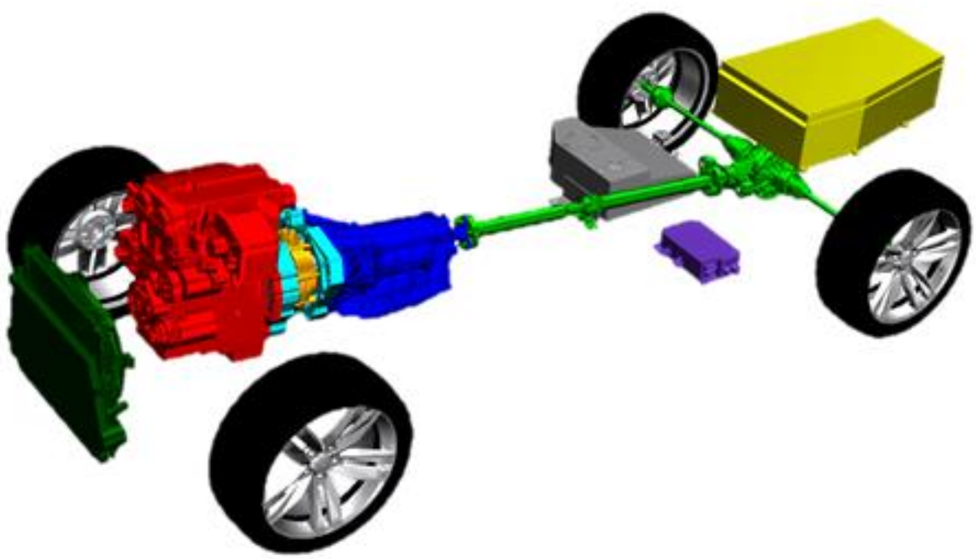
Penn State University Advanced Vehicle Team
Universal Powertrain
Statement of Work

October 4, 2019



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Executive Summary

The Penn State Advanced Vehicle Team (AVT) is a student organization that strives to reengineer vehicles to lower fuel consumption while maintaining the specifications of the customer's needs. Vehicles from automotive suppliers are modified with a hybrid powertrain in order to improve fuel efficiency and all-around performance. Hybrid powertrains are one of the most significant yet complicated ways to improve vehicle performance. Hybrid powertrains combine traditional internal combustion engines with an electric power system and motor producing power from multiple sources of energy to improve efficiency.

The Universal Powertrain team has 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 does not know what their next vehicle is going to be, the specifications of the powertrain must be compatible with a wide range of vehicles.

Through market research and knowledge from previous competitions, the team was able to create a list of weighted performance metrics to satisfy the customer needs of the AVT team. Hybrid-electric configurations, previous designs, patents, competition scoring, and competition specifications were thoroughly researched. The technical approach of the team goes through the concept selection process of the various powertrain configurations as well tools and methods the team plans to use to deliver a final product. The team will also perform a budget analysis which must stay within a yearly budget of $1000 and an overall powertrain cost in the range of $20,000-$50,000. The deliverables of the project follow a critical path of research, powertrain selection, component selection, modelling, and vehicle integration which must be completed in a timely manner. The team has scheduled tasks in a Gantt chart that must be followed in order to meet the deadlines of their deliverables.

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1.0 Introduction

The Penn State Advanced Vehicle Team (AVT) is intended to reengineer vehicles to lower fuel consumption while maintaining consumer demand (About PSU AVT, n.d.). Stock vehicles are modified in order to improve fuel efficiency and all-around performance. Hybrid powertrains are one of the most significant factors in improving performance. By combining traditional internal combustion engines with an electric power system, the energy efficiency can be significantly increased. Previous projects have resulted in the creation of a charge-sustaining (CS) series hybrid 2000 GM Suburban, a CS parallel hybrid 2002 Ford Explorer, a CS through-the-road parallel hybrid 2005 Chevrolet Equinox, a charge depleting (CD) series hybrid 2009 Saturn Vue, a CD series hybrid 2013 Chevy Malibu, and most recently a CD parallel hybrid 2016 Chevy Camaro (Neal, 2019).

Hybrid powertrains come in several different configurations, each with several benefits and drawbacks. A series powertrain has an electric motor provide power to the wheels. The motor receives energy from a battery pack charged by a generator powered through an internal combustion (IC) engine (Constans, 2013). A parallel powertrain can power the wheels by using energy from both an IC engine and an electric motor at the same time. The goal is to run the IC engine at the most efficient RPM and use the electric motor for power transients. There are several different orientations of the electric motors, referred to as P0, P1, P2, and P3 as seen in Figure 1.

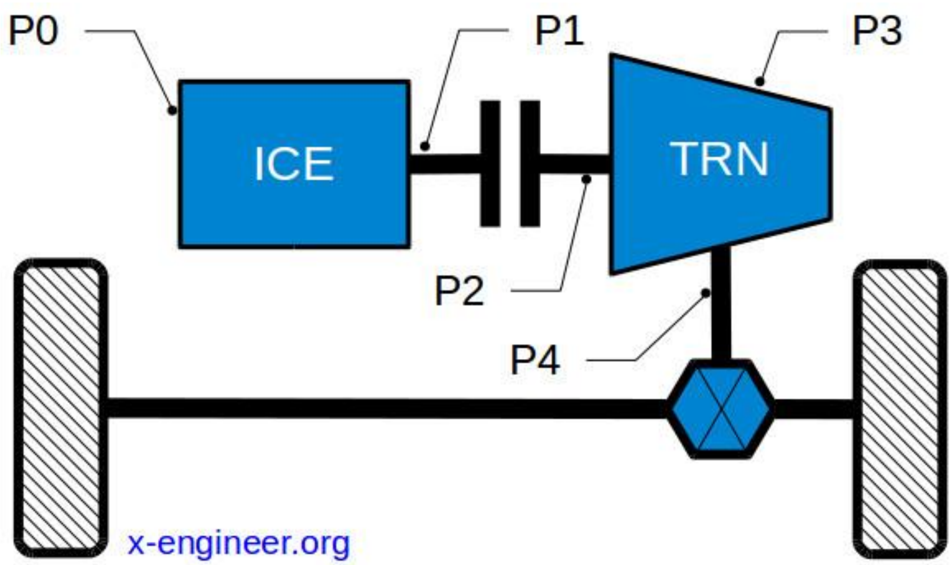

Figure 1: Electric Motor Positions in Different Parallel Powertrain Configurations (X-Engineer, n.d.)

Through-the-road powertrains have an IC engine powering one of the vehicle axles. This engine can drive the car and drives a motor/generator on the rear axle. The rear electric drive and front IC engine drive are thus coupled "through the road" (Constans, 2013). A power-split configuration contains aspects of both the series and parallel powertrains but has additional complexity. A power split device such as a planetary gear couples the IC engine to a generator and to the wheel drive (Constans, 2013).

In the United States, transportation accounts for 29% of greenhouse gas emissions (Sources of Greenhouse Gas Emissions, 2017). The primary emissions of concern are carbon dioxide, NOx (Nitrous Oxides), and other hydrocarbons such as methane. Greenhouse gases do not have equal effects; certain gases such as N_2O, have nearly 300 times the effect of carbon dioxide (Greenhouse Gas Equivalencies Calculator, 2018). Fuel choice can also play an important role in determining the power, efficiency, and emissions based on whether the fuel is gasoline, ethanol, diesel, compressed natural gas, or another form of stored energy (Fuel Effects on Vehicle Emissions, 2018). The quantity of environmental hazards emitted is determined by the amount of hydrocarbon burned, the type of hydrocarbon burned, and any filters or scrubbers used between the engine and the environment. The use of a hybrid power system should reduce the fuel consumed over a given distance and consequently reduce the harmful emissions released to the environment.

While the competition has historically focused on efficiency, emissions, and environmentally conscientious concerns, the performance of the car and consumer appeal must be considered. There are currently about 4.55 million electric-gasoline hybrid light vehicles in the US, with an additional 1.6 million electric or plug-in hybrid vehicles, and both categories are projected to grow in the future (Annual Energy Outlook, 2019). A market survey was done to determine the expected vehicle characteristics of a future stock competition car (Motor Trend, n.d.) (Car and Driver, n.d.). The vehicles included were previous competition cars and popular 2019 cars. These vehicles are then broken down based on whether IC engines, hybrid powertrains, or full-electric motors are used to provide power to the wheels. The averaged specifications for these vehicles can be seen in Table 1.

Table 1: Market Analysis Powertrain Specifications

Powertrain Type	Calculation	Weight (lb)	Horsepower	Torque (lb-ft)	lb/hp	lb/tq	0-60 (seconds)	City MPGe	Highway MPGe
IC	Average	3532.33	218.00	221.56	16.66	16.55	7.58	22.11	29.78
	Stdev	425.84	51.20	55.35	2.52	2.93	1.30	4.88	5.93
Hybrid	Average	3319.50	152.25	181.25	22.11	21.22	8.33	48.75	45.50
	Stdev	351.74	27.49	84.67	2.76	8.85	1.01	6.65	4.65
EV	Average	3636.50	201.50	275.00	18.69	13.31	6.55	125.75	107.00
	Stdev	156.31	45.33	30.99	3.84	1.10	0.92	2.63	8.12
Total	Average	3506.76	198.65	224.65	18.42	16.89	7.51	52.76	51.65
	Stdev	363.03	50.88	64.55	3.54	5.21	1.26	43.43	32.84

In order to determine baseline specifications for a future vehicle, a survey of all 2020 gasoline and hybrid vehicles was conducted with data from the Environmental Protection Agency (EPA) (Fuel Economy Data, 2019). The results for combined MPG and emissions can be seen in Table 2.

Table 2: 2020 EPA Vehicle Environmental Data

Vehicle Category	Air Pollution Score (10=best)	Combined MPG	Greenhouse Gas Score	Combined CO_2 (g/mile)	Number of Vehicles in Market
Small SUV	5.279	24.05	4.844	380.4	276
Midsize Car	5.586	32.53	6.310	312.6	174
Small Car	4.253	24.44	4.897	383.4	348
Hybrid Vehicle	6.600	80.88	9.800	148.4	20
All above	4.898	26.07	5.187	366.9	798

Given the prevalence of Small (crossover) SUVs in the market and historical competition vehicles, the team's powertrain is being designed to accommodate a crossover SUV. Using popular crossover SUV models as a basis, the vehicle is assumed to have a weight of about 3750lbs, height of 67.1in, width of 74.1in, and length of 185.8in (Motor Trend, n.d.). For packaging purposes, the overall size and engine compartment size will be assumed to be smaller to ensure components will fit in several vehicles.

1.1 Initial Problem Statement

The powertrain design of a vehicle is a critical component to determining the performance specifications of the car. In order to facilitate future PSU AVT teams, this group is tasked with creating a powertrain that will be able to be used in a range of expected future competition cars. While the exact vehicle specifications are not known, assumptions based on previous vehicles can be used to determine how the powertrain will perform. In particular, the type of powertrain, specific electrical and mechanical components, mounting locations, and energy storage methods will need to be determined.

1.2 Objectives

This project will comprise of designing a hybrid powertrain for a future competition vehicle. The design will show the type of hybrid and the general orientation of components in a CAD model and small-scale physical model. Specifications for each component will be listed, and if the component depends on more exact vehicle specifications, a range of acceptable values will be provided. Expected vehicle performance ranges will also be calculated, however electronics variables such as optimally programming the motor controllers are beyond the scope of this project. In order to better assist future teams, recommended installation instructions and procedures will accompany the design.

2.0 Customer Needs Assessment

The Penn State Advanced Vehicle Team will be the customer of the final product. Whatever powertrain design is used must be able to be a viable option for the next efficiency-improving vehicle competition. Because each design decision has trade-offs, the customer needs the team decides are vital to determining the relative importance amongst the design metrics and specifications.

2.1 Gathering Customer Input

Before going through the design process, multiple assumptions were made about the customer needs. Through meetings with the team advisors, reading prior documentation on the team's SharePoint, and researching the competition scoring, a list of customer needs that the final product must fulfill was created. These customer needs include vehicle dynamics, being environmentally friendly, fuel efficiency, affordability, and serviceability. From these customer needs multiple metrics were determined to help score the success of the design and make an informed choice. A table of the customer needs and metrics can be seen in Table 3.

Table 3: Customer Needs Matrix with Metrics for the Universal Powertrain Design.

		Metrics							
		Weight of Powertrain	Size	Cost	Number of Components	Installation Time	MPG/ MPGe	Horsepower	Emissions
Customer Needs	Vehicle Dynamics	X						X	
	Environmentally Friendly						X		X
	Fuel Efficient	X					X		X
	Affordable			X					
	Serviceable		X		X	X			

2.2 Weighting of Customer Needs

In order to effectively score each powertrain configuration, the relative importance of the different customer needs and metrics needed to be determined. An analytic hierarchy process (AHP) matrix scores the importance by creating the weights associated with each score. The scoring and final weights of each metric can be found below in Table 4.

Table 4: AHP Scoring Matrix with Final Metrics Weights.

		Metrics								Weight
		Weight of powertrain	Size	Cost	Number of Components	Installation Time	MPG/MPGe	Horsepower	Emissions	
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%

The AHP matrix determined that miles per gallon equivalent (MPG/MPGe) was the most important design metric. Fuel efficiency is a major component of the Ecocar team competition and is desirable for consumers from a financial and environmental standpoint. Coming in at a close second was the emissions metric because reducing the amount of greenhouse gas emissions is an important part of making the vehicle more environmentally sustainable. The next most important metric is cost as the team must be able to have the components donated or be able to afford purchasing new parts. Size of the powertrain is the next highest weighted parameter because the powertrain components selected must be packaged within a reasonable amount of space of the assumed vehicle.

Horsepower is the next metric that must be measured as the amount of power the vehicle makes will be crucial to overall performance in several acceleration-based categories. Installation time is another important metric because the powertrain must be able to be implemented or repaired in a reasonable timeframe for future teams. The overall weight of the powertrain was also scored because the weight of the powertrain as well as the weight distribution will affect the vehicle dynamics and efficiency of the car. Lastly, the number of components is an important metric as the more parts in the system adds complexity and failure points, reduces efficiency, and may increase service time. These general metrics will be used to score and select a powertrain type which will be discussed in section 5.2 later in this report.

3.0 External Search

The external search section focuses on utility and design patents that already exist to potentially be used or referenced by the Universal Powertrain team's initial project. Since the team's task is concentrated on coming up with a model adaptable powertrain design for crossover SUV, external search examines patents and existing design regarding possible implementations for the change in appropriate target specification. Examining previously dealt design schematics will provide technical and nontechnical instruction to build reliable, and efficient powertrain.

3.1 Patents

Patents researched for Universal power team closely ties with the major goal of external research. Patent examines fundamental efficiency and power configurations that guides to optimal configurations. Section 3.1.1 discovers high torque configuration in hybrid powertrain, this section will help universal hybrid team to distinguish high torque powertrain configurations for crossover SUV. Section 3.1.2 illustrates the muti-mode hybrid transmission used to split IC engine power between wheel and generator. Section 3.1.3 explores in optimal IC engine to Motor power ratio and corresponding efficiency

3.1.1 Hydrocarbon fuelled-electric series hybrid propulsion systems

Inventor: Jay J. Bowman, **Patent #:** CA2787764C
Summary: This Patent filed by Jay J. Bowman is currently assigned to ePower Engine Systems LLC. This patent presents methods, circuits, and devices for controlling the traction-motor speed of electrically propelled vehicles for control of the vehicle or its driving motor to achieve the desired performance, e.g. speed, torque, programmed variation of speed for braking under such real-life situations relating driver fatigue. The scope of this patent is intended for semi-tractor trailer trucks. Since expected future powertrain will require heavier and higher torque to operate, looking at design method and approach for a hybrid system of semi-truck can inform Universal Powertrain team with the specifications to obtain the high reliability in heavier purpose hybrid power systems.

3.1.2 Multi-mode hybrid transmission

Inventor: Shaun E. Mepham, Jonathan P. Brentnall, Cameron P. Williams, Eric Sharkness, Felipe V. Brandao, **Patent #:** US8523734B2
Summary: This Patent was initially filed by Shaun E. Mepham, Jonathan P. Brentnall, Cameron P. Williams, Eric Sharkness, Felipe V. Brandao and currently assigned to Ricardo Inc. This transmission is for transmitting power from the prime mover to a stored source of energy. This invention has advantages of both parallel and series, similar to power split configuration today, while reducing the

number of parts such as additional planetary gear. Figure 2 Schematically represents the transmission in accordance with an embodiment of the present invention. Figure 3 exhibits three-speed hybrid transmission cross-sectional view of the hybrid transmission. Figure 4 illustrates cross-sectional view of four-speed hybrid transmission.

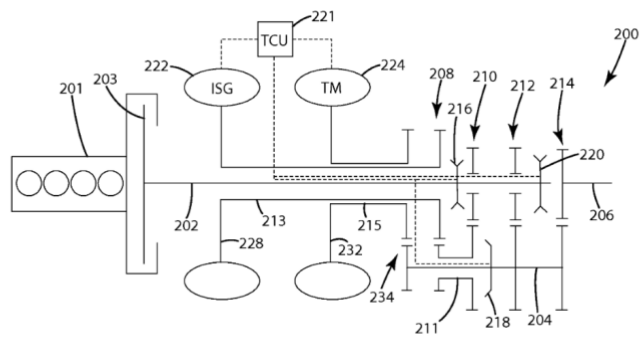

Figure 2: Schematic Representation of a Three-Speed Hybrid Transmission (Shaun E. Mepham 2009)

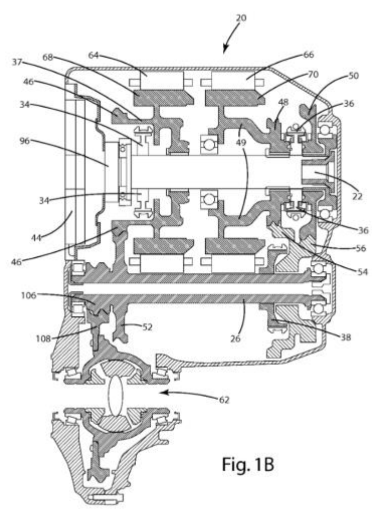

Figure 3: Cross-Sectional View of The Hybrid Transmission (Shaun E. Mepham 2009)

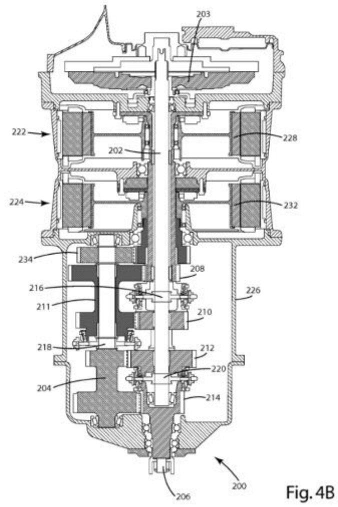

Figure 4: Cross-Sectional View of The Hybrid Transmission (Shaun E. Mepham 2009)

3.1.3 Hybrid electric vehicle

Inventor: Alex J. Severinsky, **Patent #:** US5343970A

Summary: This Patent filed by Alex J. Severinsky and currently assigned to Abell Foundation Inc. shows when the hybrid system was at the prototype phase. The patent demonstrates the problem and solutions for the power ratio between the IC engine and the motor. Mechanical parts including shaft strength are especially relevant to the recent Camaro powertrain issue. As Universal Power team's decision will be the onset of further advancement in powertrain design, fundamental understanding of power ratio and its efficiency will help build a successful powertrain design for the EcoCAR competition. Figure 5 represents the Plot of Output Power vs RPM of engine to help with deciding configurations of IC and motor setup in Universal Powertrain team. Figure 6 schematically illustrates the Hybrid drive system setup. Figure 7 illustrates cross sectional view of mechanical coupling of clutch and torque transfer unit.

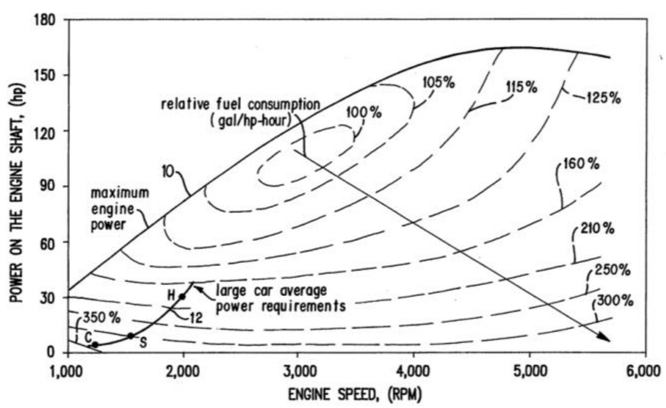

Figure 5: Plot of Output Power Versus RPM for a Typical Internal Combustion Engine (Alex J. Severinsky 1992)

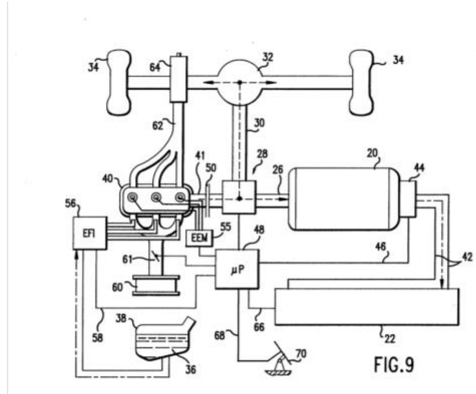

Figure 6: Schematic Diagrams of The Hybrid Drive System (Alex J. Severinsky 1992)

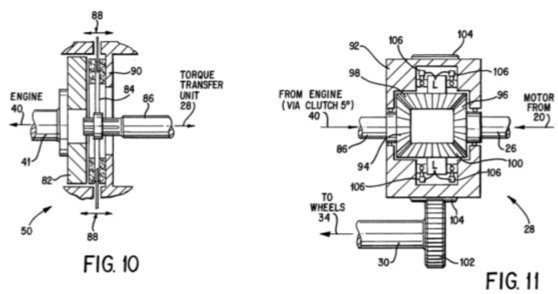

Figure 7: Cross-Sectional View of a Clutch Forming Frictional Coupling(left), Torque Transfer Unit(right) (Alex J. Severinsky 1992)

3.2 Existing Products

Gas-electric hybrid vehicles have been around for 20 years. Gasoline is the primary fuel source, with electricity as the second source. These vehicles have the ability to salvage the lost energy from braking and can operate in more efficient regimes. Different hybrid types have various capabilities and drawbacks. A competition proven and a market proven product are discussed in the following section.

3.2.1 Previous Ecocar

PSU Ecocar 3

The model for Ecocar 3 competition is a 2016 Chevy Camaro. A “P2” Charge-depleting, parallel hybrid powertrain system is customized and Equipped on the car.

A 2.0L LTG E85 203 kW output engine, along with an electric motor made by YASA, model name P400, with a 65 kW peak power output is mounted to an 8-speed auto transmission.

Figure 8 is the CAD model of the Ecocar 3 Camaro with the YASA motor and Table 5 is the performance specification of the Ecocar 3.

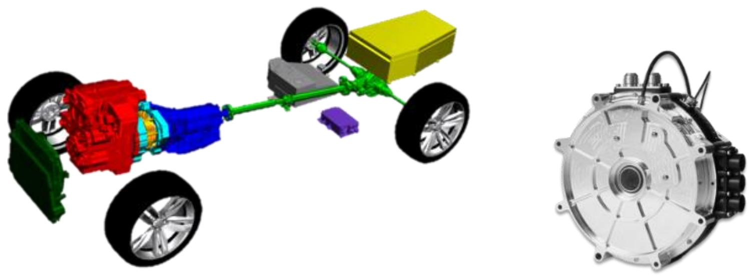

Figure 8: 3D Model of the Ecocar 3 Powertrain and YASA motor (Andy Saran, 2017)

Table 5: Camaro Performance Specifications (Gary Neal, 2019)

0-60mph	5.965s
50-70mph	3.45s
60-0mph	128ft
Weight	1779kg
Lateral g's	0.76g
UF-Weighted Total Energy Consumption	50.1 MPGe
Total Vehicle Range	250 miles
CD Mode Range (blended)	28.1 mi (blended)

3.2.2 Popular Products on the Market Today

Series Hybrid: BMW I3 REx
A gasoline range extender engine with inline two-cylinder engine is used in the BMW C650GT maxi-scooter and is equipped as the generator of the series powertrain. The REx engine develops 34 hp; 34 PS (25 kW) and 41 lb. Ft;(55 Nm) at 4,300 RPM, which operates when battery capacity drops to a pre-specified level. Under EPA five-cycle testing, the i3 REx has a total range of 240 km (BMW of North America, 2019). An example of this powertrain can be seen in Figure 9.

Figure 9: BMW i3 Powertrain (BMW of North America, 2019)

Parallel Hybrid: Toyota Prius Prime
Toyota Prius Prime is a plug in parallel with an EPA-rated all-electric range of 25 mi (40 km) and an EPA rated fuel economy of 133 mpg-e (25.9 kWh/100 mi) in all-electric mode (EV mode). The Prius Prime has an EPA-rated combined fuel economy in hybrid mode of 54 mpg in city driving, and 53 mpg in highway. The EPA-estimated total driving range is 640 miles and the EPA-estimated EV Mode64 driving range i25 miles. The hybrid system has a net power of 121 hp (90 kW) with the 1.8-Liter 4-cylinder engine and a permanent magnet AC synchronous motor with an 8.8 kWh battery capacity (Toyota Motor Sales, 2019). The Prius powertrain components are shown in Figure 10.

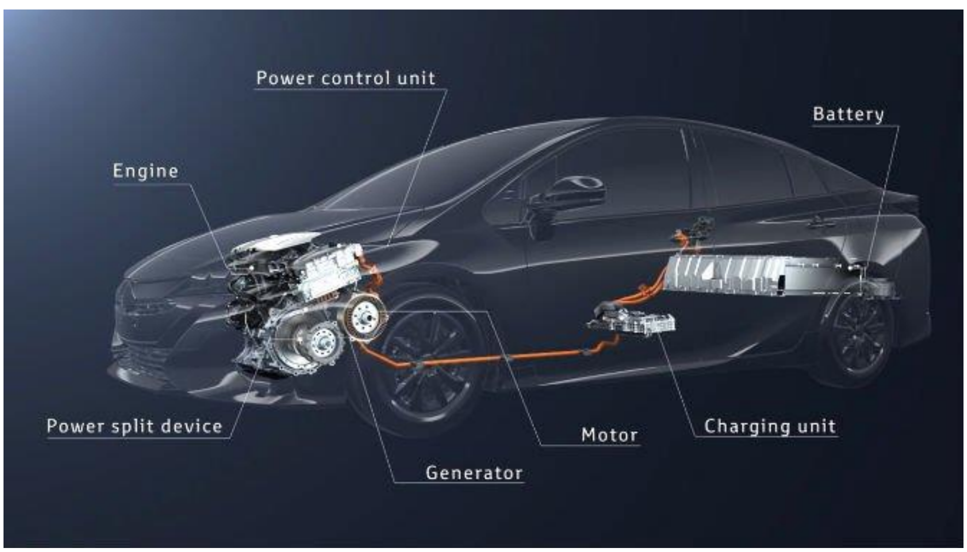

Figure 10: Toyota Prius Prime Powertrain (Toyota Motor Sales, 2019)

4.0 Engineering Specifications

The team can control the scope of the project by determining the engineering specifications necessary for success. In this section, the team will make educated assumptions to define importance, threshold values, and objective values for the specifications. These specifications are carefully chosen based on the requirements from previous EcoCAR competitions as well as new assumptions which were made after completing market research and identifying customer needs and can be found in Table 6 (Robert

Jesse Alley, 2014). The team will continue to update any specifications as the project progresses to ensure the successful design of the powetrain.

Table 6: Target Specifications

Specification No.	Specification	Importance (1=not very, 5=very)	Threshold Value (1)	Objective Value (2)	Units
1	Powertrain weight	4	<1200	800	lb.
2	0-60mph Time	4	<9	15	sec
3	50-70mph Time	5	<4	3	sec
4	60-0mph	5	>45	35	meters
5	Battery Pack Capacity	5	>10	20	kWh
6	Weighted Green House Gas Emissions	5	<250	125	g/mile
7	Battery Weight	4	<600	300	lb
8	Audible System Noise	3	<80	70	db
9	Installation Time	5	<4	3	months
10	System Cost	5	<50,000	20,000	$
11	Fuel Tank Capacity	4	>8	12	Gallons
12	Vehicle Range (Gas+Electric)	5	>200	300	Miles
13	Electric Range	5	>20	25	Miles
14	Trunk Storage	2	>25	50	% of original size
20	Human Capacity	3	>2	4	People
21	Distance before service	5	>2000	50000	Miles
22	MPGe	5	>35	50	MPGe
23	Number of electric motors	3	<4	1	Electric motors
24	Fuel Tank Size	3	<20	8	Gallons

25	Time to Refuel/Recharge	4	<8	<1	Hours

(1) **Threshold** - A minimum acceptable value of an attribute considered achievable within the available cost, schedule, and technology at low-to-moderate risk.
(2) **Objective** - The objective value is the desired operational goal achievable at a higher risk in cost, schedule and technology. Performance above the objective does not justify the additional expense.

This list of specifications was determined based off the customer needs, the competition requirements, as well as the basic components of a hybrid-electric powertrain. The specifications given an importance of 5 were considered critical to the customer and competition. Level 5 importance specifications include MPGe and Emissions. Specifications that were not critical were rated as a 4 and include weight and horsepower. If the specification was not critical, but was a metric that needed to be considered, the specification was given a rating of 3, such as human passenger capacity and noise. Lastly, any other specification that was not directly related to the vehicles performance or competition was given a score of 2 or 1 if even less important. These specifications will be used for the team as guidelines when choosing components or making design decisions which will be discussed in the technical approach.

5.0 Technical Approach

Using a parallel hybrid system as a reference for performance and cost, the universal powertrain team set out to do research into multiple other layouts of hybrid car powertrain as well as full electric powertrain. The powertrains that team members researched were parallel hybrid, series hybrid, through-the-road hybrid, power split hybrid, in-wheel motor EV (electric vehicle), battery electric EV, and converted EV. The team then collectively decided on general customer needs for this universal powertrain, items like having the car be both eco-friendly and come at a reasonable cost. The next step was to weigh the metrics generated using an AHP matrix. This AHP matrix determined what aspects would be most important and assisted in making a decision on the final powertrain type. Using understanding gathered through previously mentioned industry research in combination with these weights, the team created a Pugh concept scoring chart to finalize the choice with a numerical value.

To narrow down and further improve the selected powertrain, the universal powertrain team plans to use Solidworks and MATLAB Simulink to conduct any theoretical size and strength testing needed and potentially test scaled down mock-ups of battery and other electrical systems to determine overall capacity, performance, and cost. The team will use EcoCAR 3's scoring model as well as the team's listed technical specifications in order to determine the success of the powertrain.

5.1 Concept Generation

Generally, the concepts are limited to the most common types of hybrid power systems. Fuel choices are limited to gasoline, diesel, CNG, ethanol, biodiesel, hydrogen, and just electricity. In this section, the team will explore several different configurations starting with power-split, series, parallel (P2), battery electric, and through the road. This analysis will provide a better idea of the advantages and disadvantages of different hybrid powertrains and thoroughly inform values placed in decision matrices.

The power-split configuration is best known to be used in the Toyota Prius. This configuration uses a unique planetary gear set to connect the engine, motor and generator via electronics and a battery pack. An advantage of this configuration is that the motor is connected to the wheels which provides additional torque if required and also allows to charge the battery via recovered energy from the wheels. Furthermore, when the engine is not being used to power the wheels, a power-split powertrain can run at optimal speeds to recharge the battery via the generator which improves engine efficiency. One drawback of using this configuration would be that energy needs to go through a generator-battery-motor loop which results in a loss of efficiency compared to direct mechanical connection. Figure 11 shows a basic diagram of the power split system.

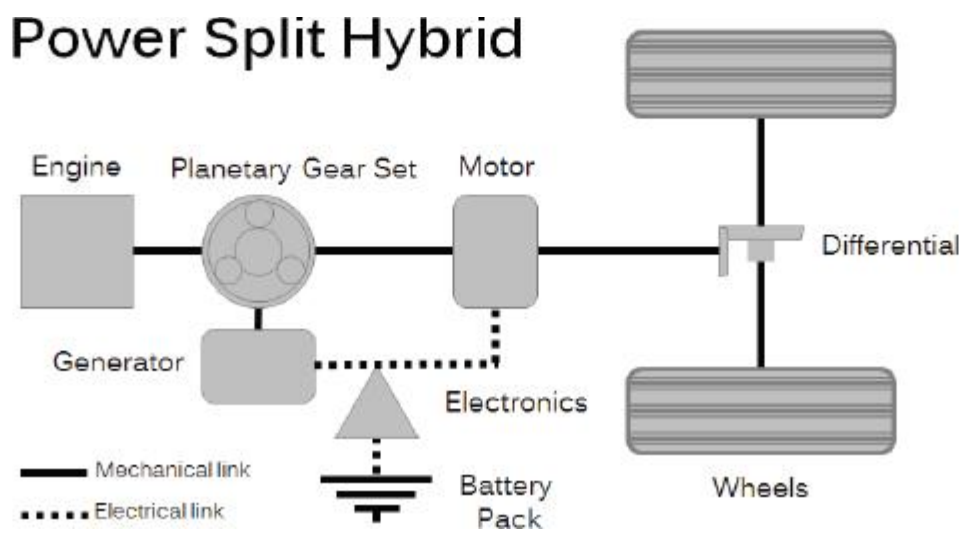

Figure 11: Power Split Hybrid Configuration (Board on Energy and Environmental Systems, 2015)

A series powertrain is designed in a way that the engine will charge the battery via a generator which will then power a motor that is connected to the wheels. A big advantage of this system is that the series configuration allows the engine to run at optimum speeds to charge the battery, resulting in operating at maximum efficiency when there is lots of starting and stopping. The motor, which is typically larger, is designed to provide maximum power/performance in full-electric mode while also being able to recover energy via regenerative braking. One of the biggest disadvantages of this system is high costs. As seen in industry examples, the series hybrid configuration typically takes a larger, heavier, and more expensive electric motor. Figure 12 shows a basic diagram of the series system.

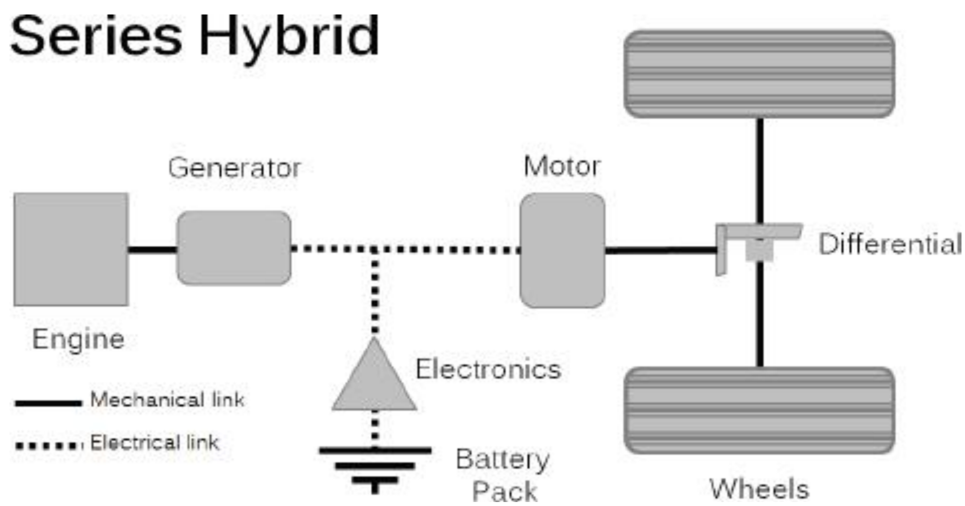

Figure 12: Series Hybrid Configuration (Board on Energy and Environmental Systems, 2015).

In a P2 hybrid configuration, a clutch is typically connected between the engine and the motor/generator. This has two main advantages, firstly, the engine's friction does not reduce regenerative braking and the transmission can be used to spin the motor/generator at higher speeds to recover more energy. One of the big challenges with the P2 configuration, comes from the need to program the optimal power distribution between the engine and motor. Figure 13 shows a basic diagram of the parallel system in the P2 configuration.

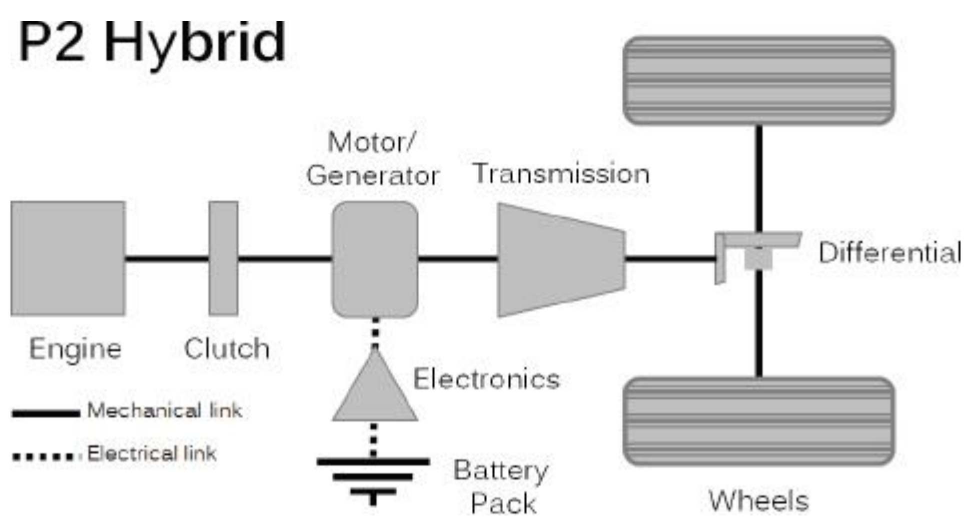

Figure 13: P2 Hybrid Configuration (Board on Energy and Environmental Systems, 2015).

In a battery electric configuration, the battery directly powers the motor which is connected to and powers the wheels. Being the most novel, "out of the box", the battery electric is the simplest configuration the team is exploring. Some advantages of this would be improved performance since power/torque will be available all the time as long as there is charge in the battery. On top of this, since battery electric has the least number of components, there will be minimal energy loss from the battery to the output in the wheels. On the other hand, the greatest disadvantage of the battery electric configuration would be the cost and weight of the larger battery pack and motor required to provide sufficient electric range. Figure 14 shows a basic diagram of a battery electric system.

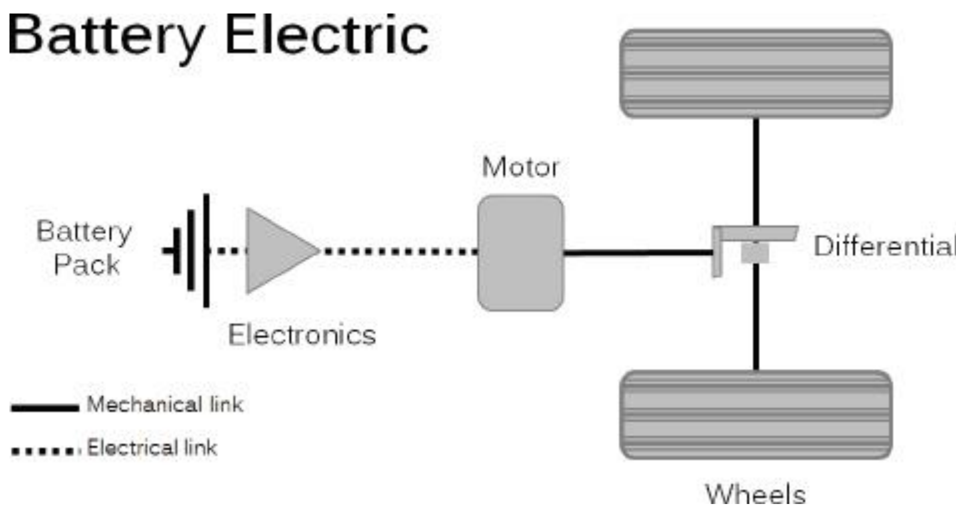

Figure 14: Battery Electric Configuration (Board on Energy and Environmental Systems, 2015).

Through the road is an alternative to a parallel powertrain that utilizes a combustion engine to power one pair of wheels and an electric motor to power the other pair. There is no mechanical linkage between the systems. The two power outputs can work together or independently depending on need, and the electric motor works as a generator powered by forward movement of the car to recharge the batteries. This system could also be built with two electric in-wheel motors for the rear which provides greater control. One of the biggest advantages of the through the road system is the ability for an all-wheel drive mode, a greater flat-torque response and improved driver's response in terms of handling and performance. However, the biggest challenge with implementing this powertrain would be packaging the electric motors within, or around the wheels (MAHLE Powertrain Ltd, n.d.). Figure 15 shows a basic diagram of a through the road system.

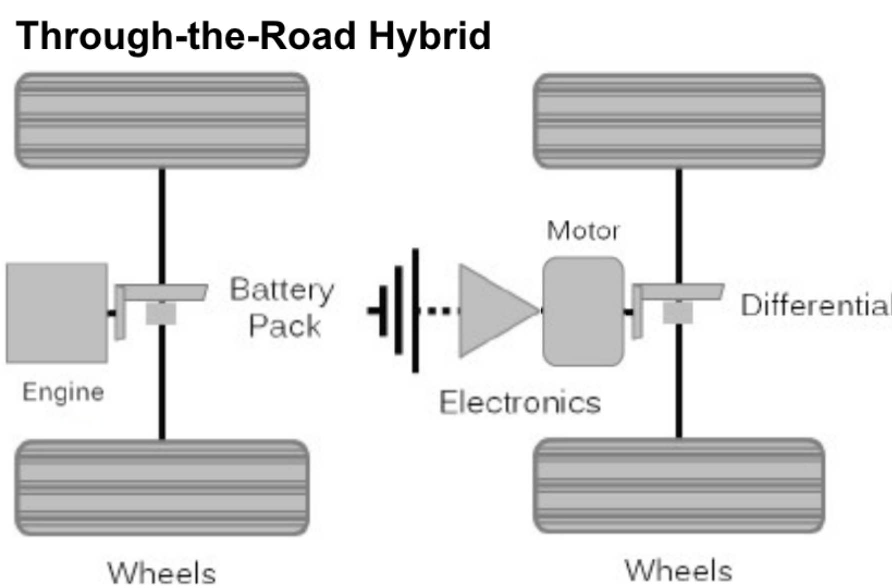

Figure 15: Through the Road Hybrid (Board on Energy and Environmental Systems, 2015).

5.2 Concept Selection

AHP matrices can be used to make an informed decision and compare several systems with many variables. Each system is given a score between 1 and 5, with 3 being approximately equal to the reference system (parallel powertrain). A score of 4 is somewhat better than the reference powertrain, with 5 being significantly better. For example, the electric drive train has significantly improved MPGe (2-3x greater) over the parallel system, and some improvement in terms of the number of components (does not require IC engine). Conversely, a score of 2 is somewhat worse than reference, while a score of 1 is significantly worse. The use of whole numbers to separate each category was used to spread the scores greater and make the optimal powertrain decision stand out, the scoring can be seen in Table 7.

Table 7: Pugh Concept Scoring matrix

		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	

Using the Pugh concept matrix, the electric, parallel, and through the road powertrains were determined to be the most likely candidates for success. Although scoring the highest, the battery electric EV has an immense cost associated with purchasing the number of batteries needed to have an adequate range to compare against other powertrains. It is expected that the battery electric powertrain would be well outside of the designated $20,000-$50,000 budget for the powertrain as a whole and is not viable with current resources.

Based on the next best scoring powertrain, the team has decided to pursue the parallel hybrid model, a setup where the combustion engine works in conjunction with the electric motor to share the work of powering the car. This arrangement allows both components to be sized smaller than other hybrid configurations, saving on cost and weight. The team's third choice is the through-the-road hybrid, a system that includes both a separate combustion engine system and an electric motor system which can be run either at the same time or independently depending on specific need. The through-the-road configuration scored lower in weight and size but made up for many deficits with features like the ability to be run as an all-wheel drive vehicle. The power split powertrain was deemed to be too complex and difficult to install for a future AVT group to pursue. Series powertrains are almost never used in production vehicles, a fact reflected in this scoring matrix. Series powertrains have higher costs, weight, and space requirements which is undesirable.

6.0 Special Topics

This project is subject to several non-technical practical constraints that will limit overall success. The primary two resources in any project are time and money and plans for both aspects are needed. A project budget for this semester can be found in Table 8. A Gantt chart project schedule is found in Figure 16. In addition, there are several risks to the overall project seen in Table 9, plans have been developed to mitigate expected issues that may arise.

6.1 Preliminary Economic Analyses - Budget and Vendor Purchase Information

This project has been allocated a budget of $1000 for the development of a universal powertrain system. The expected breakdown of costs is shown in Table 7.

Table 8: Estimated Budget for Fall 2019

Estimated Budget	
Category	**Estimated Cost**
Small-scale model materials	$50
Existing component repairs and shipping	$400
Total Spending	$450

In this preliminary estimate, the team does not expect to spend the $1000 provided, as most of the project will comprise of theoretical and computer-based modelling and research. The primary expenditures would be on any minor repairs to existing components which are not currently operable. The entire powertrain cost should be within a reasonable budget that future teams can sustain. A range of $20000-$50000 for all necessary components has been recommended by the project sponsor. As many of the components associated with hybrid powertrains tend to be quite expensive, an effort will be made to use existing components available in the garage or in existing AVT vehicles that will no longer be in use. Until these components have been verified to be operable or repair quotes have been received, the team is unable to determine which items will need to be purchased out of the AVT budget.

6.2 Project Management

During the extent of the semester, the Universal Powertrain team will keep 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 can 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 16 below.

% Complete	Task Name	Duration	Start	Finish	Resource Names
87%	**Powertrain Selection Summary Document**	**27 days**	**Tue 9/3/19**	**Wed 10/9/19**	**Team Deliverable**
100%	**Market & Customer Analysis**	**15 days**	**Tue 9/3/19**	**Mon 9/23/19**	**JG**
73%	**Powertrain Research**	**15 days**	**Tue 9/17/19**	**Mon 10/7/19**	NO,AM,DN,JP,JG,AK
16%	**Component List Document of Powertain**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**Team Deliverable**
19%	**Electric Motor Selection**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**AK**
25%	Electric Motor Research	19 days	Tue 9/24/19	Fri 10/18/19	AK
0%	Electric Motor Decision Matrix	3 days	Mon 10/21/19	Wed 10/23/19	AK
0%	Electric Motor Decision Summary	3 days	Thu 10/24/19	Mon 10/28/19	AK
19%	**Fuel Selection**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**NO**
25%	Fuel Research	19 days	Tue 9/24/19	Fri 10/18/19	NO
0%	Fuel Decision Matrix	3 days	Mon 10/21/19	Wed 10/23/19	NO
0%	Fuel Decision Summary	3 days	Thu 10/24/19	Mon 10/28/19	NO
0%	**Motor Controller Selection**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**DN**
0%	Motor Controller Research	19 days	Tue 9/24/19	Fri 10/18/19	DN
0%	Motor Controller Decision Matrix	3 days	Mon 10/21/19	Wed 10/23/19	DN
0%	Motor Controller Decision Summary	3 days	Thu 10/24/19	Mon 10/28/19	DN
19%	**IC Engine Selection**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**JG**
25%	IC Engine Research	19 days	Tue 9/24/19	Fri 10/18/19	JG
0%	IC Engine Decision Matrix	3 days	Mon 10/21/19	Wed 10/23/19	JG
0%	IC Engine Decision Summary	3 days	Thu 10/24/19	Mon 10/28/19	JG
19%	**Battery Pack Selection**	**26 days**	**Tue 9/24/19**	**Tue 10/29/19**	**AM**
25%	Battery Pack Research	19 days	Tue 9/24/19	Fri 10/18/19	AM
0%	Battery Pack Decision Matrix	3 days	Mon 10/21/19	Wed 10/23/19	AM
0%	Battery Pack Decision Summary	3 days	Thu 10/24/19	Mon 10/28/19	AM
19%	**Packaging/Integration Components Selection**	**25 days**	**Tue 9/24/19**	**Mon 10/28/19**	**JP**
25%	Packaging/Integration Component Research	19 days	Tue 9/24/19	Fri 10/18/19	JP
0%	Packaging/Integration Component Matrix	3 days	Mon 10/21/19	Wed 10/23/19	JP
0%	Packaging/Integration Component Summary	3 days	Thu 10/24/19	Mon 10/28/19	JP
0%	**Cost Analysis of Powertrain Components**	**4 days**	**Thu 10/24/19**	**Tue 10/29/19**	**Team Deliverable**
0%	**Model of Powertain Assembly**	**26 days**	Wed 10/30/19	Wed 12/4/19	**Team Deliverable**
0%	**Powertrain Assembly Report**	**10 days**	**Tue 11/26/19**	**Mon 12/9/19**	**Team Deliverable**

Figure 16: Universal Powertrain Semester Gantt Chart

The critical path of the project can be simplified into four major accomplishments which are research, powertrain selection, component selection, modelling, and vehicle integration. The team must first research the customer, market, and the various powertrain configurations in order to understand the needs and specifications of the powertrain. Next, the team must choose the configuration of the powertrain that best meets the needs of the customer. In addition, the team must choose each component of the chosen powertrain, so the previously determined specifications are met. Next, the components must be modelled in CAD so assemblies can be tested. Lastly, the final powertrain assembly must be modelled to assure that all the components fit together.

In order to reduce the critical path, the team has set up subtasks which must be completed before the main objective is complete. This allows the team to further delegate tasks between members and volunteers in order to meet the project deadlines.

6.3 Risk Plan and Safety

The team does not expect to encounter many significant physical hazards while working on this project. However, work may be done with and around the existing vehicles to investigate and compare the vehicles existing powertrains. Additional testing may be done on spare or salvageable powertrain components to determine if the parts are operable. Strict adherence to all machine shop and Larson Institute policies will be used whenever working in this manner. Work on any physical systems will be conducted with a minimum of two people involved, and proper PPE will be used. In addition, system work will only be done by those familiar with the associated procedures and with an understanding of the need for the work. Although education and group deliverables are the primary intent of this project, safety is the first priority which will not be sacrificed for expedience.

This project has several risks that may prevent its eventual success. Given that the universal powertrain is primarily based on theoretical modelling the primary risk factors revolve around the project assumptions and how the future powertrain might be implemented. Unforeseen delays and complications may cause the project and schedule to slip behind the intended end date. The Gantt chart is intended to ensure that all team members stay on track and that deliverables are completed in a timely manner. The final product for this project will detail the components of the powertrain and the related performance specifications. Components included will be from parts the AVT has on-hand or items that can be purchased and that are within the overall budget. The analysis assumes that the current components will be operable or repairable, however additional issues with these parts may be discovered. Previous competitions have seen several failures with regards to mechanical parts. In the prior competition the Camaro shaft suffered several failures. More dedicated design effort will be put towards these mechanical items to ensure that critical components do not easily fail. Also, future donated parts cannot reasonably be considered, and it may be more beneficial to save money on an inferior donated part and spend the excess in other areas for improvement.

Additional risks to the success to this project arise due to the EcoCAR competition itself. The next competition vehicle is unknown, and although the Crossover SUV is a likely candidate, there is no guarantee. The powertrain should be able to accommodate a variety of vehicles; however, the powertrain cannot be made to be truly universal. Vehicle size and shape may be different to the point that the powertrain cannot function as expected. The competition should focus on emissions and efficiency, however other major components, such as an ADAS system may be scored more heavily. Component selections should account for additional power requirements to accommodate these systems. Lastly, the performance specifications may be incorrect due to inaccuracies with modelling or with errors in how the components are assembled and programmed in future years. Risk items and mitigating actions can be found in Table 9.

Table 9: Risk Plan

Risk	Level	Actions to Minimize	Fall Back Strategy
Schedule Delay	High	-Ensure Gantt chart is up to date and members are responsible for specific tasks -Build off prior work and modeling found in SharePoint -Verify members are meeting requirements for billable hours and weekly accomplishments	-Assign volunteers to any project area falling behind -Limit complexity of items assigned and focus on a completed, viable product
Availability of new components	High	-Create list of minimum specifications that would be needed to replace given components if a part is donated or found used	-Have powertrain components be somewhat interchangeable
Mechanical failure	High	-Perform vibration analysis and lifetime calculations on shafts and mounting points -Use more advanced materials to improve strength and durability	-Incorporate additional damping components to reduce stress spikes -Design powertrain so that the components most likely to fail are simple to replace
Component functionality/ availability	Moderate	-Test components before assuming that the components can be used in a future powertrain -Use components that have duplicates around the shop or in vehicles	-Repair components -Investigate purchasing components new
Competition car is not Crossover SUV	Moderate	-Ensure additional power is produced to still perform on a heavier/larger vehicle	-Use different engine to provide necessary power -Include options for rear wheel drive depending on space available
EcoCAR/competition scoring or focus changes	Moderate	-Meet or exceed general consumer expectations for vehicle performance -Even if not designed for specific challenges, a more fuel-efficient vehicle should perform better across the board	-Allow additional margin for power-using devices such as an ADAS system

Theoretical model inaccuracies	Low	-Perform physical test if possible or write procedure for future group -Run test cases using existing vehicle specifications against known performance	-Research existing, simplified correlations -Use different modeling software
Engine compartment is too small/wrong geometry	Low	-Design components to fit in a minimum amount of space -Focus on having spatially uniform geometry, i.e. limit the number of long parts jutting out from main powertrain	-Downsize components -Investigate effort needed to expand engine compartment or shift other components
Software/Programming	Low	-Assume that performance is based on conservative power output programming	-Dedicate additional time and group members for future optimization of software

6.4 Communication and Coordination with Sponsor

Sponsor:

- Gary Neal

The Universal Powertrain team has its project manager, Ali Kazmi, attend steering committee meetings to address other teams and communicate with Gary Neal. The rest of the team will have an opportunity to address any further concerns during the staff meetings and/or via SharePoint. Steering committee meetings will take place every Monday from 5:00 – 6:00 PM while staff meetings will occur every Monday from 7:45 - 8:00 PM.

7.0 Team Qualifications

The Universal Powertrain group is full of many qualified students who have ranges of experiences and skills that will contribute to the success of the project. A short biography of each student can be found below.

Ali Kazmi

Ali Kazmi is a senior studying mechanical engineering and his role on the Universal Powertrain team is project manager Ali worked in the oil and gas field this summer where he gained valuable hands on experience with the processes involved in flowback production. He was involved in many problem-solving activities managing water tank levels on continuous drilling operations. While working on the wind turbine project, he gained experience with these manufacturing processes: drilling, tapping, milling and using the lathe. On another project in his Mechatronics lab, he gained experience programming Arduinos to operate a robot car. Ali also has experience using Solidworks, and Autodesk CAD programs where he has been able to learn the fundamentals of 3D modeling and FEA simulations.

Jason Gaydos

Jason Gaydos is a senior studying Mechanical Engineering and his role on the Universal Powertrain team is the scheduler. Jason has also had lots of machining and fabrication experience in the Learning Factory and FAME lab on campus. In addition to his fabrication skills, he has had years of hands on experience working on and modifying cars as a job in high school and now as a hobby. Jason has had three internships throughout his college career working at Bridgestone for two summers as well as General Motors last summer.

Alex Moore

Alex Moore is a senior Mechanical Engineering student and his role in the Universal Powertrain team is file system organizer. He has experience with machining, carpentry, electronics work, design for laser cutting and 3D printing, SolidWorks, and Matlab. In his spare time, Alex has worked on small personal projects with Arduino and Raspberry pi. His varied interests allow him to be a flexible member of any project, and in the Universal Powertrain he hopes to bring his interest in battery technology to improve upon current options. Creative solutions and out of the box concept generation are given when he is part of a team.

Nicholas Osmond

Nicolas is a Senior studying Nuclear and Mechanical Engineering and is the note taker for the Universal Powertrain team. Nicholas attempts to fix things instead of replacing them and enjoys taking apart mechanical systems to understand how they function. He works at the Breazeale Nuclear Reactor on-campus as a reactor operator. Nicholas conducts experiments, checks and maintains many of the auxiliary systems, and take groups on tours. After graduation he will enter the US Navy through the NUPOC program and eventually become a Naval Reactors Engineer based out of Washington D.C.

Ju Young Park

JuYoung Park is a senior studying mechanical engineering and his role on the Universal Powertrain team is design journal keeper. From childhood, JuYoung actively participated in science project competitions such as water rocket and model glider. For two years during high school, JuYoung has dealt with CAD software and related fabrication devices like 3 Axis CNC machine, lathe, and 3D printer. For a project he has built a V-8 engine block mechanism and electric skateboard with computer aided designing, and wind turbine profiled with lab-tested propeller profile data from UIUC with corresponding equations to maximize electricity output. From previous design experiences, creative designing and rapid prototyping remained as power tool. These experiences will facilitate testing out different designs and failure at testing stage to come up with a functional final product.

<u>David(Muzhi) Na</u>

David Na is from China and David always love everything about cars. Due to his interest since childhood, David is pursuing a Material Science and Engineering undergraduate degree at Penn State. The undergraduate program includes theoretical study and laboratory experience. David thus is familiar with the knowledge of material development and test equipment operation. David believes that material science can greatly improve human life. His motto is: Spotting opportunities, craving for innovations.

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