7 \text{ lbs} = 16.4 \text{ lbs}$$

$$W_3 = (SA \ast t \ast \rho) + 7 \text{ lbs} = 7,390 \text{ in}^2 \ast \frac{1}{32} \text{ in} \ast 0.036 \frac{\text{lb}}{\text{in}^3} + 7 \text{ lbs} = 15.1 \text{ lbs}$$

where $SA$ is the respective surface areas of the models, $t$ is the thickness of the carbon fiber, and
$\rho$ is the estimated density of the carbon fiber. The weight of Design 2 was not estimated due to the
wheel well CAD no accurate to what the fabricated geometry would be. As can be seen, Design 3
decreases the current weight of the body by over 33% and is lighter than Design 1 by 1 lb. This
reduction of about 9 lbs results in an overall vehicle weight decrease of 10% which will
significantly increase the vehicle’s efficiency. Thus, Design 3 is optimal compared to the current
body and the other monocoque designs when considering vehicle weight.

2.1.5 GROUND CLEARANCE

When designing a vehicle, another important consideration is the ground clearance, or distance
between the undercarriage of the vehicle to the ground. In most high-speed street racing vehicles,
the ground clearance should be minimized in order to reduce the amount of turbulence that will be
generated by the rough components of the undercarriage [16]. While this is the case for normal
road vehicles, the concept does not apply to prototype vehicles like the NIU Supermileage vehicle.
Due to the streamline body design of the vehicle, it is best to elevate the vehicle’s underbody and
increase the ground clearance due to the smooth nature of the body [16]. As seen in Figure 27
below, Design 3 has very little negative pressure under the vehicle when compared to Design 1.
The ground clearance implemented in Design 3 created a less restrictive path for air to travel, which is seen by the little to no negative pressure seen on the underbody. On the contrary, Design 1 has a large amount of negative pressure on the underbody which leads to negative lift and increased drag, both of which are not advantageous for an energy efficient vehicle [16].

2.1.6 WHEEL FAIRINGS

Wheel fairings are necessary features to cover a large portion of the rotating wheels on the vehicle. Similar to consumer vehicles, the rotating wheels cause significant drag by creating swirling vortices of air [17]. This preventable drag prompted the necessity of creating wheel fairings to cover the wheels to improve the aerodynamics of the vehicle. However, putting additional structures outside the main shell will lead to an increase of drag, so the fairing profile should be as efficient as possible. To do this, the wheel fairings in Design 1, shown below in Figure 28, mimic a teardrop/airfoil pattern with zero lift in either direction to avoid shearing forces outward or inward. It’s also critical to ensure that the front wheel fairings do not create swirling that would increase the drag caused by the rear fairing. Thus, Design 3 features a semi-elliptical profile that has minimal effect on air flow underneath the middle of the vehicle, and on the sides.
In addition to aerodynamics, an important design consideration for the front wheel fairings is being wide enough to accommodate the turning radius. However, since the gaps of the fairings act as a passage for air to “leak” into the body, it may be beneficial to components to seal off the gaps. The difficulty with sealing it is to prevent rubbing against the wheel as it rotates while the vehicle is in motion. Nonetheless, Design 3’s wheel fairing design still produces less drag and disturbance to the air flow than the wheel fairings in Design 1.

2.1.7 NOSE CONE

Another critical design feature of the vehicle design is the curvature of the nose cone. This curvature is directly responsible for how efficient the air flows around the front of the vehicle, as a large amount of the drag is dependent on the frontal area. Two main nose cone shapes are ellipsoid, like a Boeing 747, or ogive, like a rocket. At subsonic speeds, the ellipsoid is optimal with similar drag to ogive while being easier to fabricate [18]. Therefore, the three designs considered all included ellipsoid-shaped nose cones with different angles of curvature.
As seen above in Figure 29, the pressure contours vary significantly based on the curvature of the nose cone. Design 2 is more ogive-shaped with a point which leads to a larger spread of high pressure as compared to Designs 1 and 3. One of the largest differences between the designs is the maximum pressure caused at the front of the vehicle. Designs 1 and 2 have similar maximum pressures but the maximum pressure of Design 3 is about 50% that of the other designs. To verify the lower maximum pressure wasn’t simply an outlying value, additional pressure contours of Design 3 were analyzed from the side view and the 3D profile of the geometry, Figure 30.
2.1.8 TAIL DESIGN

In commercial vehicle aerodynamics, a vacuum is created in the rear of the vehicle as it moves through the air. The sharp geometries of the rear window and trunk result in the delamination of streamlines from the body, causing this vacuum where the air cannot fill quick enough. The forces caused by the rear vacuum are much larger than that created by the frontal pressure, resulting in more importance to optimize the tail design than the nose cone [19].

Figure 31: Side view pressure contour of Design 1 (top) and Design 3 (bottom)

When analyzing Design 1 in Figure 31, the tail design creates a considerable rear vacuum with a pressure difference of about 75% the maximum frontal pressure. That large pressure difference in turn causes a significant amount of drag force caused by the turbulence of the air as it delaminates from the streamlined body. While it may appear that Design 3 also has a rear vacuum, there is not actually a significant change between the frontal pressure and rear pressure. Thus, the tail design of Design 3 converges slow enough to prevent detachment of streamlines along the boundary surface of the body and avoiding the creation of a large rear vacuum.
2.2 PROTOTYPE

The main shape of the vehicle will be created using 3k 2x2 twill weave carbon fiber layered with a Lantor Soric XF matrix layer and infused with high strength infusion epoxy. The carbon fiber stack-up will be laid out in negative molds made of high-density foam. Figure 32 shows the bottom mold to be used for fabrication.

![Figure 32: Polyurethane foam fabrication of vehicle lower half (back and front view)](image)

There are five molds in total consisting of the top half, bottom half, two front wheel fairings, and the rear hatch. The mold is fabricated using a five-axis CNC router which allows for more intricate mold design. One of the more intricate details includes the lip and groove feature that is cut out of the top and bottom molds. It allows for flush mating of the top and bottom halves of the vehicle which increases ease of assembly and decreases overall aerodynamic drag. The lip and groove is possible to fabricate since the molds are designed to be split in half for the easy removal of the carbon fiber shell, otherwise the mold removal would be impossible for the cured parts. The molds also include indentations for wheel fairings and hatches to indicate the locations of where carbon fiber should be cut out. Indentations for Dzus clip (quarter turn quick release) fasteners is an additional feature that allows for the clips to be flush with the shell when the top
and bottom half are fastened together. This was designed through additional protrusions from the lip and groove feature.

The fabrication plan for the carbon fiber body uses a vacuum bagging, resin infusion process. In this process, a mold release wax is applied to the surface of the mold before the first layer of carbon fiber is placed. This allows for removal of the cured part without damaging the part surface. The first layer of carbon fiber is then placed in the mold, with care taken to ensure the material is smooth against the geometry of the mold. Before the second layer of carbon fiber is put into the stack-up, the critical structural areas of the body are reinforced with Lantor Soric XF matrix material to provide additional stiffness. Some examples of critical areas include near the mating lip and groove of the top/bottom bodies, around the mating surfaces between the wheel fairings and the bottom body, and near the mating surfaces of the rear hatch and top body. Once the Soric material is laid, the second layer of carbon fiber can be placed to finalize the stack-up for the body material. Finally, a layer of vacuum bag film and a layer of peel ply material need to be laid down on top of the carbon fiber. The peel ply needs to be laid in between the carbon fiber and the vacuum bag to ensure the part does not cure to the vacuum bag film. Another benefit of the peel ply is to absorb any excess resin that is pulled from the reservoir. The vacuum bag, which is the top-most layer, is sealed to the mold surface to allow for a vacuum to be pulled.

The most critical component of the vacuum infusion process is the ability to apply not only a vacuum to the material stack-up in the mold, but to also be able to pull resin from a reservoir through the carbon fiber material. In order to pull vacuum, a slitted tube is placed around the edge inside the vacuum bag. The numerous slits in the tube ensure that an equal vacuum is applied across the entirety of the mold. The entry of the tube into the vacuum bag is prone to leakage, so it is critical to ensure proper sealing around the tube. This tube is then attached to a vacuum pump which runs continuously throughout the resin curing process. Since equal resin infusion is dependent on a complete vacuum, a vacuum gauge is placed in series with the vacuum tube to measure the pressure. Another tube, which is connected to a reservoir of mixed resin, is placed inside the vacuum bag on the opposite side of the vacuum entry. This tube provides entry for resin to be pulled through the carbon fiber material. One of the primary benefits of the resin infusion process is to ensure equal distribution of resin throughout the part as compared to applying the resin by hand.
The strength of the carbon fiber body is dependent on the resin used as the composite matrix material. By itself, the two layers of carbon fiber are flimsy, similar to an everyday blanket. However, once the resin material hardens, the composite body becomes rigid. Therefore, a medium cure infusion epoxy from Composite Envisions was selected as the resin material for the body. This resin provides higher strength and an extended pot life of 120 minutes compared to the resin used by the team in the past which had a pot life of 30 minutes. The extended pot life is critical to prevent any hardening of the resin before the whole part is infused across the 11 ft length.

Once the vacuum pump has pulled enough resin to infuse the entire body, the entire setup is left alone for 24 hours. This wait time allows for the entirety of the resin in the part to cure. After fully cured, the vacuum bag and peel ply can be pulled off and the composite part is pulled from the mold.

The chassis fabrication of the prototype consists of panel stack ups using Nomex honeycomb and CNC machined Rohacell 31 IG-F, a high strength to weight ratio foam, adhered to the carbon fiber with 3M DP420 structural adhesive. The honeycomb structure consists of three ½” panels stacked (totaling 1.5”). The machined Rohacell foam perfectly matches the body’s curvature and allows for the honeycomb to be parallel to the ground. This allows for all mounted assemblies such as the steering, engine assembly, and firewall to be mounted safely. The machined foam is shown in Figure 33 below.

Figure 33: Foam for body stack up
The entire vehicle stack-up can be seen in Figure 34 in which the carbon fiber shell is cyan/transparent, with the machined foam in yellow and Nomex in red stacked on top.

Figure 34: Core material stack-up

An aluminum tubing roll hoop and firewall was also created to protect the driver from the engine and transmission systems. The firewall is created from 1/32” aluminum tubing welded to a 0.032” aluminum plate and mounting to the Nomex using three bolts. These bolts allow for easy removal if future modifications are needed. Cross bars are included for additional stiffness and provide mounting locations for the driver’s safety harness. This is shown in Figure 35 below.

Figure 35: Firewall and rollbar
Integrated in the roll-hoop design was the rear wheel mount. Aluminum tubing extends from the firewall to the rear wheel hub that allows for large vertical load provided by the rear wheel. This is shown in Figure 36 below.

![Figure 36: Rear wheel mount](image)

The aluminum extensions were designed in a way that still allow for simple removal and ease of access to the engine components. With this setup, the engine should be able to be removed without removing any of the cross beams.

In addition to the rear wheel mount, a front wheel mount will be integrated in the prototype. The front assembly includes seven components that are welded together and bolted to the Nomex. The use of gussets in the assembly allow for high vertical loads that take place in the front wheel area. This design is shown in Figure 37 below.

![Figure 37: Front wheel mount (left) | Full wheel assembly (right)](image)
All components will be attached to the Nomex panel through the use of custom 6061-T6 Aluminum potted inserts. These inserts are designed to allow for high strength epoxy to flow around them when inserted into the Nomex panel, creating an extremely durable mounting location that will use 3/8-24 UNF screws. The potted insert CAD can be seen in Figure 38 below.

Figure 38: Simulated epoxy (left) | Potted insert CAD (right)

The entire vehicle CAD can be seen in Figure 39 which includes the subassemblies and different views.

Figure 39: Isometric view (top left) | transparent side view (bottom left) | top view (right)
The turning radius was improved from 32 ft to 25 ft (20% improvement), the center of gravity is 2 inches lower than the old vehicle, the frontal cross-sectional area was reduced by 15%, the side cross-sectional area was reduced by 3%, the body weight was reduced by 28% and overall weight by 11%. Many features were added such as removable wheel fairings in case of damage, lip and groove mating features for all joining surfaces of the body, and a high level of modularity such that all internal subsystems can be redesigned if desired.

The overall vehicle redesign was successfully finished along with the desired outcomes including aerodynamic geometry improvement and weight reduction. While the mold timeline change did not allow for final fabrication of the vehicle during the semester, the team has prepared for final delivery of the molds and fabrication of the body after the conclusion of the senior design course. Future body fabrication will allow for confirmation of estimates.

3.0 REALISTIC CONSTRAINTS
3.1 ENGINEERING STANDARDS

When designing a highly fuel-efficient vehicle, there are not many engineering standards that directly apply when creating the external shell. Many databases can be referenced such as NACA airfoil designs or streamline body shapes, but few engineering standards can be applied with direct impact. Past work on the vehicle’s carbon fiber shell have addressed the ASTM D7264/D7264M-07 standard. These standards outline a test method for flexural properties of polymer matrix composite materials, which applies to the considerations that must be made when fabricating the body from carbon fiber and epoxy resin. While none of the standards were able to directly influence the initial designs of the vehicle, they can inform the fabrication process such that material can be saved by forgoing some experimental developments. The 2013 NIU Supermileage Team used the ASTM D7264/D7264M-07 standard to develop an experimental plan that described the optimal layering of carbon fiber based on the testing apparatus suggested by the standard. The recommendation made by the 2013 team will heavily influence the fabrication of the new body.

3.2 ECONOMIC CONSTRAINTS

The team has secured significant funding from Navistar International which includes mold materials, fabrication time, and other materials needed such as carbon fiber, rivnuts, and resins. The team also applied for and won the Enhance Your Education (EYE) Grant through the Honors
department. Through this award, the team had additional funding of $1,000. For these reasons, economic constraints are minimized for the project through the team’s proactive efforts.

3.3 ENVIRONMENTAL CONSTRAINTS

The operating environment of the vehicle should take place outdoors with little to no rain. The vehicle cannot operate in extreme conditions and should be operated in an ideal temperature of 80 °F or 27 °C (ambient/room temperature). Due to the vehicle design, the materials used and geometries of the vehicle do not allow for operation in rain as this can limit driver visibility in addition to decrease tire traction that can create safety issues.

3.4 SUSTAINABILITY CONSTRAINTS

The goal of the vehicle redesign is to reduce overall weight and is limited by the amount of the material that can be used to fabricate the design. By developing the body in a mindful way, the mold fabrication can be performed such that less waste is created. Furthermore, when the carbon fiber body is laid up within the mold, careful consideration will be made when determining the amount of carbon fiber used so that there is no excess waste.

3.5 MANUFACTURABILITY CONSTRAINTS

The redesign is constrained by the method of fabrication that the monocoque undergoes. Due to the organic shape of the vehicle, the fabrication constraints are driven by the operational ability of the mold fabrication machine. The limitations of the machine determine the ability to directly fabricate a negative mold to then lay carbon fiber. Further consideration is that the dimensions of the design are constrained by the maximum producible dimensions of the machinery (e.g., the body cannot be 10 feet long if the machine only has an operational range of 8 feet). These concerns were worked out with Navistar as all five molds were able to be produced on their CNC.

3.6 ETHICAL CONSTRAINTS

In order to abide by ethical concerns, the vehicle was fully designed by the students on the senior design team. While Navistar International has offered the help of some of their chief engineers, they are only allowed to assist the team with specific questions brought to them. This is also a requirement that was explicitly stated by the Society of Automotive Engineers Collegiate Design Series coordinators.

3.7 HEALTH and SAFETY CONSTRAINTS

The overall safety considerations are mandated by the Society of Automotive Engineers (SAE) Supermileage committee and the Shell Eco-Marathon 2021 chapter 1 and chapter 2 rules.
The redesign needs to meet the safety measures required in order to successfully complete technical inspection and compete in both competitions. These safety constraints range from vehicle size, firewall material, driver visibility, and allowable structural load at the roll hoop. The issue with these constraints by SAE and Shell is that the rules are updated every year such that a redesign of the vehicle will need to be considered in the future. The opportunity can be taken to predict possible rules and regulations that may be implemented so that future teams do not need to redesign the vehicle again.

Furthermore, limitations regarding component vibration is a constraint. The vehicle can be designed to be very lightweight initially, but structural mounting points for the subsystems need to be implemented throughout. Larger subsystems require high structural integrity to avoid damage to the carbon fiber through uncontrolled and undamped vibration.

3.8 SOCIAL CONSTRAINTS
Section not used.

3.9 POLITICAL CONSTRAINTS
Section not used.
4.0 SAFETY ISSUES

Much of the safety precautions taken and implemented in the vehicle redesign are outlined and mandated by competition rules such as SAE and Shell Eco Marathon. The mandated rules taken as safety precautions are shown in Table 1 found in Section 1.2.1, but for ease of viewability, the table can be found below in Table 2.

**Table 2: SEM vehicle dimension requirements [10]**

<table>
<thead>
<tr>
<th>Shell Eco-Marathon Vehicle Dimension Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. height: 1000 mm (39.37 in)</td>
</tr>
<tr>
<td>Min. track width: 500 mm (~20 in) [measured between tire midpoints of front wheels]</td>
</tr>
<tr>
<td>Min. wheelbase: 1000 mm (39.37 in) [front wheel axle to back wheel axle distance]</td>
</tr>
<tr>
<td>Height-to-track width ratio &lt; 1.25</td>
</tr>
<tr>
<td>Total width &lt; 1300 mm (51.18 in)</td>
</tr>
<tr>
<td>Max. length &lt; 3500 mm (~11.5 ft)</td>
</tr>
<tr>
<td>Max weight: 140 kg (~310 lbs)</td>
</tr>
</tbody>
</table>

The optimal design chosen (Design 3) has dimensions that conform to the required specifications for vehicle safety, including a nose crumple zone. The overall vehicle dimensions of the selected vehicle include a length of approximately 11 ft, a track width of approximately 22 inches and driver compartment average cross section of about 18 inches. All of these dimensions fall in the allowable dimensions of the rules.

Structural integrity of the vehicle will be addressed through the use of high strength materials in addition to carbon fiber. This includes the Nomex honeycomb which is to be used along the rollbar/firewall and along the bottom of the vehicle to support driver weight, steering assembly, and engine mounting. The firewall will be made of aluminum tubing and act as a roll bar in case of an accident and be able to withstand a force of 1100 N (250 lbf) per SAE structural guidelines.

The components will be directly mounted to the Nomex Honeycomb through the use of potted inserts and epoxy. An important safety component includes the proper mounting of the safety belts that will hold the driver in case of roll over. This is the primary component, apart from the helmet, that provides safety to the driver. Proper mounting locations of the 5-point harness will be used to ensure that it will not fail under load.
As previously mentioned, the vehicle should also operate within a safe environment. This includes clear days with limited to no rainfall for optimal driver visibility. Due to no ability for windshield wipers to be implemented, the vehicle should not be operated under harsh conditions.

5.0 IMPACT OF ENGINEERING SOLUTIONS

The primary goal of the vehicle design is to operate with high fuel efficiency. NIU Supermileage’s main focus has always been aerodynamics and weight reduction to produce an ultra fuel-efficient vehicle. In previous years, the vehicle has earned up to 1,888 miles per gallon (mpg) placing within the top three spots for ten consecutive years. The goal is to try new and innovative ways to improve fuel efficiency and stay competitive. This vehicle redesign and selection has decreased aerodynamic drag and sideload while also having weight reduction since rolling resistance is the biggest component in energy loss. The overall performance goal of the redesign is to achieve at least 2000 mpg, breaking previous NIU Supermileage records.

The techniques used to increase fuel efficiency of the Supermileage vehicle redesign are also applicable to current vehicle industries. The automotive industry has recently focused more on fuel economy of their vehicles along with improved aerodynamics. The focus of fuel efficiency is impactful to decreasing carbon emissions that is causing significant damage to the environment. Decreasing the amount of carbon emission that happen strictly from vehicle usage can have a large impact on overall carbon emissions per capita. This is why a vehicle redesign, in which the overall focus is to improve fuel efficiency, directly impacts the decrease of carbon emissions and betters the environment. Having a vehicle with this fuel efficiency will also have an economic impact. Oil industry prices are constantly increasing and creating financial burdens to own and continually use a vehicle. Owning a highly fuel-efficient vehicle can cause a decrease in the oil consumed and purchased, causing overall more affordability.
6.0 LIFE-LONG LEARNING

Senior Design allows for a various number of skills to be developed throughout the year, both individually and as a team. The carbon monocoque vehicle redesign gives the opportunity to highly develop technical skills that can better prepare students for industry. Already, 3D modeling skills have increased through the understanding of surface modeling. Knowledge of SolidWorks capabilities has increased rapidly and allowed for complicated surface modeling skills to be mastered to fully design such an organic shape. Other software techniques that have improved over the semester also include ANSYS Fluent simulation and how to properly mesh the vehicle for the most accurate simulation. This skill development was critical especially in vehicle selection and optimization. Current learning environment conditions due to COVID-19 have allowed for a focus on communication development as a team through an all-virtual environment. Online sharing platforms such as Microsoft Teams has been heavily used and allows for shared control of a person’s screen and real-time shared collaboration of the vehicle design. Slack is also used to share files and discuss items “offline” or when not in a video call. Project planning similar to an industry setting is implemented through the use of Microsoft Projects and shows task tracking through the year and project dependencies. Trello is also useful to the team in task tracking.

Collaboration with large industry partners such as Navistar allowed for the team to talk with multiple Senior Engineers who specialize in vehicle design, CAE (computer aided engineering), and fabrication. This helped in preparing for future in depth design discussions with upper-level engineers in future careers. The entire fabrication process will prepare the students to design for manufacturability and learn manufacturing techniques. The overall vehicle design requires mold design and fabrication technique development. Finally, the use of carbon fiber, Nomex honeycomb, and Soric will help to develop fabrication skills with the use of these specialized composite materials and how to properly fabricate the overall carbon fiber monocoque vehicle.
7.0 BUDGET AND TIMELINE

7.1 BUDGET

For this capstone project, the primary funds went towards the purchasing of carbon fiber, Nomex honeycomb, soric matrix strengthener, and resins used to fabricate the vehicle body. The NIU Supermileage Team has already led a successful funding proposal from Navistar who is willing to donate shop time on their 10 ft x 10 ft 5-axis CNC, expertise on layup mold fabrication, mold materials such as HDPE foam, and additional funding necessary to complete the project. The funding has been confirmed and the vehicle designs were finalized with Navistar International. Below is a table that lists the materials needed with given descriptions and associated costs. The material requested were enough to fabricate two bodies in case of fabrication issues with the first attempt. If the first body is successful, the team will consider fabricating two bodies such that both the internal combustion engine (ICE) vehicle and battery-electric vehicle (EV) can have a carbon fiber monocoque chassis. An estimate of cost can be seen in Table 3 below.

Table 3: Budget for carbon fiber monocoque chassis

<table>
<thead>
<tr>
<th>NIU Supermileage Capstone - Carbon Fiber Monocoque Chassis Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product</strong></td>
</tr>
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<td>Mold foam (HDPE)</td>
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<tr>
<td>Carbon Fiber Weave</td>
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<tr>
<td>Soric strengthening matrix</td>
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<tr>
<td>Nomex Honeycomb core (flex sheet)</td>
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<td>Nomex HC core laminate</td>
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<tr>
<td>Epoxy resin and hardener</td>
</tr>
<tr>
<td>Miscellaneous</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

The carbon fiber weave of 60” twill (2x2 3k) is the main fabrication layer used to create the monocoque vehicle. The required yardage is due to the carbon fiber being laid across an approximate 3 ft x 3 ft x 10 ft surface in multiple layers. Furthermore, this adds significant buffer room as the 3 ft x 3 ft x 10 ft does not account for the curvature of the body. The following Nomex honeycomb and soric strengthening matrix will be used as layers between the different carbon fiber layers. The varying sizes of the honeycomb are dependent upon placement within
the monocoque design. Epoxy resin, hardener, and miscellaneous are all the varying components necessary to fabricate the carbon fiber monocoque chassis.

7.2 TIMELINE

The entire schedule was compiled into one Gantt chart to allow for visualization of the Senior Design timeline shown in Figure 40 below.

![Gantt chart for project tracking](image)

The start of the semester began by preparing for a technical presentation and overview of the project to present to Navistar for funding. The early budget proposal to the company would allow for understanding of the entire project budget that can be applied. While budgeting was being secured, the initial design process began. The process to begin the first design was dependent upon the set specifications determined by the team, dimensions of current subsystems, and initial review of other team designs. The preliminary three vehicle designs began on October 12th, 2020 and lasted through early November before the designs were completed. From the three alternative designs, the optimal design was found to be Design 3. ANSYS Fluent simulations were used over the course of the semester to find the most optimal design for final fabrication. Design reviews will begin with faculty advisors, Supermileage sponsors, and Supermileage alumni over winter break. Once the design is reviewed and finalized, the fabrication process will begin. The
scheduling is planned be based upon the availability that Supermileage’s sponsor can provide on their CNC machine in order to machine the mold that will be used for carbon fiber fabrication. After the mold is fabricated, the different fastening systems and subsystems can be installed in the vehicle. Testing will then commence as the team prepares for the use of the vehicle in competition. Overall, most of the tasks are dependent upon the completion of the previous tasks. This allows for prioritizing specific tasks over another to accomplish the overall project goal. Some of the major milestones to note from the Gantt chart is the competition of the three vehicle designs, optimal design chosen, and fabrication of the vehicle.

8.0 TEAM MEMBERS CONTRIBUTIONS TO THE PROJECT

8.1 TEAM MEMBER 1

Lauren Bangert’s project contributions included work on the preliminary design choices. She worked individually to create Design 2, which involved the understanding of solid body loft modeling in SolidWorks with the use of cross-sectional sketch lines provided from PAC-Car II top and side view photos. She also worked alongside Matt to create Design 3, which was the optimal design for the project and will continue to work on model finalization. Due to the change in vehicle geometry, the steering was also required to be redesigned. She worked to CAD these internal components so they could be used to help finalize dimension of the optimal Design 3.

8.2 TEAM MEMBER 2

Todd Durham’s project contributions included much of the optimal design justification. He learned how to properly use ANSYS Fluent for CFD simulations of all three design iterations to determine the optimal design. On top of that he also was able to calculate the individual weights of the vehicles and their respective drag coefficients. This included intensive research on boundary conditions and other Fluent simulation procedures.

8.3 TEAM MEMBER 3

Matt McCoy’s project contributions involved much of the preliminary design choices in addition to performing the optimal design selection with Lauren and Todd. He individually was able to recreate old CAD from the original Supermileage vehicle using a surface modeling method in SolidWorks to create Design 1. In addition to this, he also worked with Lauren to create Design 3. This used the same surface modeling method along with knitting together the individual surfaces to form a solid body. He also aided Todd in Fluent simulations with both understating and discussion. Matt was the team leader for the project and also led the Navistar funding securement.
8.4 TEAM ALL

Although not a required selection, a note on overall contribution by the team as a whole should be considered. The team worked well together aiding each other on specific processes whether it be calculations, simulation methods, design methods, etc. The reports were completed together from start to finish, along with proper corrections on each report. Although different individual tasks were assigned, the team still had input on each other’s individual tasks to work together. In-depth team discussions and presentations took place, including funding proposal and confirmation from Navistar International, design discussions, optimization discussions, and fabrication discussions.

9.0 CONCLUSION

At the start of the fall semester, the team took on a project that had been a discussion point within the NIU Supermileage team for many years. The overall goal was to replace the original 10-year-old design that is comprised of an aluminum tubing frame with a carbon fiber shell. The goal was to replace it with a carbon fiber monocoque body, all while abiding by the rules mandated by SAE and the Shell Eco-Marathon. This body design change would also improve the vehicle’s aerodynamics and reduce weight. Understanding the cost, material, and advanced fabrication methods that would be required to complete this goal, the team presented the project to Navistar International for funding and fabrication assistance. The team secured funding from Navistar in the form of in-kind and monetary support. The overall goal of the project was to complete a design by the beginning of January 2021 for Navistar to begin mold fabrication for the vehicle. These goals were met. In spite of many unexpected delays, the molds are being fabricated by Navistar and the team will be able to fabricate the carbon fiber chassis in the summer of 2021.

The team initially designed three variations of carbon fiber monocoque designs that were modeled using SolidWorks by employing surface modeling techniques to create smooth, streamlined geometry. Limiting, but very important, constraints in the design process that were considered include operational environment, manufacturability, health and safety of the driver, etc. The optimal design selection process used ANSYS Fluent simulations to determine each alternative designs’ aerodynamic characteristics including pressure fields and drag. Design 3 was ultimately selected as the optimal design based upon the dimensions that would properly fit the subcomponents, the overall reduction in weight of the vehicle, and its drag coefficient. The design was then modified to be fully fabricable. Mold fabrication began by Navistar by using a 5-axis
CNC mill to cut the negative shape of the vehicle out of high-density foam. The high-density foam mold will then used to lay carbon fiber twill weave and sandwich Nomex honeycomb core and Soric material to provide more rigidity to the carbon fiber body of the vehicle.

After the vehicle’s fabrication, the subcomponents of the previous vehicle can be installed, thus completing the overall goal of designing and fabricating a carbon fiber monocoque body for the NIU Supermileage vehicle.

8.4 TODD DURHAM’S HONORS CAPSTONE EXPERIENCE

Over the course of this Honors capstone project, the team accomplished tasks together while maximizing efficiency by acknowledging each team member’s strengths and weaknesses. Due to my limited experience in static FEA simulations, I eagerly accepted the challenge to learn how to conduct simulations in Ansys Fluent to determine the aerodynamic properties of the overall vehicle body design. Another reason that I felt prepared to take on this challenge was because my desktop computer provided the most computational power available to group. The results of the simulations enabled the team to optimize critical geometries to decrease aerodynamic drag and reduce pressure differentials around the vehicle’s front and rear areas. Overall, the major accomplishment from the fall semester was the creation and optimization of the exterior vehicle design.

This led to the spring semester focusing on modifications for manufacturability of the body and the design of internal subassemblies to mount the rest of the vehicle’s components, such as the engine, wheels, and driver safety mechanisms. My primary contributions during the spring semester included splitting the vehicle CAD to allow for separation of the wheel fairings from the lower body before sending the model to Navistar, creating a procedure for evaluating which density of foam core to purchase, and designing the firewall, rollbar, and rear wheel mounting subassemblies. These contributions helped pave the groundwork for the future Supermileage team to fabricate this vehicle body once the molds have been received from Navistar.

The Honors capstone experience has given me additional experience on working as a team to accomplish what seemed like an impossible task at first. The team entered this year with little knowledge how to fabricate carbon fiber, mold design, or aerodynamic design. However, we persevered and approached those that we knew may be able to help us learn more about topics that
we had limited knowledge. I would like to thank my teammates Lauren Bangert and Matthew McCoy for making this capstone project be one that I will remember for the rest of my life.

10.0 REFERENCES


11.0 ACKNOWLEDGMENTS

The team would like to thank the project advisors Dr. Nicholas Pohlman and Dr. David Schroeder for their continued support throughout the semester in design guidance and advice as the project progressed.

We would also like to thank Mash Angolkar and Mitchel O’Day from Navistar International, as they generously provided their time to help secure significant monetary and in-kind sponsorship from Navistar. This project would not be possible without the financial assistance and expertise provided by Navistar. Jaimi Smith was instrumental in refinishing the surface model and ensuring the vehicle molds could be fabricated with the desired design. Chris Sorich and Bill Popek were critical in fabricating the molds. There are many others at Navistar International in both the Lisle and Melrose Park facilities that helped in this endeavor.

The Honors Program also helped fund the senior design project through the Enhance Your Education (EYE) Grant with funds of $981.89. These funds helped the team purchase many of the fabrication materials for the vehicle including the foam used for machining and epoxy.

Additionally, the team would like to thank Joey Cross and members of the 2013 NIU Supermileage Team as they provided critical information that allowed the team to compare their new design to past designs employed by the Supermileage Team, in addition to understanding some of the experimental carbon fiber tests that were performed previously.

Finally, the team would like to thank Thomas Corbett and Josh Helsper for their assistance in design consultation and ANSYS Fluent support.
12.0 APPENDIX
12.1 UPDATED SPECIFICATIONS

OPERATIONAL SPECIFICATIONS

Environmental:
- Operating Environment: Outdoors (no rain)
- Ideal Temperature: > 80°F or 27°C (ambient)

Safety:
- Should not exceed 40 mph due to vibrations

TECHNICAL SPECIFICATIONS

Physical:
- Material:
  - 2x2 3k twill weave carbon fiber roll
  - 1.5” Nomex honeycomb core
  - Soric strengthening matrix
  - Infusion Epoxy for body
  - 3M DP420 structural adhesive epoxy
  - Rohacell 31 IG-F Foam
  - High Density Polyurethane Foam
  - Rivnuts and potted inserts for fastening

Mechanical:
- Width: < 3500 mm
- Length: 2800 mm < 3500 mm
- Weight: < 140 kg
- Height-to-width ratio: < 1.25
- Min. Allowable Force: 1100 N

Software:
- Modeling:
  - Dynamic Tessellation Software
  - Fluid Simulation Software
  - Parametric CAD Software
- User Interfaces:
  - Keyboard, mouse
- Hardware Interfaces:
  - Monitor, DAQ
- Comm. Protocols:
  - Wi-Fi, Ethernet
- Software Features:
  - IGES, STEP, SLDPRT, ASSMBLY, Parasolid ($x_1$)
- Computer Requirements:
  - Operating System: Microsoft Windows 10, 8 or macOS X
  - Processor: Intel Core i5 or equivalent
  - Memory: > 8 GB RAM

Safety:
- Limited visibility is of concern
- Only restraints are by seatbelt; there are no airbags

Maintenance:
- Ensuring the carbon fiber is intact and embedded sensors are functioning properly