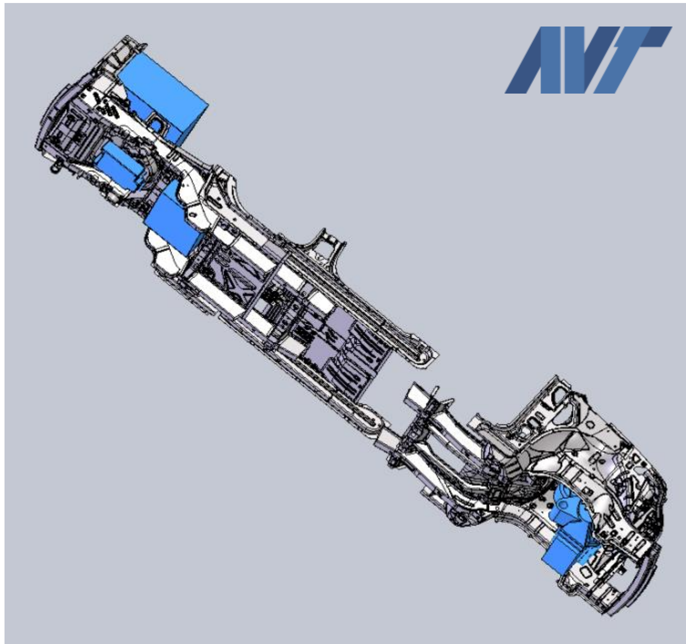
Universal Powertrain

Penn State AVT, Heart of Gold, Universal Powertrain Final Report



12/13/2019

Ali Kazmi	Svk5805@psu.edu	929-354-6188
Jason Gaydos	Jwg5671@psu.edu	484-947-3761
Alex Moore	Ajm6921@psu.edu	484-274-9091
Nicholas Osmond	Nro5034@psu.edu	412-538-7112
Ju Young (James) Park	Jzp5714@psu.edu	415-463-9930
Muzhi (David) Na	Mfn5074@psu.edu	814-862-8960

Executive Summary

The Universal Powertrain team had been tasked with developing a powertrain to meet the customer needs of Penn State's AVT team in order to succeed at any future competitions. Since the team did not know what the next competition vehicle is going to be, the specifications of the powertrain must be compatible with a wide range of vehicles. Through initial market research, the team decided that a crossover SUV would be the most appropriate vehicle to design the powertrain around.

The Universal Powertrain Team started with conducting initial market research to determine the target specifications of the powertrain design. With the specifications and customer needs determined, the team was able to select the hybrid configuration that would be used in the powertrain which is a P2 Parallel configuration. Once the powertrain configuration was selected, the team used various AHP and Pugh concept scoring matrices to select the components that would be used in the powertrain. These components include the internal combustion engine, fuel type, electric motor, motor controller, and battery storage system. After the components were selected, each component was modeled in CAD and placed in a full vehicle model to determine the packaging configuration. An adapter plate and belt linkage were modeled to connect the electric motor to the drivetrain in addition to a battery box to house the battery storage components. The team also used Solidworks FEA to simulate the loading and fatigue life of the spline shaft of the powertrain. A manufacturing plan and material selection of the components was completed to ensure the future teams could produce the necessary components. In addition, a Simulink model was made in which the specifications of the powertrain were input and various drive cycles were tested to determine the performance of the vehicle. These performance results were then compared to the customer needs and technical specifications that were determined at the beginning of the project.

In addition to the design and technical details, the Universal Powertrain team was able to keep track of the team's progress throughout the semester with a detailed Gantt chart to ensure the completion of the team's deliverables. A risk plan was also used to analyze any potential conflicts or safety concerns that the team could face throughout the semester. Finally, a cost analysis and bill of materials was completed to make sure the team stayed within the project's $50,000 budget.

Table of Contents

1.0 Introduction

According to the Energy Information Association, over the next 30 years vehicle driven miles will increase while fuel consumption will decrease over the same period (U.S. Energy Information Administration, 2019). This fuel decrease will only be possible through the creation of more efficient vehicles which has led to the current industry focus on hybrid and electric transportation. In addition, crossover SUVs are expected to become increasingly popular and be the focus of efficiency-driven vehicle competitions such as EcoCAR. These facts led the Universal Powertrain team to work on developing a high-efficiency powertrain for use on a future, unknown crossover SUV for the next Advanced Vehicle Team (AVT) competition.

The EcoCAR competition focuses on several areas including vehicle performance in terms of handling and acceleration, consumer acceptability, and vehicle efficiency over a range of conditions and drive cycles. This team is using the EcoCAR 3 competition rules and market research of automotive trends as the basis of the technical specifications. The goals of this report are to identify key powertrain components to be used, how those components will be packaged in the vehicle, and the expected performance characteristics of the vehicle. Due to the team not having a physical vehicle or available components, all testing was done virtually through software such as MATLAB Simulink and SolidWorks.

The specific project plan and timeline is detailed in Section 6.1, however many of the steps followed a similar design process. Background research was conducted to gain a basic understanding of the topic or component. Important metrics were then created and assessed to determine relative weights. Several concepts were generated or researched from existing products. These concepts were then scored against each other to determine the highest ranked option. Following selection, validation was performed to ensure that the system would function together as a whole and no components chosen were incompatible with any other decisions or components made.

The project required no direct manufacturing at this stage. However, after modeling efforts the Universal Powertrain team laid out the manufacturing process that future groups should follow to physically create the different parts of the powertrain. Most parts requiring manufacturing are custom mounts, needed to mate the selected components into a vehicle body that is not designed for them, with the only large pieces requiring custom fabrication being the energy storage system case and the electric motor's adapter plate.

The final powertrain was tested using a virtual model, designed in MATLAB Simulink, that ran the components through drive cycles outlined by the EPA. The EPA provides an example each of city driving and highway driving, and these were imported into the model to generate miles per gallon estimates. On top of the EPA drive cycles, the team generated a custom drive cycle in State College, PA that included both urban and highway driving. This custom drive cycle was used to validate the typical efficiency results a consumer would observe.

The customer needs and related specification categories provided the basis of the project. The team was able to determine quantifiable metrics that each component needed to comply with, as well as an optimal reach goal to aim for to exceed specifications. Many of the customer needs dealt with items pertaining to the combined weight of the vehicle, performance that would be expected from the vehicle, and total cost of the vehicle. Using these metrics, the team was able to weigh metrics for each component subsystem and conduct research accordingly.

The project utilized a Gantt chart to lay out scheduling and task responsibilities, and careful monitoring and updating of the chart proved to be an invaluable tool in combination with the team's risk plan when dealing with delays caused by team scheduling conflicts or companies delivering quotes weeks after the initial request. The team's risk plan outlines possible risks and ways the team could avoid possible conflicts throughout the semester and in the team's future.

2.0 Detailed Design

In order to provide the Penn State Advanced Vehicle Team with a competition vehicle for the next EcoCar as well as prepare for projected industry trends, the Universal Powertrain team was tasked with designing a full hybrid powertrain to fit into a crossover SUV. The "Universal" nature of the powertrain comes from the prediction rather than exact selection of a vehicle, and as such the powertrain needed to be designed to fit or be adaptable in a wide range of SUVs.

Beginning with research into each component necessary for the powertrain, the team used AHP and Pugh concept selection matrices to weigh multiple possible options and narrow down on a final component in each section: engine, motor, motor controller, energy storage system, fuel, and packaging. Once each component was selected, each one was modeled separately in Solidworks, assembled into the electrical and combustion assemblies, and then fitted into a CAD model of a Chevy Equinox, chosen for its small size for a crossover SUV. This ensured that all components would fit in any SUV larger than the Equinox and validated all packaging decisions made during component assembly. A virtual model of the powertrain and body was simulated in MATLAB Simulink to generate estimated performance specifications such as 0-60mph acceleration time, miles per gallon, and total torque outputted by the system. Utilizing some of these specifications, a model of the spline shaft, identified as a common failure point in previous vehicles, was run through Solidworks FEA to ensure that the material chosen to fabricate the part would be able to withstand all forces.

2.1 Design Features and Relation to Technical Specifications

While designing the powertrain, there were many technical specifications and design features in which the Universal Powertrain team wished to accomplish. Like any hybrid vehicle, the design goals were to maximum fuel efficiency and range while reducing the amount of energy used and the greenhouse gas emissions. In addition to fuel economy, the team strived to design a powertrain that also has respectable vehicle dynamic performance parameters such as 0-60mph time, stopping distance, and handling. To do this, the team chose designs that produced enough power, were lightweight, and could package in a way that would reduce the vehicle’s center of gravity. Another important aspect of packaging was to maximize storage space and interior space to increase the vehicles capacity and customer satisfaction. The specific customer needs and vehicle technical specifications are discussed in greater detail in sections 3.0 and 4.0 respectively.

2.2 CAD Models and Drawings

For the final steps in the design of the Universal Powertrain the individual components were modeled in CAD in order to ensure the powertrain could work as a system. The components that were modeled include the electric motor, motor controller, battery modules, fuel tank, engine, adapter plate, and belt linkage. These components were then assembled into a full vehicle model to verify the system could package into a crossover SUV.

Unlike the other components, the electric motor and motor controller were both modeled using engineering drawings that were supplied by the manufacture which produced very accurate CAD models. The electric motor and motor controller CAD models can be seen in Figure 1.

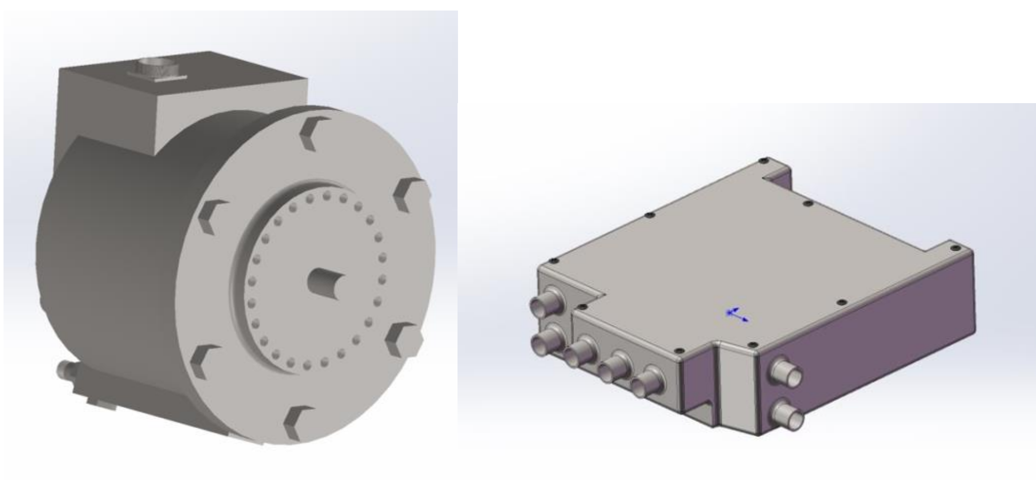


Figure 1: Remy Motor (left) and Dana Motor Controller (right)

The fuel selected for this powertrain is ethanol, and which has lower emissions than gasoline but is only about 70% as energy dense. Because of this, a larger ten-gallon tank, seen in Figure 2, needed to be created to hold an equivalent amount of energy to what would have been a smaller gasoline tank. The tank was also designed to be able to be rapidly detached and attached during competition. As per the EcoCar format, the fuel tank needs to be taken off of the car and replaced onto the car during weighing in a span of thirty minutes.

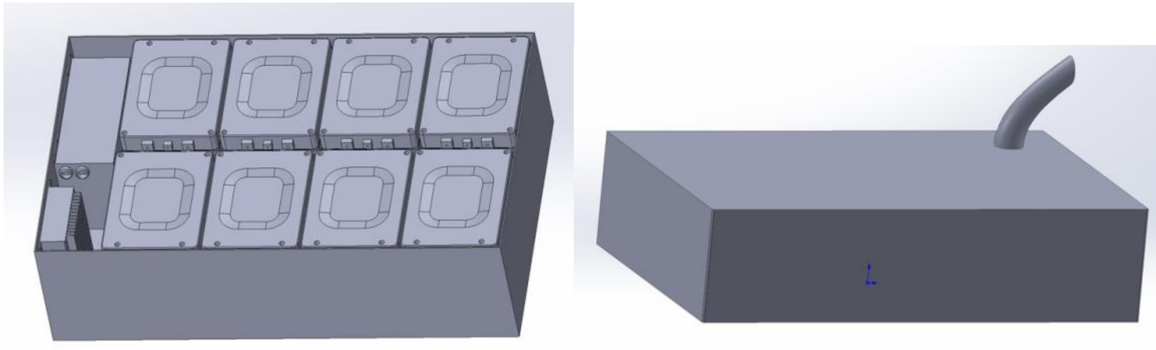


Figure 2: Nissan Leaf Modules (left) and Fuel Tank (right)

Due to previous year's point losses in the customer score portion of grading during competition, the first approach for the location of the battery pack was anywhere but the trunk, as that was the location that previous teams had placed battery packs. The trunk was identified as the best location for the battery and the effort shifted into potential ways to retain customer usability while still using the trunk. Seen in Figure 2, the case was oriented to use as much of the width of the trunk as possible, and as little of the height, allowing the customer to place objects on top of the battery. The high voltage connections of the battery's Nissan leaf modules are kept towards the center, where the individual modules are easier to bus bar together and less likely to short out against the sides of the case in the event of an accident or damage to the case. Not pictured in the CAD design are a pair of static pressure fans that would be placed on the outside of the case in locations deemed unobtrusive to the rest of the trunk to push air through the case and cool the components inside.

The CAD model that was used for the internal combustion engine, shown in Figure 3, is a previous model of the GM LTG engine which is a 2.0L turbocharged engine. The reason this model was used in the packaging assembly was because the team was unable to find a model of the GM LFV engine. The team determined that the LTG modeled would be the closest representation of the LFV engine based on what was available. The linkage between the electric motor and the drivetrain required an adapter plate to be designed which was based off the bell housing shape of the LTG engine. A mock transaxle was also modeled from the general shape of the GM 10 speed transmission to estimate the packaging constraints within the engine bay. The linkage between the electric motor and the input shaft of the transmission consists of two gears, a tensioner, and a high strength rubber belt which can be seen in Figure 3. These components will most likely need to be custom made which will be discussed in further detail in section 3.0.

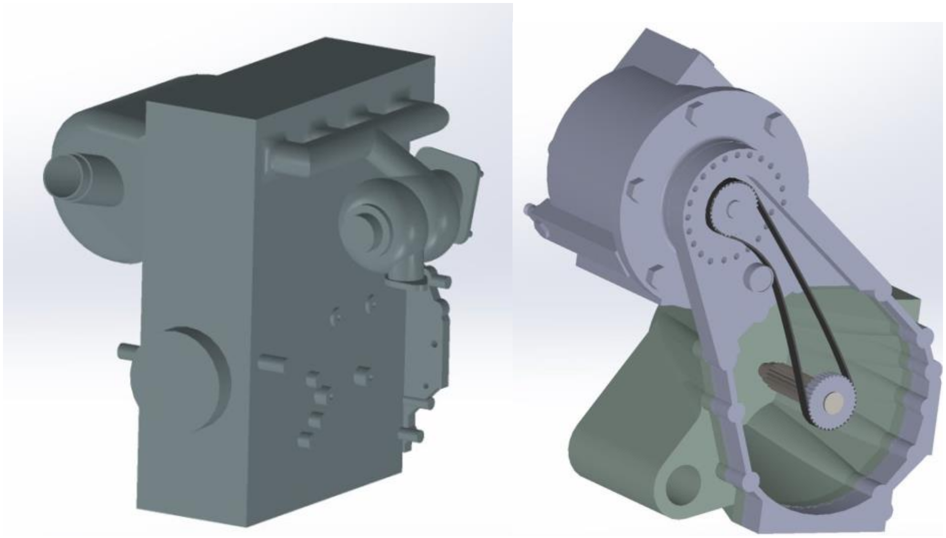


Figure 3: Internal Combustion Engine Model and Electric Motor Belt Linkage

Prior to designing packaging components for Universal Powertrain, an AHP matrix was generated and referenced for making packaging design decisions. Table 1 shows the AHP matrix for designing packaging components.

Table 1: AHP Matrix of Packaging Component Design Methodology

		Metrics						
		Simplicity to Manufacture	**Cost**	**Size/packaging**	**Weight**	**Adaptability**	**Total**	**Weight**
Metrics	**Simplicity to Manufacture**		**0.5**	**0.8**	**0.7**	**0.5**	**2.5**	**10.9%**
	Cost	**2.0**		**1.0**	**1.5**	**0.5**	**5.0**	**22.3%**
	Size/packaging	**1.3**	**1.0**		**2.0**	**1.0**	**5.3**	**23.8%**
	Weight	**1.4**	**0.7**	**0.5**		**1.3**	**3.8**	**17.1%**
	Adaptability	**2.0**	**2.0**	**1.0**	**0.8**		**5.8**	**25.9%**
						Sum	**22.4**	**100%**

In order to assure the adaptability of components that the team modeled to fit into any vehicle, the Universal Powertrain team chose a Chevrolet Equinox chassis to ensure the powertrain could fit in the smallest SUV model the team had access to. Under the hood, the engine and transaxle were mounted transversely in the engine bay with the adapter plate and electric motor mounted in parallel. The battery modules, battery control module, and battery box were placed in the trunk of the vehicle. The motor controller and fuel tank were mounted beneath the vehicle in order to lower the center of gravity and to ensure enough surface area for heat transfer to the motor controller. Multiple views of the full vehicle model can be seen in Figure 4.

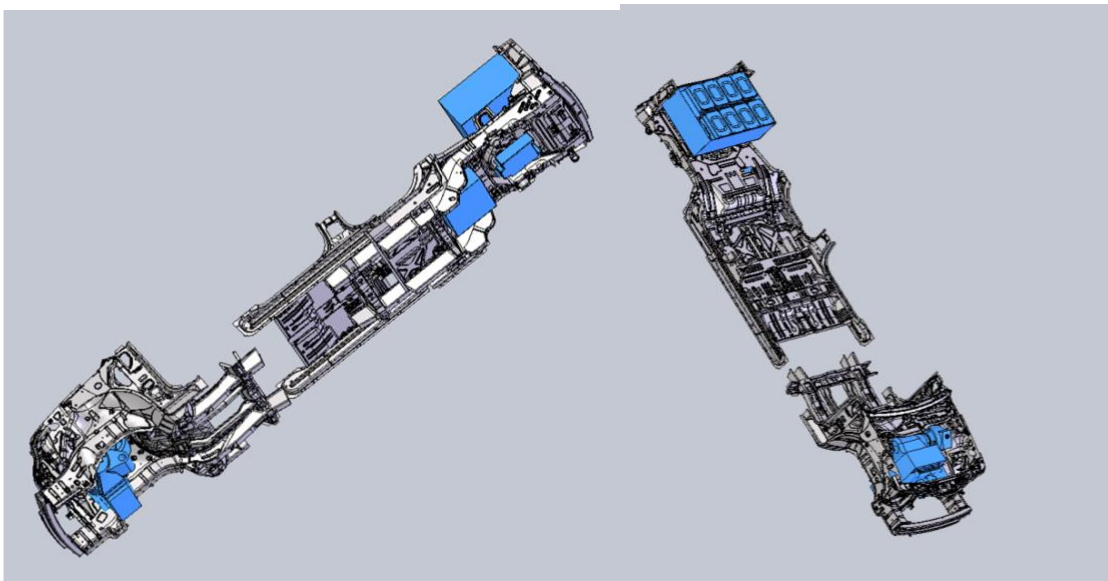


Figure 4: Full Vehicle Packaging Model

2.3 Material and Material Selection Process

Although the Universal Powertrain project will incorporate many commercially available components, several portions of the powertrain will need to be manufactured and assembled by the AVT. The selection of these components' material is important to ensuring that the component will be functional, long lasting, lightweight and cost effective

Packaging components had been made to assemble and operate with main powertrain components while universally ensuring the fit inside smaller sized chassis. The Universal Powertrain team has designed a spline shaft, gas tank, and adapter plate that will need to be manufactured from a specific material.

For the spline shaft, materials that can withstand high cyclic loading are steel and titanium. Materials like aluminium and carbon fiber would non-ideal for the torque spikes that the shaft would see. Considering the cost of the manufacturing, a high yield steel was chosen which is a highly resilient material that can withstand the loads and fatigue that the shaft with see during its life cycle. Considering the metrics determined in the packaging AHP matrix, AISI 4340 steel was chosen for the shaft. FEA analysis of the shaft will be further discussed in section 2.5.

The gas tank is to be constructed of a material that is weldable and can be formed into the required shape. A possible option is to use 3003 aluminium for the body of the fuel tank. The aluminium, or any other material chosen, should be anodized or have corrosion resistance due to E85's affinity for water and the fact that fuel may be sitting in the tank for long periods of time during maintenance and testing.

The adapter plate will be constructed out of 6061 aluminium which is a compromise between being cheap, lightweight, and strong. Aluminium was chosen over steel due to the weight of steel which would nearly double the mass of the components. Titanium could be used which is lighter than steel and stronger than aluminium, but the cost of titanium is much higher. The machineability of aluminium is much better than steel or titanium so the manufacturing cost of making the component would also be reduced.

One of the primary deliverables of the Universal Powertrain project is a CAD model of how the components would fit together in a hypothetical vehicle. In order to demonstrate the expected orientation, a 3D print of the components was created using Polylactic Acid (PLA) plastic. PLA was chosen because PLA is commonly used for prototype 3D prints and was readily available to the team at little cost. The prototype of the engine-motor-transmission assembly can be seen in Figure 5.

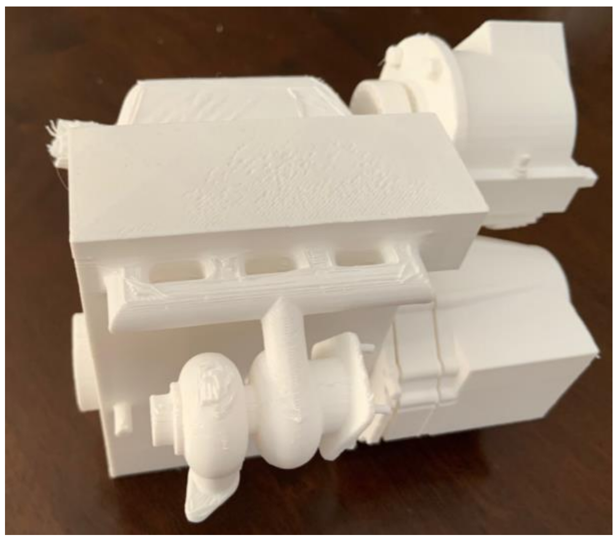


Figure 5: 3D Printed PLA Powertrain Model

2.4 Component and Component Selection Process

This section outlines the decision-making process of the 2019 Universal Powertrain Team. The purpose of this section is to expedite the process of designing and installing a more efficient powertrain system into a future competition car. This section details the top component choices for several different powertrain subsystems: the engine, fuel type, electric motor, batteries, motor controller, and key packaging parts. Each team member was assigned a different component of the powertrain that was deemed critical to the overall success of the powertrain. The process of component selection started with initial research to generate AHP matrices, which were then used to compare and prioritize the metrics that guided each design decision. Weighting criteria from the AHP was used to score the list of components to generate a Pugh scoring matrix. Later the team selected parts by examining the components at the overall powertrain system level. Components were specifically chosen for use in a small-sized crossover SUV with a P2 parallel hybrid powertrain designed for use in a competition similar to EcoCAR 3. If a different vehicle is used, or a future group decides to work with a different type of powertrain, the components listed below may not be optimal selections and should be re-evaluated.

2.4.1 Powertrain Configuration

Before making any selections of specific components for the Universal Powertrain, the powertrain configuration had to be decided. The first step in this process was researching the market to determine the customer needs and specifications which are explained in more detail in section 4.0. Additionally, the team researched various powertrain configuration which included fully electric, power split, series, parallel, and through the road hybrid systems. An AHP matrix, which can be found in Table A 1 in Appendix A, was made to determine the weights of the metrics in which the configurations would be scored. Afterwards, a Pugh concepts scoring matrix, found in Table A 2 in Appendix A, was used to choose the Parallel hybrid configuration. There are various configurations of the Parallel powertrain in which the team had to narrow down even further.

There are many different configurations of the Parallel hybrid systems which depend on the location of the electric motor. In a P0 configuration the electric motor is before the engine and is typically connected via gears or pulleys. This layout is typically the easiest motor configuration to install but poses packaging concerns in the engine bay. In a P1 configuration, the electric motor is connected directly to the front of the crankshaft between the engine and transmission. The P2 configuration connects the motor to the input shaft of the transmission and is coupled so that the motor will move at the same speed of the engine unless gears or belts alter the speed. A diagram of a P2 hybrid configuration can be seen in Figure 6.

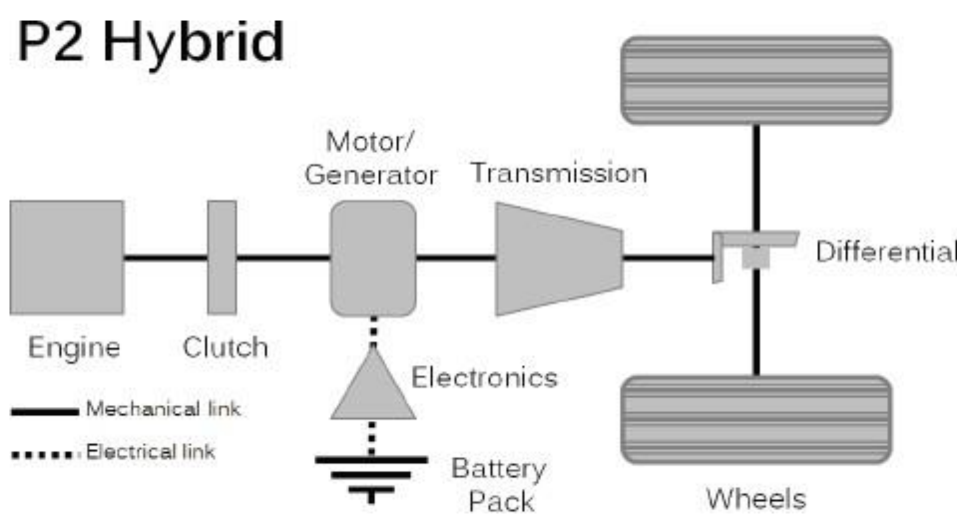


Figure 6: P2 Hybrid Configuration (National Academies Press, 2015)

A P3 configuration consists of an electric motor that is integrated in the transmission of the vehicle. The P3 is a very complex configuration which consists of an expensive transmission or transaxle so it most likely not feasible for the team. Lastly, the P4 configuration is connected to the rear axle or differential of the car and is typically an all-wheel drive (AWD) or rear wheel drive (RWD) vehicle. The P4 configuration is the most efficient parallel systems since the motor is connected to the least number of rotational components. However, since the team does not know what the next competition vehicle will be and most vehicles are front wheel drive (FWD), this configuration is not ideal. To select which Parallel configuration to use, the team created an additional Pugh Concept scoring matrix which can be found in Table A 3 in Appendix A that led to the decision to use the P2 hybrid configuration.

2.4.2 Energy Storage System

To provide power for the motor, the vehicle needs some form of ESS (Energy Storage System). The ESS research and analysis involved investigation into both premade, fully packaged battery systems and secondhand modules to be constructed into student-built battery systems. ESS research and analysis included AHP and Pugh concept matrices for cell chemistry, chargers, battery management systems, and the final modules built into packs. The selected ESS consists of Nissan Leaf Modules, an Orion 2 BMS and a Manzanita Micro PFC20-XM charger.

When all options were weighed together, the Nissan Leaf based battery pack scored best because the modules cost the least and performed well in all other categories, providing plenty of current, ample capacity, and enough voltage to power the Remy motor. The scoring matrix to select this pack can be seen in Table A 5 in Appendix A, and the metrics that informed the matrix can be seen in Table A 4 in Appendix A. The only downside to the modules is the battery cells' possible age, as these modules are sourced from cars that already used them. This aging could lead to degraded performance, and the team should ensure prior to purchasing modules that there is an adequate margin to the end of the batteries' lifespans. A bonus not considered by the scoring matrix is safety, modularity, and complexity of assembly. Since the modules are designed to be bus barred together using standard bolts and bus bars instead of soldering or spot welding, the assembly should be much easier for future teams, as well as safer. Connections can be secured and easily checked for completeness.

When fully assembled into a pack, all modules will be placed flat into stacks six modules high, and with the contacts turned inwards. The height of the pack should allow the maximum amount of points to be saved in the customer opinions section and the choice to turn all contacts inwards was made to ensure safety and reduce energy losses when connecting modules into a full pack. In the event of damage to the case, the dented in side panels would contact the structural shell of the modules rather than the bus bars and high voltage connections, limiting risk of harming anyone in the vehicle.

2.4.3 Internal Combustion Engine

In every hybrid electric vehicle there is an internal combustion engine which turns chemical energy into rotational kinetic energy via combustion. For the Universal Powertrain design, a P2 parallel configuration will be used which means the internal combustion engine provides power directly to the drivetrain unlike a series hybrid configuration where the engine powers a generator. There are a wide range of internal combustion engines used in vehicles today and there many factors that went into choosing the best engine for the Advanced Vehicle Team's application.

Before deciding on a specific engine for the powertrain an AHP matrix needed to be made in order to weigh the importance of various metrics which can be used to describe an engine's performance. These metrics include weight, packaging, cost, horsepower, torque, emissions, and efficiency which can be seen in Table A 6 in Appendix A. These weighted metrics were then used to score a variety of engines that exist in the market today. A Pugh concept scoring matrix was then used to determine the engine configuration which can be seen in Table A 7 in Appendix A. The inline 4-cylinder engine was chosen, and a list of engines was gathered in conjunction with data from the Environmental Protection Agency. The list of engines was further reduced to include engines produced by General Motors as team leadership wished to maintain technical support. With the list of engines completed, an additional Pugh concept scoring matrix was select the specific engine that would be used in the powertrain. The scoring matrix can be found in Table A 8 in Appendix A which resulted in the selection of the GM Ecotec LFV engine, pictured in Figure 7.

Figure 7: Ecotec LFV Engine (Car and Driver, 2019)

The selected engine is a 1.5L turbocharged GM Ecotec LFV engine which produces 163 hp, 184 lb-ft of torque and has an estimated 30.9 mpg for a 3500 lb vehicle. The engine block and cylinder head are made from cast aluminum which provides a lightweight design. The engine also comes from the factory with a start/stop feature which improves overall fuel economy during stop and go traffic. The LFV is a spark ignition engine which requires gasoline or ethanol to provide combustion which will be discussed further in the fuel selection section.

2.4.4 Fuel Selection

For vehicles to have practical range some form of on-board energy storage is required. The most common form of energy storage for consumer vehicles is gasoline, however there are several other options. The primary considerations for fuel selection were the energy density, emissions, cost, and safety of the fuel. Energy storage options included gasoline (E10), ethanol (E85), compressed natural gas (CNG), diesel (B0), biodiesel (B20), hydrogen fuel cells, and batteries. From previous competition vehicles, the AVT has shown safe operating experience using diesel, gasoline, and ethanol (E85) as well as high voltage systems made of batteries.

The fuel selection was determined by comparing several different metrics of each fuel type. The most important parameters for each fuel were determined to be the emissions, efficiency, and safety. Table A 9 in Appendix A shows the full AHP matrix where fuel packaging, cost of components, and energy density are also weighed. Emissions were determined by use of the GREET model from Argonne National Lab which has extensive data on many different fuel types as well as the emissions output of each fuel. One of the most comprehensive emissions numbers is the gCO2e/mile WTW. This value accounts for some chemicals, such as N2O which has about 300 times the impact as CO2 (Environmental Protection Agency, 2018). In addition, the WTW designates that the value is "well to wheel" or the lifetime emissions of the fuel from extraction to the vehicle to actually being used in the vehicle. Each fuel source can have a different efficiency based on how energy transfers. For example, batteries powering an electric motor can be upwards of 95% efficient, while the diesel cycle is about 20% more efficient than gasoline due to a higher compression ratio being used. From previous competition vehicles, the AVT has shown safe operating experience using diesel, gasoline, and ethanol (E85) as well as high voltage systems made of batteries. The use of high-pressure or very high voltage systems comes with additional safety risks which must be considered.

After scoring each concept, seen in Table A 10 in Appendix A, the top two selections were batteries for the electric motor and ethanol (E85) for the engine. The LFV engine can be converted from gasoline to ethanol so these choices are compatible. The ethanol selection is designated as E85 indicating that the fuel is 85% ethanol and 15% gasoline. E85 is more commonly known as Flex Fuel as seen at the pump in Figure 8.

Figure 8: Flex Fuel Option at Gas Station (What is Sheetz Unleaded Flex Fuel?, 2019)

Ethanol has less energy density than gasoline so each stroke of the engine requires more fuel to be consumed, and a larger overall fuel tank. In addition to tuning the engine for ethanol, fuel sensors must be added to measure the exact percentage of ethanol content and other components that may be prone to corrosion need to be replaced. However, E85 has a higher octane rating which can improve performance depending on the engine tuning. The emissions of E85 are lower when compared to gasoline which is aligned with the goals of the EcoCAR competition.

2.4.5 Electric Motor Selection

Electric motors are one of the key components of a hybrid electric vehicle. In a P2 (Parallel) hybrid configuration, such as the one in Figure 6 that the team has chosen, the electric motor is placed between the engine and transmission. Using a Hybrid Supervisory Controller (HSC), the vehicle can be powered using the engine alone, the electric motor alone, or by a combination of both systems.

To determine which electric motor to choose, the team created an AHP customer needs weighting matrix that can be seen in Table A 11 in Appendix A. Since these electric motors will be running continuously, the team considered continuous power and torque to ensure these motors can run without overheating and malfunctioning. The team also considered peak power and torque to maximize the performance of the vehicle this motor goes into. Cost was considered since the team is limited to a budget for the overall powertrain. Size and packaging were considered to ensure the selected motor can fit without any issues. Lastly, weight was considered to maximize from weight reduction and alleviate performance.

The results of the AHP weighting matrix ranked continuous power and torque the highest. This was expected since running the motor continuously over rated specifications could cause the motor to overheat or malfunction. Cost was the next most important metric since the team must stay within a budget. Size and packaging followed cost. Ideally, the team would choose the smallest electric motor; however, compromises can be made within this metric to accommodate for overall performance and functionality. Peak power and torque came next because these parameters do not contribute to efficiency as much but do contribute to the vehicle's acceleration. The weight of an electric motor is very low when compared to the weight of the full powertrain, about 6 to 10%. For this reason, weight is the least important metric when compared to the rest.

Next, the team used the weights from the AHP matrix to create a Pugh-scoring matrix. The Remy HVH250-115 was chosen as the reference electric motor since the specifications lied closely to the median when compared with the other potential motors. Lastly, specifications such as such as continuous/peak power and torque were adjusted for the YASA P400 and P750 motors that were originally designed to operate at 700V but are being run at 400V due to the teams' high voltage limitations. Looking at the Pugh-scoring matrix seen in Table A 12 in Appendix A, the YASA P750 scored the most points; however, the YASA is not feasible for the team to use this motor in a P2 configuration since it's a high torque/low RPM motor that maxes out at about 1500 RPM. Any motor the team chooses should be compatible with the maximum RPM of the chosen engine. For this reason, the Remy HVH250-090 seen in Figure 9 became the next best choice for the team to consider for the

Universal Powertrain. Here are some key specifications of this motor: Peak Current - 272 A, Voltage DC - 320 V, Continuous Power - 80 Hp, Peak Power - 110 Hp, Continuous Torque - 148 lbft, Peak Torque - 240 lbft, Max RPM – 10,600 rpm, Weight – 74 lbs, and Cost - $0

Figure 9: Selected Remy HVH250-090 Electric Motor

2.4.6 Motor Controller Selection

A motor controller in an electric or hybrid vehicle is a device that acts as intermediary between batteries and motors, which serves to govern the manner the performance of an electric motor in coordinating with user's desired input. A motor controller might include a manual or automatic means for starting and stopping the motor, selecting forward or reverse rotation, selecting and regulating the speed, regulating or limiting the torque, and protecting against overloads and faults. In a P2 parallel configuration hybrid, the motor controller solely governs the electrical power output in the powertrain. There were multiple specification that the motor controller had to fulfil in order to select the best motor controller for AVT's application. In order to find the solution of the future powertrain, the team needed to find a motor controller that is capable of supporting the battery and motor selections.

The DANA TM4 C0150HV is the motor controller the team has chosen to utilize in the Universal Powertrain. The DANA motor controller has a the 320-450V operating voltage, a max output current of 575 Arms, and a 180Kw maximum output power. The DANA motor controller is shown in Figure 10.

Figure 10: Dana TM4 T0150 Motor Controller (DANA, 2019)

An AHP matrix found in Table A 13, was used to weight the metrics that the motor controller would be scored by. Continuous current determines the continuous electrical output power during the driving and is important for most of usual use. The peak current provides the maximum electrical power output which lasts couple seconds. The input voltage range ensures the adaptability of the voltage range of the battery and motor. Cost is important for the budget and size is important in terms of packaging the whole powertrain.

Additionally, a Pugh concept scoring matrix, seen in Table A 14, was scored based on the specifications and AHP weightings to determine a score for each motor controller. The DANA TM4 C0150HV, seen in Figure 10 was the best scoring motor controller and will be utilized in the Universal Powertrain. The DANA TM 4 C0150HV has a the 320-450V operating voltage, a max output current of 575 Arms, and a 180Kw maximum output power. These specifications are compatible with the Nissan Leaf battery pack and Remy NVH250 Motor.

2.5 Mechanical Design Analysis

Previous eco car projects had issues with the transmission input spline shaft. To analytically test the Universal Powertrain's design, the Finite element analysis method was performed to find maximum stress and corresponding safety factor to materials chosen. The actual process could include a few more variables to change the force and torque number, however, those variable's vicinity scale is minuscule compared to the main peak torque of 575Nm. Thus, neglecting small variables like rolling friction, FEA assumption is valid and useful to estimate maximum von Mises stress. The test result is shown in Figure 11.

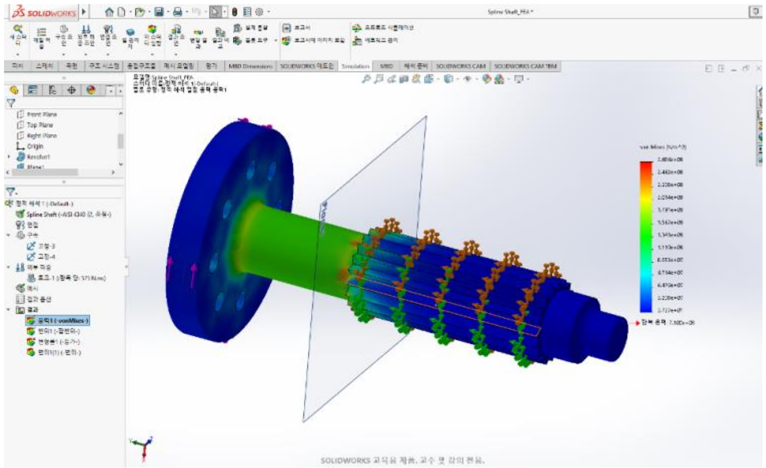


Figure 11: Finite Element Analysis of Von Mises Stress in Spline Shaft

The maximum stress induced by 575Nm torque turns out to be 268MPa. With the motor fully reversed, the stress would correspond to -151MPa under -325Nm. In material selection, choosing one with significantly greater yield strength is desirable. Universal had set the target specification of the factor of safety to be greater than 2. The material should be resilient enough to withstand torque spikes without failure. High yield strength steel, AISI 4340 was chosen for shaft material to meet such criteria. Since 710MPA is the yield strength of the metal, Shaft is expected to have factor of safety rating of 2.6. Figure 12 demonstrates the factor of safety in FEA analysis.

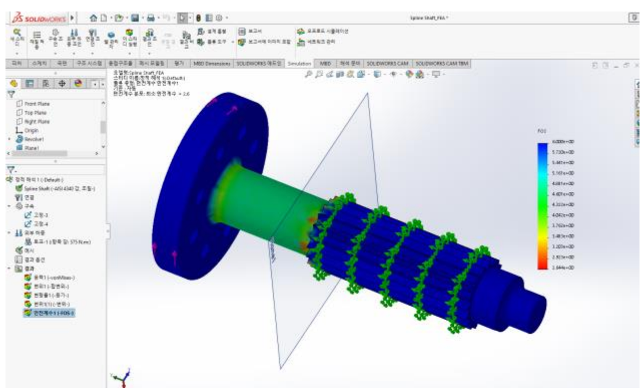


Figure 12: Finite Element Analysis of FOS in Spline shaft

In order to verify the results of the FEA analysis, hand calculations were completed. The maximum torque to be applied to the shaft is estimated to be 575Nm, the maximum of the engine and motor combined. **Error! Reference source not found.** displays the spline shaft dimensions.

Error! Reference source not found.: Spline Shaft Dimensions

The shear stress can be calculated by

Equation 1:

$$\tau = \frac{Tr}{J}$$

The shaft used for this project has a diameter of 32.5mm which can be inserted along with the 575Nm torque into Equation 1.

$$\tau = \frac{575Nm * 0.01625m}{\frac{\pi}{32} * (0.0325m)^4} = 85.3MPa$$

In order to determine the failure modes and better-compare to the FEA analysis, the von-Mises stress is calculated for shear stress alone as

Equation 2:

$$\sigma_{von\ Mises} = \sqrt{3} * \tau$$

Which becomes:

$$\sigma_{von\ Mises} = \sqrt{3} * 85.3MPa = 147MPa$$

A correction factor for the stress concentration should also be included to account for the decrease in diameter at the end of the shaft where torque is applied.

Equation 3:

$$K_{static} = A(\frac{r}{d})^b$$

Where r is the radius of curvature and d is the diameter of the shaft. The constants A and b can be determined by correlations which relate d and D, the diameter of the larger radius of the shaft. Correlated values for:

$$\frac{D}{d} = \frac{104mm}{32.5mm} = 3.2$$

Are approximately A=0.905 and b=-0.342 which can be inserted into Equation 3 to yield:

$$K_{static} = 0.905(\frac{5mm}{32.5mm})^{-0.342} = 1.72$$

This stress concentration factor can then be multiplied by the von Mises stress to get the corrected stress for comparison to the FEA results.

Equation 4:

$$\sigma_{von\ Mises,corrected} = \sigma_{von\ Mises} * K_{static}$$

$$\sigma_{von\ Mises,corrected} = 147MPa * 1.72 = \mathbf{253MPa}$$

The FEA analysis resulted in a stress of 268MPa, indicating good agreement between the computer model and hand calculations.

The expected lifetime of the shaft can also be determined by conducting fatigue analysis. Fatigue calculations rely on the fact that stress oscillates and the body undergoes repeated loading which can cause failure much below the expected yield point. The curve for AISI 4340 is depicted in blue in Figure 13.

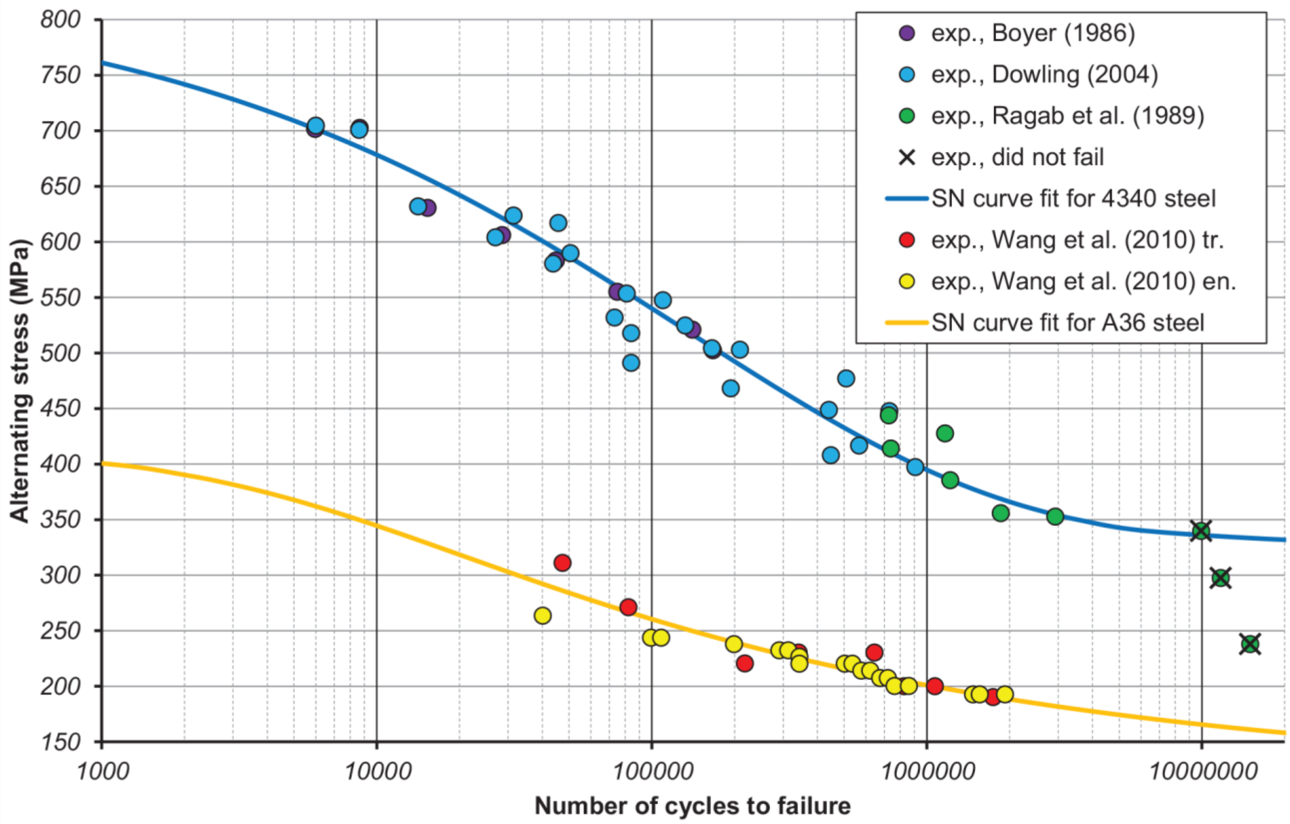


Figure 13: Alternating Stress and Cycles to Failure for AISI 4340 (Gorash, 2018)

The alternating stress depends on both the maximum and minimum stress.

Equation 5:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

The FEA results for +575Nm and -325Nm can be inserted into Equation 5 to yield:

$$\sigma_a = \frac{268MPa - (-151MPa)}{2} = 209.5MPa$$

At 209.5MPa, the shaft would have be expected to have an infinite life cycle of alternating between maximum positive and negative torque. Investigation of the referenced tests by Boyer, Dowling, and Ragab did not reveal whether the stress was due to axial load, bending, or torsional load. Previous courses at Penn State have recommended a correction factor of 1.67 to account for torsional loading if the reference test is based on axial loading. Using this correction factor would result in an alternating stress equivalent of 350MPa corresponding to approximately 30 million cycles. While engine shafts are expected to go through significantly more revolutions over the vehicle's lifetime, 30 million represents the number of cycles alternating between maximum and minimum torque which would only occur during harsh acceleration followed by harsh braking.

3.0 Manufacturing Process

While the Universal Powertrain team did not manufacture any physical components during the semester long project, many of the components that were designed will require specific manufacturing processes which will be outlined in this section.

3.1 Adapter Plate

The adapter plate which interfaces between the engine, transmission, and electric motor can be made in an efficient and cost-effective manner. As the adapter plate would be made out of high strength aluminum, which is cheaper to machine than if steel or harder materials were used. The plate would be made in a total of 4 components that would be bolted together. These components would consist of an inner flange, the center plate, a plate cover, and an outer flange. These components could be made simply by water jetting the shapes and post processing them in a 3 axis CNC mill.

3.2 Battery Box

The battery box will be made from aluminum and would be made in a process which consists of sheet metal fabrication and welding. Due to the size of the battery box, each panel would need to be individually cut out either using some form of CNC machinery or precisely by hand using a band saw and hole drill. Threaded rods to support the modules would be added and welded to the bottom of the case. Panels would be welded together to form the sides of the case and the lid would be affixed to the rest of the case with riveted hinges and clamps.

3.3 Fuel Tank

The manufacturing process of the fuel tank would be similar to the battery box in which aluminum sheet metal would be cut out using a form of CNC machinery such as a waterjet or plasma cutter. The sheet metal would then be bent into shape using a break or hand tools then the gaps would be TIG welded together. The fuel filler neck would be bent on a tube bender and then welded to the top of the tank along with any fuel fittings or mounts for the fuel pump. Once fabrication is completed, the fuel tank would be sent out to be anodized to reduce corrosion from the environment.

3.4 Miscellaneous Packaging Components

While the many of the components that will be required for the integration of the powertrain that was developed, there are other additional components that may need to be modified which will consist of various manufacturing processes. One of the most critical modifications may consist of modifying the subframe of the vehicle which would involve cutting and welding new mounting locations for the engine and transmission. Other mounts may need to be manufactured for packaging the fuel tank, battery box, and motor controller when the final vehicle is chosen.

4.0 Test Results and Discussion

The Universal Powertrain project did not consist of any physical assembly or testing of components. Virtual simulations needed to be conducted to determine how the system would perform under a variety of conditions. The assembly simulation of packaging all the components in an example vehicle can be seen in Figure 4. Acceleration, efficiency, and range calculations were conducted using MATLAB Simulink to design the vehicle and powertrain. The Simulink model layout for these tests can be seen in Figure 14.

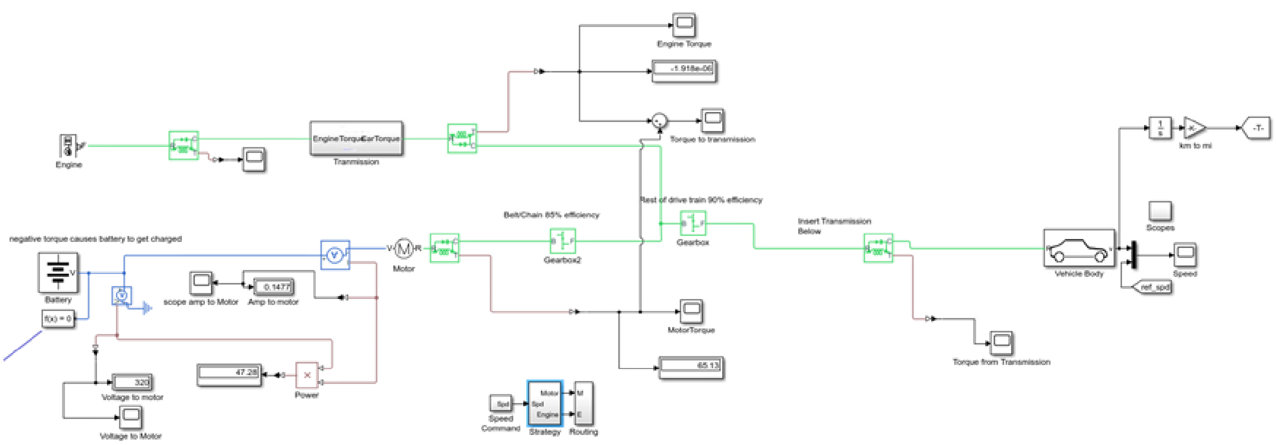


Figure 14: Simulink Model for Universal Powertrain, Parallel Hybrid

Torque is provided to the vehicle wheels via both the internal combustion engine and an electric motor. The motor is able to both charge and discharge from the battery depending on the engine output and demanded speed. Battery, motor, and engine parameters are modeled after available specifications determined during research. Note that the engine brake specific fuel consumption is modeled after a 1.5L turbocharged 2016 Honda L15B7 due to available data (Environmental Protection Agency, 2018).

The system tests were run by inputting drive cycles which have a specified velocity at certain times. Two EPA drive cycles were tested, the EPA highway cycle seen in Figure 15, and the EPA urban drive cycle seen in Figure 16.

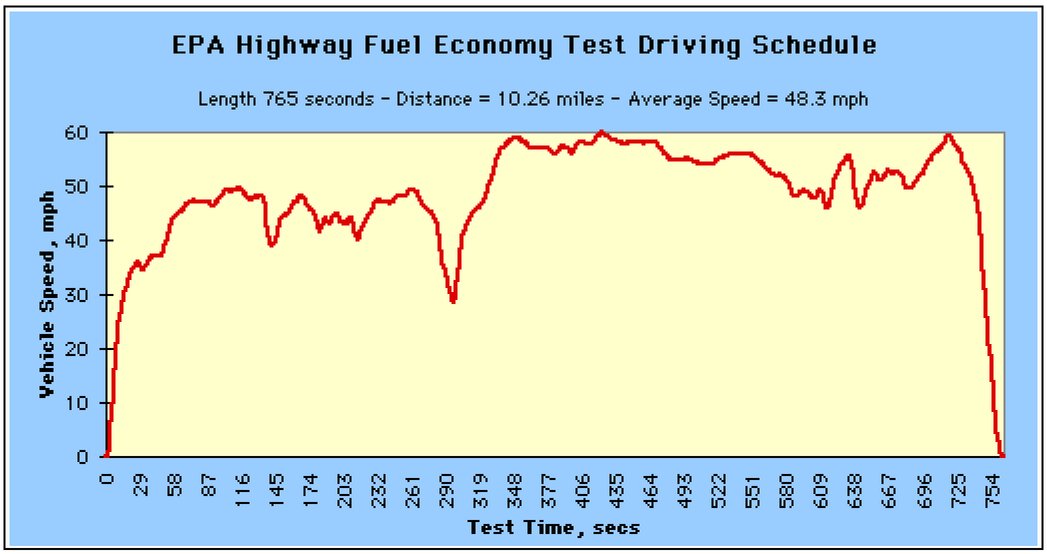


Figure 15: EPA Highway Drive Cycle (Environmental Protection Agency, 2019)

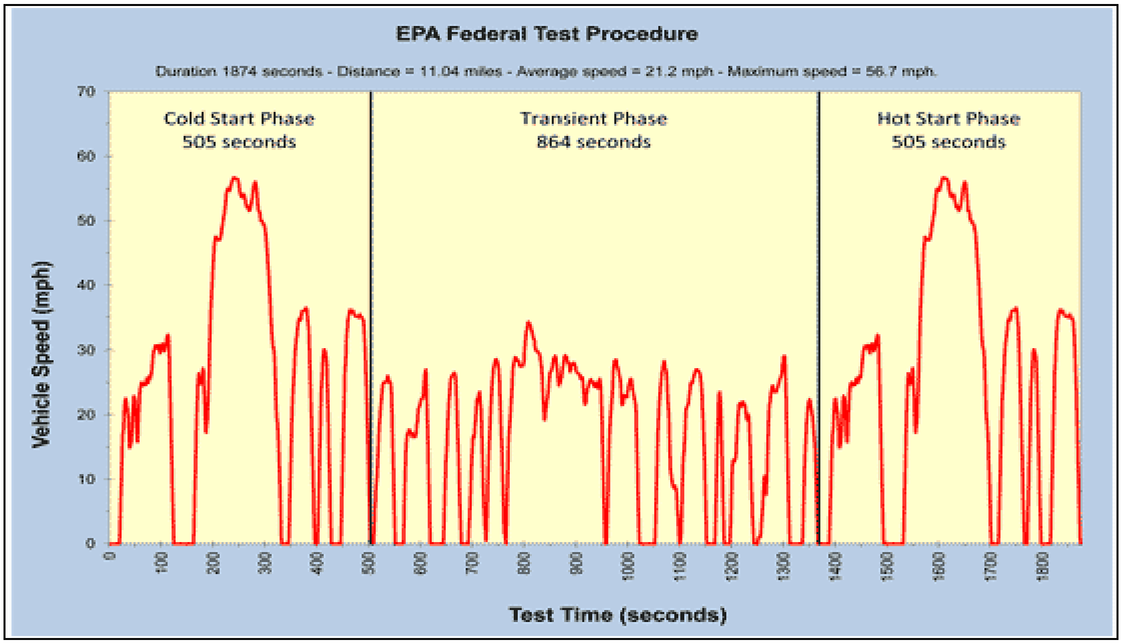


Figure 16: EPA City Drive Cycle (Environmental Protection Agency, 2019)

The two cycles are used for the highway and city mileage commonly found when describing vehicle efficiency. An additional method to express efficiency is the combined gas mileage which is calculated by

Equation 6:

$$Combined\ MPGe = (0.55 * City) + (0.45 * Highway)$$

The EcoCAR competition typically includes a longer-range efficiency test which can take several hours in real-world traffic and roads. To model a real-world scenario, two team members were sent on an approximately one-hour drive around State College with both city style and highway style driving. Speed data was recorded off the vehicle's OBD port. The route taken and speed along each section can be seen in Figure 17.

Figure 17: State College Drive Cycle

The mapped speed data was then converted to discrete points to be inputted into the Simulink model. The input values can be seen in Figure 18, the cycle is mostly highway driving, however speeds reach higher values than in the EPA test with a maximum near 90mph. The average speed is only 41mph which is slower than the highway EPA's average of 48mph..

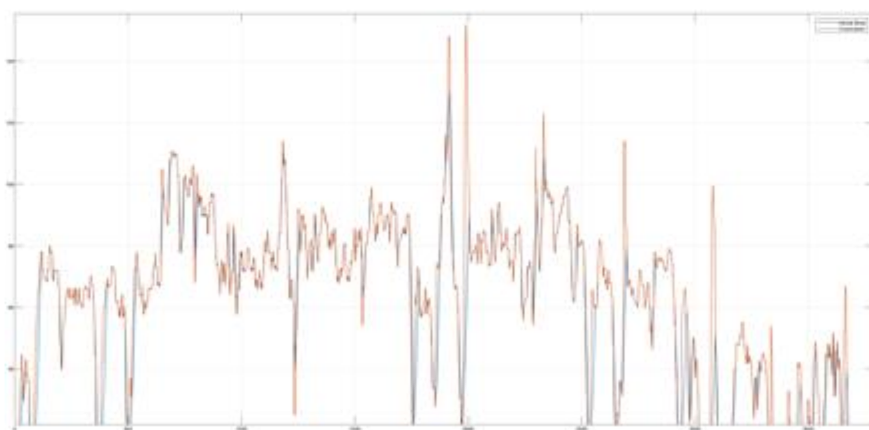


Figure 18: State College Drive Cycle

Acceleration tests were done adding a step input to the reference velocity and looking at the time taken for the vehicle velocity to reach the specified value, either 60mph from 0mph or 70mph from 50mph.

The model originally contained a simplified torque split algorithm where the engine operated at a constant throttle and the motor would either provide energy or regenerate energy depending on whether the vehicle was moving at the demanded velocity. Although an optimized torque-split algorithm was beyond the scope of the Universal Powertrain project, slight modifications were made to provide better response in high-acceleration and high-speed drive cycles. The equation for the updated engine throttle used in the model is:

Equation 7:

$$Engine\ Throttle = Baseline(user\ defined) + \left(\left|1 - \frac{Vactual}{Vref + 1}\right|\right)$$

The limits for throttle are from 0 to 1, which correspond to 0% and 100% engine throttle. The +1 in the denominator of Equation 7 is to avoid divide by zero errors. When the velocity is in units of kmh, the +1 does not contribute significantly to throttle changes. For the acceleration tests, the throttle was set at 1 (100%) to model the driver fully depressing the accelerator.

The efficiency for each drive cycle was determined by dividing the distance travelled by the amount of fuel consumed by the engine. Each test was run in charge-sustaining (CS) mode where the battery charge at the beginning and end of the drive cycle was no more than 0.02Ah below its starting charge, or the battery was slightly above the starting charge by the end of the cycle. Besides changing the reference velocity drive cycle for each test, two additional factors were altered to optimize fuel consumption. The baseline engine throttle and gear ratio between the engine and wheels were modified for each test. In the Simulink model there is no transmission, so a gear ratio between 1 and 4 is used for each efficiency test. The results from Simulink testing can be seen in Table 2

Table 2: Performance Specifications from Simulink Model

Metric	**Threshold Value**	**Results**
0-60 mph time (s)	<9	10.77
50-70 mph time (s)	<4	5.45
Electric Range (miles)	>20	58

Vehicle Range (miles)	>200	300
MPGe combined	>35	34.6
City mpge		28.1
Highway mpge		42.7
State College mpge		35.6
WTW Emissions (gCO2e/mile)	<250	198 WTW, 255 PTW (GREET MODEL) 236 WTW, 252 PTW (EcoCAR)

Note that while the MPGe values assume that the fuel is gasoline, the emissions values are corrected for ethanol and the lower energy density of E85.

The vehicle met the team's specification for range and emissions by a significant amount. There are some competing effects between the fuel choice of E85, which contains about 70% the energy of gasoline and would reduce range, and the lower emissions provided by E85. The 10-gallon fuel tank should be sufficient to provide over 300 miles of range when coupled with the electric motor. The MPGe value was within 2% of the specification which is well within the uncertainty of the model. As expected, the highway mileage is significantly higher than the city mileage, however both are greater than traditional crossover SUV's such as the Chevy Blazer with 22/27 city/highway MPG. The proposed components in the Simulink model did not reach the specifications for acceleration in the 50-70mph test. This failure may have been the result of a deficiency in the Simulink model. Gear shifting is not included in the model so the engine is not operating at maximum power output for the longest amount of time during the acceleration.

Overall, the Simulink model contains several aspects that improve the fidelity and confidence in results. Each component has some sort of associated time delay associated to reflect component response. Several efficiency losses are placed throughout the model. Between the engine output and motor connection there is a 5% loss to account for auxiliary systems. There is a 15% loss between the motor and engine shaft to account for belt or chain efficiency. Also, there is a 10% loss between the output shaft and the wheels to represent additional powertrain losses. Rolling and air resistance are included in the model, as well as some electrical losses in the battery.

However, there is also room for improvement within the model. Effort can be directed towards adding in a transmission to account for changing gear ratios. The torque split should also be optimized to farther improve performance. In addition, the battery is essentially modelled as a voltage source, and additional charging and discharging effects can be added based on the battery chemistry and specifications. Lastly, there are no thermal effects included in the model for either the battery or the engine. The EPA urban cycle seen in Figure 16 includes cold, transient, and hot periods where the engine and exhaust components are increasing in temperature. Cold engines are expected to have lower efficiency and significantly increased emissions.

5.0 Customer Needs Self-Assessment

After completing the market research, the team used the customer needs as well as competition requirements to create a list of target specifications. Some of these most important specifications of the Universal Powertrain are highlighted in Table 3 to assess the projects' achievements.

Table 3: Customer Needs Technical Specifications

Specification No.	Specification	AVT Powertrain	Threshold Value (1)	Objective Value (2)	Units
1	Vehicle Weight	4000	<4500	3500	lb.
2	0-60mph Time	10.77	<15	9	sec
3	50-70mph Time	5.45	<4	3	sec
4	Battery Pack Capacity	20	>10	20	kWh
5	Weighted Green House Gas Emissions	198 WTW	<250	125	gCO2e/ mile
6	Battery Weight	490	<600	300	lb
7	System Cost	47,550	<50,000	20,000	$
8	Fuel Tank Capacity	10	>8	12	Gallons
9	Vehicle Range (Gas+Electric)	300	>200	300	Miles
10	Electric Range	58	>20	25	Miles
11	Human Capacity	4	>2	4	People

12	MPGe Combined	34.6	>35	50	MPGe
13	Time to Refuel/Recharge	4	<8	<1	Hours

The team's designed Universal Powertrain estimated a total vehicle weight of about 4000 lbs which was within the threshold value, but over the target which was 3500 lb. The team believes the weight of the batteries and electric motor contributed the majority of the additional weight to the vehicle. While 0-60mph time was within objective range, the 50-70mph time was not. The team was unable to change the gears during simulations of the powertrain, which meant that these times are a result of running in one gear. The team expects these times to be well below objective values after this issue is resolved. The battery weight, fuel tank capacity, and combined MPGe were also within the objective range. The battery weight was higher than expected due to limitations posed by current battery technology and the team's budget.

On the other hand, the team succeeded in meeting peak battery capacity, greenhouse gas emissions, cost, vehicle range (gas+electric), electric range, human capacity and recharge time requirements as per the customer needs.

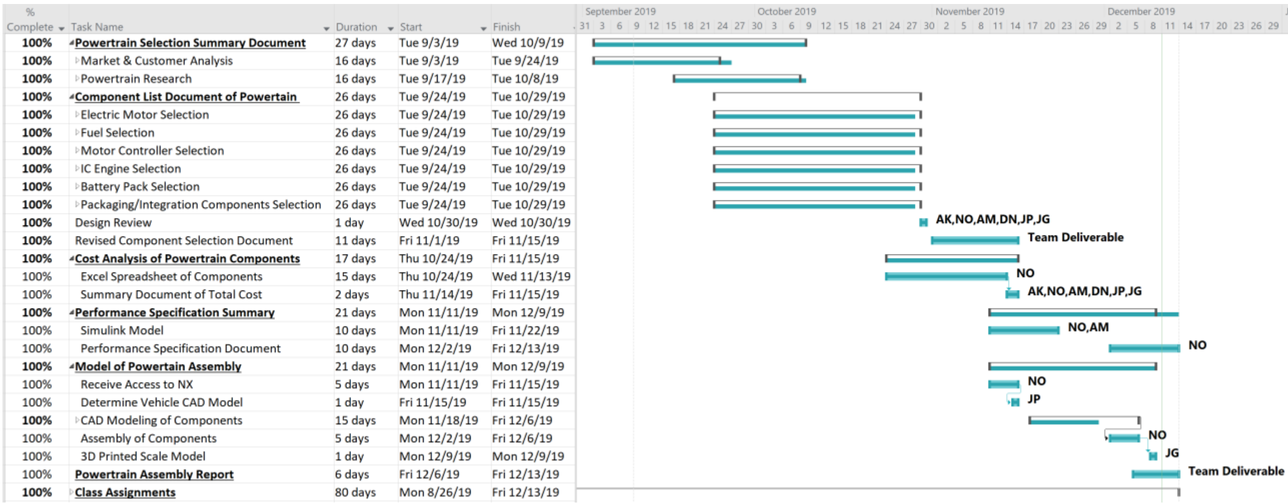
In summary, based on customer's needs scale from 1 – 10, where 10 is meeting all needs. The Universal Powertrain scored 7/10. This number was calculated by assigning each color in the table above a weight. Green equals 1, yellow equals 0.5, and red equals 0. The weighted numbers are then added together and divide by the total number of specifications to equal 70%.

6.0 Project Management Summary

In order for this project to be successful, several key actions needed to be taken. There was a limited time frame for all deliverables to be accomplished. To ensure timely completion risk factors were identified and a project schedule was created. Each team member was responsible for certain tasks and there were frequent meetings with team leadership to verify assumptions and results. Critical items which could slow down the entire project were designated as priorities and had multiple team members involved. Cost was a factor during all design decisions. AVT leadership recommended a maximum budget of $50,000 for all the powertrain components. Future teams should be able to construct the powertrain under this budget, leaving funds available for other vehicle systems. Overall, the Universal Powertrain project intends to set the framework for future powertrain designs so that the AVT can be successful in the next competition.

6.1 Project schedule

During the extent of the semester, the Universal Powertrain team kept track of the progress of the project using a Gantt chart. The team's scheduler organized the Gantt chart into team deliverables with tasks and subtasks which individual members responsible for. With a Gantt chart the team was able to plan out the hierarchy of the deliverables as well as keep track of each task's individual progress. The team's semester Gantt chart can be seen in Figure 19.



% Complete	Task Name	Duration	Start	Finish
100%	Powertrain Selection Summary Document	27 days	Tue 9/3/19	Wed 10/9/19
100%	Market & Customer Analysis	16 days	Tue 9/3/19	Tue 9/24/19
100%	Powertrain Research	16 days	Tue 9/17/19	Tue 10/8/19
100%	Component List Document of Powertain	26 days	Tue 9/24/19	Tue 10/29/19
100%	Electric Motor Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	Fuel Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	Motor Controller Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	IC Engine Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	Battery Pack Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	Packaging/Integration Components Selection	26 days	Tue 9/24/19	Tue 10/29/19
100%	Design Review	1 day	Wed 10/30/19	Wed 10/30/19
100%	Revised Component Selection Document	11 days	Fri 11/1/19	Fri 11/15/19
100%	Cost Analysis of Powertrain Components	17 days	Thu 10/24/19	Fri 11/15/19
100%	Excel Spreadsheet of Components	15 days	Thu 10/24/19	Wed 11/13/19
100%	Summary Document of Total Cost	2 days	Thu 11/14/19	Fri 11/15/19
100%	Performance Specification Summary	21 days	Mon 11/11/19	Mon 12/9/19
100%	Simulink Model	10 days	Mon 11/11/19	Fri 11/22/19
100%	Performance Specification Document	10 days	Mon 12/2/19	Fri 12/13/19
100%	Model of Powertain Assembly	21 days	Mon 11/11/19	Mon 12/9/19
100%	Receive Access to NX	5 days	Mon 11/11/19	Fri 11/15/19
100%	Determine Vehicle CAD Model	1 day	Fri 11/15/19	Fri 11/15/19
100%	CAD Modeling of Components	15 days	Mon 11/18/19	Fri 12/6/19
100%	Assembly of Components	5 days	Mon 12/2/19	Fri 12/6/19
100%	3D Printed Scale Model	1 day	Mon 12/9/19	Mon 12/9/19
100%	Powertrain Assembly Report	6 days	Fri 12/6/19	Fri 12/13/19
100%	Class Assignments	80 days	Mon 8/26/19	Fri 12/13/19

Figure 19: Universal Powertrain Gantt Chart

Previously the team determined the critical path project path which included researching the customer, market, and the various powertrain configurations in order to understand the needs and specifications of the powertrain. Next, the team had to choose the configuration of the powertrain that best meets the needs of the customer. In addition, the team had to select each component of the chosen powertrain, so the previously determined specifications are met. Next, the components had to be modelled in CAD so assemblies could be tested. Lastly, the final powertrain assembly had to be modelled to assure that all the components fit together.

From the critical path, the Universal Powertrain team had to determine the scope and deliverables of the project. The team decided that the primary deliverables would be a powertrain selection summary, a component list of the Powertrain, a cost analysis of the powertrain components, a performance specification summary, a CAD model of the powertrain assembly, and lastly a powertrain assembly report. Due to some scheduling conflicts and delays, some of the initial deadlines of the deliverables had to be adjusted as many of the delays were out of the teams control. For example, the cost analysis document was intended to be completed earlier, but the team had to wait longer than expected to receive quotes from companies. In summary, the Universal Powertrain team chose a set of deliverables at the beginning of the semester which were scheduled in a Gantt chart and have since been able to complete all the deliverables.

6.2 Purchase Information

While designing the Universal Powertrain, the team had to keep the cost of each component and manufacturing process in mind. A cost analysis of how the team would plan to spend the provided budget is outlined below in addition to a detailed bill of materials for the entire powertrain.

6.2.1 Budget

The overall budget for this powertrain was originally to be between $20,000 and $50,000. The approximate price breakdown for each component can be seen in Figure 1Figure 20.

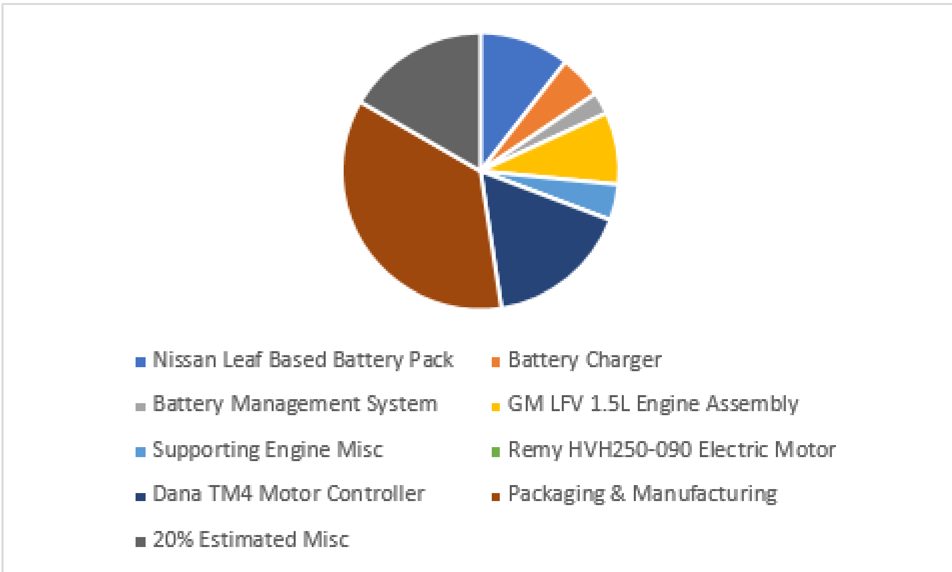


Figure 20: Pie Chart of Universal Powertrain Budget

The overall expected cost of this powertrain should be approximately $47,550. This value assumes that the Remy HVH250-090 motor available to the AVT can be used without any significant costs to verify operation. The budget does include a 20% miscellaneous category to cover unknown expenses and ensure that there is funding available in the event one or more components need to be replaced. A more specific price breakdown can be seen in the Bill of Materials section.

6.2.2 Bill of Materials

A bill of materials is created to show a comprehensive inventory of the specific components, as well as the quantities of each, shown in Table 4.

Table 4: Universal Powertrain Bill of Materials

Item	Quantity	Cost ($)
GM LFV 1.5 Engine assembly	1	4000
Supporting Engine Misc	1	2000
Dana TM4 Motor Controller	1	8000
Nissan Leaf Generation 2 Battery Pack	1	4000
Custom Fabricated Battery Case	1	1000
Battery Charger	1	2400
Battery Management System	1	1225
Remy HVH250-090 Electric Motor	1	0
Packaging & Manufacturing	1	17000
20% Estimated Misc	1	7925
Project Total		47550

The most expensive portion of the Universal Powertrain that the team estimated was the cost of manufacturing the various components that would assist in the packaging and integration of the powertrain. Next, the various portions of the battery storage system which included the Nissan Leaf battery pack, battery management system, and battery case totalled $8625. The DANA TM4 motor controller costs $8000 which was a direct quote from DANA. The GM LFV internal combustion engine has an estimated price $4000 which was based on the assumption that the engine would be purchased brand new. Cost could be saved by finding a used engine, but the price variation in the used market made the price difficult to estimate. Costs of supporting engine components includes estimated costs of the wiring harness, exhaust manifold and ECU and Ethanol conversion kit. The Remy HVH250-090 electric motor was previously donated to the team so there is no additional cost. Lastly, the estimated 20% miscellaneous cost was also included in the bill of material to account for any underestimates or unexpected costs.

6.3 Risk Plan and Safety

At the beginning of this project several risks were identified which could have impeded the progress and ultimate success of the Universal Powertrain project. Throughout the entirety of the project actions were taken to mitigate the risks. The team conducted all work in the garage in a safe manor in accordance with stated procedures and had no injuries nor were any team members placed in an unsafe situation. As with any project there is a limit on the total amount of time available to complete necessary tasks. By adhering to a Gantt chart and having biweekly progress updates, the team was able to stay on track. For this stage of the project, work is in the theoretical and modelling stage. As such, many of the risk factors associated with the project revolved around either the CAD and Simulink models or the uncertainties of not knowing the competition or vehicle specifics. When possible, virtual values or models were compared to real world data. In addition, components were chosen with wider ranges of values in order to accommodate different or added components. The risks addressed during this project can be seen in Table 5.

Table 5: Risk Plan During Project

Risk	Initial Level	Actions Taken to Minimize Impact	Post-Project Analysis
Schedule Delays	High	-Ensured Gantt chart is up to date and members are responsible for specific tasks -Built off prior work in Sharepoint and team leadership's input -Verified members are meeting requirements for billable hours and weekly accomplishments	-All deliverables will be completed at the conclusion of the project -Almost every deliverable was completed on-time, personnel were shifted as needed if one area fell behind
Availability of new components	High	-Chose components with wider operating range than expected to accommodate future upgrades -Created scoring matrices to be able to readily accept new concepts	-Most components exceed technical specifications for assumed vehicle -When the team learned there was free access to the HVH250-090 motor, the analysis was quickly redone to include the new motor

EcoCAR/competition scoring or focus changes	Moderate	-Based design off competition goals and general consumer preferences -Added excess electrical capacity to account for additional of ADAS processors and cooling systems	-The vehicle has improved efficiency performance compared to many similar-style vehicles -Cabin intrusions in the trunk (battery placement) still allows significant storage room
Engine compartment is too small/wrong geometry	Low	-Used smallest crossover SUV-style chassis model available -Modeled adapter plate between engine, transmission, and motor	-The Equinox has a smaller chassis than most crossover SUVs, components should fit in anything of equal size or larger
Theoretical model inaccuracies	Low	-Compared model results to previous EcoCAR results -Conducted "State College" drive cycle to input real world data	-Efficiency values are close to what is expected of hybrid vehicles (Fuel Economy, 2018) -Model parameters can be easily altered with additional data if components change

The Universal Powertrain project is intended to be in preparation for the next efficiency-based vehicle competition. As the project continues or the powertrain is implemented additional risks may influence the ultimate success of the powertrain. These risks generally revolve around the continued uncertainty of the exact competition parameters and the availability of components. The primary risks are due to changing technology and competition requirements. As the automotive industry continues to shift towards hybrid and electric vehicles the expectation is that technology will improve and have a reduced cost. Additional analysis will need to be conducted as new components become available, and the design of the powertrain may need to change. See Table 6 for the future risk plan.

Table 6: Long-Term Risk Plan

Risk	**Level**	**Actions to Minimize Risk**	**Fall Back Strategy**
New Technologies Offer	High	-Avoid purchasing components until closer to competition date	-Sell outdated components to fund purchasing new technologies -

Potential Improvement		-Research latest technologies to be aware of market solutions	
EcoCAR competition objectives change	Moderate	-Stay up to date with competitions -Encourage diverse focus of AVT so that several areas are improved	-Determine if there are other efficiency-focused competitions to enter
Competition car is not Crossover SUV	Moderate	-Ensure additional power is produced to still perform on a heavier/larger vehicle -Work on alternate packaging options to fit in sedan-like vehicles	-Add multiple electric motors or more powerful motors for heavier vehicle -Reduce size of battery or select smaller engine for sedan-like vehicles
Schedule Delays	Moderate	-Create Gantt charts to schedule and plan long-term activities -Use previous work to ensure subsequent teams are not "reinventing the wheel"	-Switch powertrain model to simpler option such as battery electric, may be more costly -Task multiple teams to powertrain development
Component Functionality	Low	-Make component testing a priority -Verify component operability prior to physical assembly	-Purchase new components verified to be operable by manufacturer -Attempt repairs where possible
Funding Availability	Low	-Ensure that some budget is set aside to fund a powertrain	-Use on-hand or used components whenever possible to reduce costs

7.0 Conclusions and Recommendations

In conclusion, the Universal Powertrain team was able to develop, model, and simulate a P2 parallel powertrain that could be adapted to be used in a variety of crossover SUVs. Table 7 shows the Universal Powertrain compared against the U.S.New's top production hybrid SUV, the 2020 RAV4 Hybrid (U.S. News & World Report, 2019).

Table 7: Universal Powertrain Vs. (Market Lead) 2020 RAV4 Hybrid (Toyota, 2019)

	Universal Powertrain	2020 RAV4 Hybrid
Curb Weight (lbs)	4000	3800
Engine Size	1.5L Turbocharged	2.5L
City MPGe	28.1	41
Highway MPGe	42.7	38
Combined MPGe	34.6	40
Peak Combined Power (hp)	273 (110 @ 320 V)	321 (118 @ 650 V)
Peak Combined Torque (lb-ft)	250 (250 @ 320 V)	333 (149 @ 650 V)

Although both vehicle's weigh just about the same, the Universal Powertrain performs significantly better on the highway than it does in the city while the RAV 4 performs better in the city than on the highway. This may be due to the fact that the RAV4 could be utilizing the electric motor during city driving more than the Universal Powertrain's design. One way that the future team may be able to improve efficiency is by programming the powertrain to run only using the electric motor at lower speeds and during stop and go traffic.

The Universal Powertrain's current specifications provide future AVT teams a platform to build on. Seen in the table above, the 2020 RAV 4 Hybrid operates the electric motor at 650V. It is recommended that future AVT teams look into designing a new system that operates at 650V. The chosen DANA TM4 motor controller already meets the specifications required for this upgrade. In addition, the selected electric motor, Remy HVH250-090, can generate 201 hp and 236 lb-ft compared to 2020 RAV4's, 118 hp and 149 lb-ft. This will drastically increase the efficiency of the Remy HVH250-090 that may compensate for the inefficiencies of the internal combustion engine.

As technology advances, some of these components are expected to become obsolete in the upcoming years. The battery and electric motor are two of the first components expected to become outdated as electric vehicles are becoming more common and more efficient. The next competition is expected to take place several years from the creation of this report so the components may be outdated. If significant improvements in terms of performance and cost have occurred for the battery and motor systems then a fully electric vehicle would likely be the best option. The Universal Powertrain team recommends that future teams investigate a fully electric vehicle first, especially looking at newly available technologies.

8.0 References

"2020 Toyota RAV4 Exterior Specs & Options." New Cars, T. S. (n.d.).

Car and Driver. (2019). *Deep Dive: GM's New Small Engine Family*. Retrieved from Car and Driver.

DANA. (2019). *Motor Controllers - TM4*. Retrieved from DANA TM4.

Environmental Protection Agency. (2018). *Benchmarking a 2016 Honda Civic 1.5-Liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines.* EPA.

Environmental Protection Agency. (2018). *Greenhouse Gas Equivalencies Calculator*. Retrieved from EPA.

Environmental Protection Agency. (2019). *Dynamometer Drive Schedules.* EPA.

Fuel Economy. (2018). *Compare Side-by-Side*. Retrieved from Environmental Protection Agency.

Gorash, Y. a. (2018). *On Cyclic Yield Strength in Definition of Limits for Characterization of Fatigue and Creep Behaviour.* Open Engineering.

National Academies Press. (2015). *Cost, Effectiveness and Deployment of Fuel*. Retrieved from Board on Energy and Environmental Systems.

Peters, L., Johnson, M., & Davidson, K. (2001). A Novel Approach to Four-Bar Synthesis. *10th ASME Design Automation Conference*, 234-250.

Toyota. (2019). *2020 Toyota RAV4 Exterior Specs & Options*. Retrieved from New Cars, Trecks, SUVs & Hybrids.

U.S. Energy Information Administration. (2019). *Annual Energy Outlook 2019 with Projections to 2050.*

U.S. News & World Report. (2019). *Hybrid SUV Ranking*. Retrieved from U.S. News & World Report.

What is Sheetz Unleaded Flex Fuel? (2019). Retrieved from Performance Ford Clinton.

Appendix:

Appendix A: Pugh Concept & AHP Scoring Matrices

In this appendix, the various AHP and Pugh concept scoring matrices will be found. These matrices were used by the Universal Powertrain team to select the powertrain configuration, various powertrain components, in addition to design methods.

Table A 1: Powertrain Configuration AHP Scoring Matrix

		Metrics								
		Weight of powertrain	Size	Cost	Number of Components	Installation Time	MPG/MPGe	Horsepower	Emissions	Weight
Metrics	Weight of powertrain	X	0.5	0.8	1.0	0.8	0.3	2.0	1.1	8.4%
	Size	2.0	X	1.3	3.0	1.5	0.5	0.7	0.5	12.2%
	Cost	1.3	0.8	X	3.0	3.0	1.0	1.5	0.8	14.7%
	Number of Components	1.0	0.3	0.3	X	0.2	0.3	0.3	0.3	3.6%
	Installation Time	1.3	0.7	0.3	5.0	X	0.8	0.4	0.3	11.4%
	MPGe	3.0	2.0	1.0	3.0	1.3	X	3.0	1.2	18.8%
	Horsepower	0.5	1.5	0.7	3.0	2.5	0.3	X	0.8	12.0%
	Emissions	0.9	2.0	1.3	4.0	4.0	0.8	1.3	X	18.7%

Table A 2: Pugh Scoring Matrix for Hybrid Powertrain Types

		Concepts									
		Parallel Hybrid (Reference)		Series Hybrid		Through the Road Hybrid		Power Split		Electric	
Selection Criteria	Weight %	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Weight of powertrain	8.4	3	0.252	2	0.168	2	0.168	2	0.168	1	0.084
Size/ packaging	12.2	3	0.366	2	0.244	2	0.244	2	0.244	1	0.122
Cost	14.7	3	0.441	2	0.294	3	0.441	2	0.294	1	0.147
# of Components	3.6	3	0.108	4	0.144	2	0.072	1	0.036	4	0.144
Installation Time	11.4	3	0.342	2	0.228	4	0.456	1	0.114	2	0.228
MPG/MPGe	18.8	3	0.564	3	0.564	3	0.564	5	0.94	5	0.94
Horsepower	12	3	0.36	2	0.24	4	0.48	3	0.36	4	0.48
Emissions	18.7	3	0.561	4	0.748	3	0.561	4	0.748	5	0.935

	Total Score	2.994	2.630	2.986	2.904	3.08
	Rank	2	5	3	4	1

Table A 3: Parallel Powertrain Pugh Scoring Matrix

		Concepts									
		P0		P1		P2		P3		P4	
Selection Criteria	Weight %	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Weight of powertrain	7.1	2	0.142	3	0.21	3	0.21	2	0.14	1	0.07
Size/packaging	16.8	2	0.336	3	0.5	3	0.5	4	0.67	1	0.17
Cost	17.9	4	0.716	4	0.72	4	0.72	1	0.18	2	0.36
# of Components	5.9	2	0.118	3	0.18	3	0.18	4	0.24	1	0.06
Installation Time	16.4	4	0.656	3	0.49	3	0.49	2	0.33	2	0.33
Efficiency	22.5	1	0.225	2	0.45	3	0.68	4	0.9	5	1.13
Mechanical Reliability	13.4	3	0.402	1	0.13	1	0.13	2	0.27	5	0.67
	Total Score	2.595		2.686		2.911		2.725		2.779	
	Rank	5		4		1		3		2	

Table A 4: Battery Metrics AHP Matrix

Selection Criteria	kWh	Amperage	Cost	Size	Weight		%
kWh	x	2	1	0.5	1.5	5	20.994
Amperage	0.5	x	1.5	0.5	2	4.5	18.894
Cost	1	0.6666667	x	0.8	2.5	4.92	20.644
Size	2	2	1.33	x	0.5	5.83	24.493
Weight	0.667	0.5	0.4	2	x	3.57	14.976
						23.8	100%

Table A 5: Battery Pugh Concept Selection Matrix

		Lithium Ion Battery Packs							
Selection Criteria	Weight (%)	Leaf Battery		Enerdel		Smart Modules		A123 22s3p Modules	
kWh	20.994	4	0.83976	3	0.62982	4	0.83976	5	1.0497
Amperage	18.894	4	0.75576	2	0.37788	1	0.18894	5	0.9447
Cost	20.644	5	1.0322	2	0.41288	4	0.82576	2	0.41288
Size	24.493	3	0.73479	5	1.22465	4	0.97972	3	0.73479
Weight	14.976	2	0.29952	4	0.59904	4	0.59904	2	0.29952
Scores		3.66203		3.24427		3.43322		3.44159	

Table A 6: AHP Matrix for Internal Combustion Engine

		Metrics							Total	Weight
		Weight	Packaging	Cost	Horsepower	Torque	Efficiency	Emissions		
Metrics	Weight	x	0.75	1.50	0.75	0.75	0.33	0.33	4.41	8.8%
	Packaging	1.33	x	1.25	1.50	1.25	0.40	0.75	6.48	13.0%
	Cost	0.67	0.80	x	0.75	0.75	0.25	0.80	4.02	8.0%
	Horsepower	1.33	0.67	1.33	x	0.88	0.50	1.00	5.71	11.4%
	Torque	1.33	0.80	1.33	1.14	x	0.50	1.00	6.11	12.2%
	Efficiency	3.03	2.50	4.00	2.00	2.00	x	1.33	14.86	29.7%
	Emissions	3.03	1.33	1.25	1.00	1.00	0.75	x	8.37	16.7%

Table A 7**:** Scoring Matrix for Internal Combustion Engine Configuration

		I4 (Reference)		V6		V8	
Selection Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Weight	0.09	3.00	0.26	2.00	0.18	1.00	0.09
Packaging	0.13	3.00	0.39	2.00	0.26	1.00	0.13
Cost	0.08	3.00	0.24	2.00	0.16	1.00	0.08
Horsepower	0.11	3.00	0.34	4.00	0.46	5.00	0.57
Torque	0.12	3.00	0.37	4.00	0.49	5.00	0.61
Efficiency	0.30	3.00	0.89	2.00	0.59	1.00	0.30
Emissions	0.17	3.00	0.50	3.00	0.50	3.00	0.50
Total	1.00	21.00	3.00	16.00	2.64	14.00	2.28
	Rank	1		2		3	

Table A 8**:** Inline 4-Cylinder Engine Pugh Scoring Matrix

		General Motors Engines									
		LTG		B16DTH		Ecotec I4		LFV		LCU	
Metric	**Weights**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Weight	0.09	3.00	0.26	2.00	0.18	4.00	0.35	4.00	0.35	5.00	0.44
Packaging	0.13	3.00	0.39	2.00	0.26	4.00	0.52	4.00	0.52	5.00	0.65
Cost	0.08	3.00	0.24	3.00	0.24	3.00	0.24	3.00	0.24	3.00	0.24
Horsepower	0.11	5.00	0.57	2.68	0.31	2.76	0.32	3.26	0.37	1.96	0.22
Torque	0.12	5.00	0.61	4.54	0.56	2.85	0.35	3.54	0.43	1.81	0.22
Emissions	0.17	2.50	0.43	2.50	0.43	3.50	0.60	3.25	0.55	3.25	0.55
Efficiency	0.30	3.73	1.12	5.00	1.50	4.35	1.30	4.29	1.29	4.04	1.21
Totals	1.01	3.623		3.464		3.677		3.759		3.542	

Table A 9**:** AHP Matrix for Fuel Selection

	Energy Density	Emissions	Safety	Cost	Packaging	Efficiency	Sum	Weight
Energy Density		0.3	1	0.9	0.5	0.5	3.2	9.12
Emissions	3.333333333		2	2	1.5	1	9.83	28.03
Safety	1	0.5		1.2	2	1.1	5.8	16.53
Cost	1.111111111	0.5	0.8333		0.6666	0.8	3.91	11.15
Packaging	2	0.666666667	0.5	1.50		0.5	5.17	14.73
Efficiency	2	1	0.90909	1.25	2		7.16	20.41

Table A 10: Pugh Scoring Matrix for Fuel Selection

		Fuel Types													
		Gasoline (E10)		Ethanol (E85)		CNG		Low Sulfur Diesel		BioDiesel		Hydrogen Fuel Cell		Electric/Battery	
Selection Criteria	**Weight**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**
Energy Density	9.12	4.52	0.41	2.84	0.26	5.00	0.46	4.28	0.39	3.62	0.33	0.23	0.02	0.05	0.00
Emissions	16.54	3.00	0.50	3.00	0.50	1.00	0.17	3.00	0.50	3.00	0.50	1.00	0.17	2.00	0.33
Safety	11.15	5.00	0.56	4.90	0.55	3.67	0.41	3.83	0.43	3.83	0.43	0.00	0.00	1.67	0.19
Cost	14.73	5.00	0.74	5.00	0.74	2.00	0.29	4.00	0.59	4.00	0.59	1.00	0.15	1.00	0.15
Packaging	20.41	1.67	0.34	1.50	0.31	1.58	0.32	2.22	0.45	2.00	0.41	3.33	0.68	5.00	1.02
Efficiency	28.03	0.00	0.00	0.87	0.24	0.59	0.17	0.55	0.16	0.84	0.24	4.50	1.26	5.00	1.40
Total Score		2.54		2.59		1.81		2.51		2.49		2.27		3.09	
Rank		3		2		7		4		5		6		1	

Table A 11: AHP Matrix for Electric Motors

		Metrics								
		Continuous Torque	Continuous Power	Peak Torque	Peak Power	Cost	Size / Packaging	Weight	Total	Weight
Metrics	Continuous Torque	x	1.2	4.0	2.0	1.5	1	5	14.7	24.5%
	Continuous Power	0.8	x	4.0	2.0	1.5	1	5	14.3	23.9%
	Peak Torque	0.3	0.3	x	1.0	0.8	0.7	3	6.0	10.0%
	Peak Power	0.5	0.5	1.0	x	0.8	0.7	3	6.5	10.8%
	Cost	0.7	0.7	1.3	1.3	x	0.9	4	8.7	14.5%
	Size/Packaging	1	1	1.4286	1.4286	1.111	x	2	8.0	13.3%
	Weight	0.2	0.2	0.3333	0.3333	0.25	0.5	x	1.8	3.0%
								SUM	60.1	100.0%

Table A 12: Pugh-Scoring Matrix for different Electric Motors

		Electric Motors										
		Remy HVH250-115 (Reference)		YASA P400 (400V)		YASA P750 (400V)		Remy HVH250-90		Solectria AC21-A		UQM PowerPhase100
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating
Continuous Torque	24.5	3	0.735	2	0.49	5	1.225	2	0.49	1	0.245	2
Continuous Power	23.9	3	0.717	3	0.717	3	0.717	3	0.717	1	0.239	3
Peak Torque	10	3	0.3	2	0.2	3	0.3	3	0.3	1	0.1	3
Peak Power	10.8	3	0.324	3	0.324	4	0.432	3	0.324	1	0.108	4
Cost	14.5	3	0.435	2	0.29	2	0.29	5	0.725	5	0.725	3
Size	13.3	3	0.399	5	0.665	2	0.266	4	0.532	1	0.133	1
Weight	3	3	0.09	5	0.15	4	0.12	4	0.12	4	0.12	2
	Score	3		2.84		3.35		3.21		1.67		2.567
	Rank	2		3		0		1		5		4

Table A 13: AHP Weighting Matrix for Motor Controller

		Metrics						
		Peak Current	Continuous Current	Input Voltage Range	Cost	Size	Total	Weight
Metrics	Peak Current	x	0.40	0.80	1.20	1.50	3.9	16.4%
	Continuous Current	2.50	x	1.25	1.50	2.00	7.3	30.5%
	Input Voltage Range	1.25	0.80	x	2.00	2.00	6.1	25.5%

	Cost	**0.83**	**0.67**	**0.50**	**x**	**2.50**	**4.5**	**18.9%**
	Size	**0.67**	**0.50**	**0.50**	**0.40**	**x**	**2.1**	**8.7%**

Table A 14**:** Pugh Scoring Matrix for Motor Controller

		Motor Controller											
		AMC 250A060		**AMC 125A200**		**Launchpoint Technologies**		**YASA Si400**		**DANA TM4 C0150**		**Rinehart PM250**	
Metrics	**Weight**	**Values**	**Weighted Score**	**Values**	**Weighted Score**	**Values**	**Weighted Score**	**Values**	**Weighted Score**	**Values**	**Weighted Score**	**Values**	**Weighted Score**
Peak Current	**16.4**	**2.03**	**0.332**	**1.02**	**0.167**	**1.3**	**0.2132**	**4.06**	**0.665**	**5**	**0.82**	**3.66**	**0.600**
Continuous Current	**30.5**	**1.875**	**0.571**	**1**	**0.305**	**1.05**	**0.32025**	**2.625**	**0.800**	**4.44**	**1.3542**	**5**	**1.525**
Input Voltage Range	**25.5**	**0.54**	**0.1377**	**1.75**	**0.446**	**5**	**1.275**	**4**	**1.02**	**4.5**	**1.1475**	**4**	**1.02**
Cost	**18.9**	**3.821**	**0.722**	**5**	**0.945**	**3.620**	**0.68**	**2.470**	**0.466**	**2.4**	**0.4536**	**2.24**	**0.422**
Size	**8.7**	**5**	**0.435**	**5**	**0.435**	**5**	**0.435**	**5**	**0.435**	**4**	**0.348**	**3**	**0.261**
	Total Score	**2.199**		**2.298**		**2.92**		**3.38**		**4.12**		**3.832**	
	Rank	**5**		**6**		**4**		**3**		**1**		**2**	