ON THE ELECTRIFICATION OF THE AMERICAN MUSCLE CAR:

AN ANALYSIS AND MODEL BASED DESIGN

On the Electrification of the American Muscle Car: An Analysis and Model Based Design

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Lay Abstract

The American muscle car has made a recent comeback in popularity after many years. The modern muscle car combines classic styling with modern day technology creating a car that is fun to drive and commands attention on the road. With fuel economy and emission standards becoming more stringent, American muscle cars will need to rely on the most recent technology to maintain the performance that excites their owners. To meet these future demands vehicle electrification has proven to be a solution that can greatly increase fuel economy and has also been used in high performance applications. Analysis must be completed to understand each electrification approach and which one is best suited for the muscle car segment. A model based design approach can be used to analyze each powertrain and give insights into each topology. After completing simulations of a variety of powertrains, an appropriate electrified powertrain can be proposed for an American muscle car.

Abstract

This report includes a systematic approach to defining and analyzing an electrified powertrain for use in a modern American muscle car. To provide a background and define the problem the current trends in vehicle electrification will be explored followed by a definition of the American muscle car and its technical requirements. To analyze a variety of powertrains across multiple tests, the model based design approach is used with a custom designed simulation tool. Once the simulation environment is understood multiple simulations and tests are performed on each electrified powertrain defined to gain insights into their behavior and characteristics.

Through experimental data and first principals a modeling tool is developed for the specific purpose of powertrain architecture selection. The tool provides many insights, flexible powertrain topologies, and customizable testing procedures. To ensure that the results of the tool are accurate energy balance calculations are performed on each powertrain and a comparison to commercially available software is given. To ensure that the new powertrains are improvements on their respective conventional vehicle counterparts, baseline simulations are completed and compared alongside the electrified vehicle powertrains. A selection matrix is formed to quantitatively compare and selected an appropriate powertrain for an American muscle car and a feasibility study is completed to ensure the design goals are met.

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Symbols and Abbreviations

BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy
CD	Charge Depleting
CO2	Carbon Dioxide
Coef	Coefficient
CS	Charge Sustaining
EPA	Environmental Protection Agency
EMR	Energetic Macroscopic Representation
EV	Electric Vehicle
MYFC	Fuel Consumption (amount of fuel per distance)
FE	Fuel Economy (distance per amount of fuel)
FTP	Federal Test Procedure
GHG	Greenhouse Gas
GM	General Motors
HEV	Hybrid Electric Vehicle
hp	Horsepower
HWFET	Highway Fuel Economy Driving Schedule
ICE	Internal Combustion Engine
J	Joule
kW	Kilowatt
kWh	Kilowatt Hour
mpg	Miles per Gallon
NASCAR	National Association of Stock Car Auto Racing
NHTSA	National Highway Traffic Safety Administration
NOx	Nitrogen Oxide
OPEC	Organization of the Petroleum Exporting Countries
SAE	Society of Automotive Engineers
SOC	State of Charge
UDDS	Urban Dynamometer Driving Schedule
UF	Utility Factor
ZEV	Zero Emission Vehicles

1. Introduction

The personal transportation industry has been primarily powered by fossil fuels for the past one hundred years. Recently, with advancements and technology and the public's concern of the environment and depleting resources, increasing vehicle efficiency and other energy sources have been investigated [1]. However, cars are not simply an appliance like a furnace that can be replaced with a more efficient one. People have a connection with their vehicles, what they drive and how they drive is a way of expressing themselves. This need for connection is the biggest pushback for people that disapprove of new clean technologies. There is a huge market for vehicle customization as the public continues to use their vehicles as another way to express themselves differently. There are certain vehicle expectations for different people for example, someone from the country will drive a pick-up truck, and someone who wants to show they are environmentally aware will drive a Prius, or a sports car for the intense, fast pace individual. There are lots of things that a car can tell about its owner. The connection people have with cars and what they expect from their vehicles requires a vast market and there are many different options and solutions manufactures offer to meet the needs of personal transportation. Until recently the market only supplied hybrid cars for people that valued fuel efficiency and the environment over other personal reflections like performance and rugged ability.

Fuel Economy

One of the largest factors pushing vehicle electrification is to decrease vehicles overall fuel consumption. There are a few factors that are driving the need for better fuel economic vehicles including reducing dependence on oil and cutting customers fuel costs. Reducing dependency on oil is very important to the North American economy because nearly a third of the oil used in the United States is imported from foreign countries. Overall, this costs the economy 192 billion dollars every year [2]. With such a dependency on foreign oil a disruption in supply could lead to great instability in the western economy. The majority of imported oil comes from the Middle East and 73% of the world's oil reserves are controlled by the Organization of the Petroleum Exporting Countries (OPEC). Hence OPEC can greatly influence oil prices through changing oil production and sales. Price fluctuations caused by OPEC have cost the US economy nearly 2 billion dollars between the years 2004 and 2008 [2].

The second reason for increasing vehicle fuel economy is to save customers money of fuel. On average car ownership is the second largest expense for households behind housing costs. The average Canadian spends around ten thousand dollars on transportation annually which is equivalent to nearly 20% of their overall spending [3]. Given that vehicle ownership is so costly, most customers look for ways to decrease their vehicle operating costs. Studies from consumer reports show that the least expensive vehicles to own to own in every vehicle class over a five year period are electrified vehicles [4]. After six years of ownership the yearly operating costs become greater than the carrying costs for most vehicles. The lower operating costs give hybrid vehicles even lower cost per year ownership advantage over non-electrified cars [4].

To ensure that automotive manufactures invest in fuel saving technology, the EPA has created a standard that will greatly increase the fuel economy of new vehicles. The corporate average fuel economy (CAFE) standard is a plan for the fleet average fuel economies for each manufacturer from the model years 2012 to 2025. The goal by 2025 is to achieve an average fleet fuel economy of 45 mpg for small passenger vehicles. The increase in vehicle fuel economy in 2025 is projected to save each car owner $8000 in fuel cost over the 15 year lifespan of the vehicle compared to the fuel cost of a 2012 model year car. The reduction in transportation fuel use by 2025 will also cut the dependency on OPEC oil in half [2].

Emissions and Greenhouse Gasses

Air quality is a very important aspect of human life as well as non-human life on earth. With rising public knowledge and concern for global warming, the need for cleaner vehicles is increasing. Governments have taken steps to ensure that each country is taking the necessary steps to decrease overall emissions especially greenhouse gasses (GHG), such as CO2 and NOx.

In Canada transportation accounts for a quarter of all GHG emissions and the government works closely with the EPA to create standards for vehicles. The target in 2025 is to reduce the average vehicles' GHG emissions by 50% over 2008 model vehicles [5]. Similar to the CAFE standard goals manufactures can greatly reduce their emissions and fuel consumption through the use of energy sources other than petroleum fuel.

The effects of excess CO2 production on global warming have been debated throughout the years as a possible natural warming phase. However, in 2009 the EPA has stated through what they call the endangerment finding that increased GHGs in the atmosphere threaten public health and the welfare of future generations. To be proactive in reducing GHGs the Environmental Protection Agency and National Highway Traffic Safety Administration (NHTSA) have developed and extended the program of harmonized greenhouse gas and fuel economy standards to the vehicle model year 2025. The results of the standard are projected to reduce the average personal vehicle's tailpipe emissions to an equivalent 250 grams of CO2 per mile by 2025 [6].

California has the freedom to create stricter vehicle emissions standards than the federal EPA standards. Other states cannot create their own standards but do have the freedom to adopt California's standards over the EPA's standards. California has taken the EPA's targets to the next level with the Advanced Clean Cars Program which requires each automotive manufacturer to produce and sell a certain number of zero emission vehicles (ZEVs). Until the model year 2018 hybrids and other low emission vehicles will count towards zero emission credits and after 2018 only purely zero emission vehicles will count for credits [7]. California and the other states that are adopting the program make up a large market for automobiles and automakers will have to create zero emission vehicles to maintain their place in the market.

Vehicle Electrification

Vehicle electrification is a modern term used to describe the efforts made to add electric capabilities to vehicles. By increasing the electrical functions of the overall vehicle efficiency and performance can be improved [8]. There is a broad spectrum of vehicle electrification from mild hybrid electric vehicles (HEVs) to fully electric vehicles (EVs). HEVs combine the long range capabilities of a convention vehicle with the exceptional fuel economy of electric vehicles. Some key features include engine downsizing, auxiliary load management, engine start/stop and regenerative braking. By creating vehicle goals and acknowledging the strengths and weaknesses of both internal combustion and electric propulsion a HEV topology can be determined for the target vehicle platform.

Vehicle electrification has gained recent popularity with the increase in electronic technology and growing concern for fuel consumption [9]. However, electrified vehicles are not new and have a rich history that is as old as automobiles themselves. As America became more prosperous at the turn of the twentieth century, people started to turn to motor vehicles instead of horses for transportation. To power these vehicles there were three options steam, gasoline and electric. Each option had its drawbacks and advantages. Steam requires a long time to start up and needs a lot of resources which makes it impractical for personal transportation. The internal combustion engine was improved enough in the 1800s to become a good source of propulsion for vehicles. Internal combustion engines however were very primitive and were tough to operate. The gasoline powered car required a great amount of effort from the operator, first to manually start the vehicle and then when driving to shift gears. Along with the extra effort they were very noisy, created harsh vibrations and emitted unpleasant exhaust fumes. Electric cars were very easy to operate as they did not require manual starting or gear shifting. One of the most well-known electric automotive manufacturers was Ferdinand Porsche who created his car the P1 which incorporated in wheel hub motors. Very shortly after, Porsche created the first hybrid electric vehicle by incorporating electric hub motors with a gasoline engine. The goal was to create a car with the advantages of both the electric and gasoline powertrains. At the time electric vehicles achieved better performance than their gasoline counterparts and it was an electric vehicle that was the first to reach 100 km/h. As both electric and gasoline technologies were explored, the gasoline engine was greatly improved throughout the early 1890s making it easier to start and drive. By the time Henry Ford started mass producing the Model T, electric cars were almost three times the price of a gasoline powered car which essentially made the short range electric vehicles obsolete [10].

The idea of electrified vehicles is not old, and neither is the motivation to make electric propulsion systems. The internal combustion engine has been refined to become an amazing piece of machinery however the problems people had with them in the early days are similar to the problems with them today. They require a lot of energy to operate and their emissions have been found to do damage to the environment and electric vehicles still offer the same advantaged of zero emissions and simple drivetrains.

It can be seen throughout history that electrified vehicles have not been stalled by concept generation but by the current available technology. There are a few notable technological advancements that have helped spur the recent resurgence in the field of vehicle electrification. The advances in switching technologies and batteries have been key players in the success and commercialization of HEVs [11].

2. The American Muscle Car

Class Definition

The American Muscle car had a very organic birth in the automotive industry. These are cars with very distinctive features which helped them become their very own vehicle class. Stemming from a long history that began in the late 1940s, muscle cars have evolved and become very distinct. Where standard vehicle classes are based on the overall size and weight of the vehicle, muscle cars created a new way of defining one car from the next. A muscle car can be defined as an American made vehicle with a large engine producing large amounts of power designed for high performance driving [12]. The muscle car always has offered people a car that had lots of power making it very fun to drive without the expensive price tag and impracticalities that come with driving a small sports car.

Muscle Car History

The very first muscle car is said to be the 1949 Oldsmobile Rocket 88 which featured a five liter high compression overhead valve V8 engine inside a body that had lightweight features. The car was very similar in size to the Oldsmobile 76 which had a smaller six cylinder engine. The Rocket 88 went on to win the NASCAR championship in 1950. The idea of a lightweight body with a high performance engine had proven itself and very quickly other automakers started putting V8 engines into cars. Through the 1950s Chrysler made the 300 which performed very well and AMC produced the Rambler Rebel. The 60s became the dawning age for the popularity of muscle cars. With drag racing becoming popular each automaker was making cars with larger and larger engines and upgraded drivelines. By 1964 both Ford and Mopar had a 7.0 liter engine. [13]

Late in 1964 Ford produced the Ford mustang which was a game changer and the first of a new breed of smaller muscle cars. The mustang was quickly followed by Chevrolet with the Camaro in 1966. Even though Plymouth released the Barracuda a few weeks before the Mustang, because of its popularity the Mustang takes most of the credit for the smaller muscle car movement. Muscle cars had become fairly expensive with luxury options and heavy cars the engines needed to be larger to keep up with the performance. By the end of the 1960s the high end muscle cars had engines with as much power as 450 hp. However, the increase in price of the large muscle cars was met with the introduction of smaller more simple cost effective muscle cars like the Ford Mustang and Chevrolet Camaro. The smaller muscle cars by the end of the 1960s were both faster and cheaper to buy than the larger muscle cars.

The 1970's were a tough time for muscle cars with efforts to reduce pollution and the effects of the oil embargo. Fuel types changed as the high performance higher compression engines could not handle the lower octane unleaded fuel. Insurance companies started to realize that the overpowered cars with undersized brakes and poor overall vehicle stability were dangerous and they started to charge extra for customers with muscle cars. The Mustang and Camaro survived this tough time for muscle cars still providing for customers that wanted extra performance. By the middle of the 1980s most car companies had phased out most of their rear wheel drive platforms for the cheaper more economical front wheel drives.

It wasn't until the mid-2000s that muscle cars received as much attention as they had in previous years. The release of the fifth generation Ford Mustang in 2005 drew acclaim with its retro styling and modern technology. Following in Ford's great modern muscle car success Dodge rereleased the Challenger in 2008 and Chevrolet rereleased the Camaro in 2010 after the concept was featured in the Transformers: Dark of the Moon film in 2009. Recently Ford has released the 6th generation Ford mustang and Chevrolet and Dodge are expected to follow with the Camaro and Challenger. [13] Table 1 shows a list of mentionable classic and modern muscle cars with the years their production years.

Table 1 – List of Notable Muscle Cars [14]

Classic Muscle Cars	
1968–1970	AMC AMX
1968–1974	AMC Javelin and AMX
1967–2002	Chevrolet Camaro
1970–1974	Ford Mustang
1965–2004	Ford Mustang
1969–1970	Mercury Cougar
1964–1974	Plymouth Barracuda
1967–2002	Pontiac Firebird & Trans Am
Modern Muscle Cars	
2010-Current	Chevrolet Camaro
2008-Current	Dodge Challenger
2005-Current	Ford Mustang

Modern Muscle Car Customers

Recently North American automakers have been able to revive the past muscle car enthusiasm by combining classic car styling with modern day technology. With customers that were just getting their license in the years that muscle cars just started to reign, nostalgia is motivating the original muscle car generation who now have the most disposable income of their lives. There is a generation that saw the rise of muscle cars when they were just getting their licenses. If they could not afford their dream car then, they are now at a point in their lives where they have the most disposable income. To see cars that remind them of their old dreams tempts them to buy. Even though the original muscle car generation is thought to be the major consumers of modern muscle cars, they are not the only people interested in the low cost performance vehicles. Younger generations are very interested in the cool retro look and new innovative technology found on the modern muscle cars.

Young buyers have a special appreciation for innovative technologies especially electrified vehicles [15].

The increase in internal combustion engine technology has been able to keep up with fuel economy standards as well as offer customers high performance vehicles. There is concern whether companies will be able to keep up with the increasingly stringent regulations. Retired GM Vice Chairman Bob Lutz who was a strong influence in the reintroduction of the modern Camaro said that the current muscle car revival "can last for a few more years until the fuel-economy standards become ever tougher" [15]. Manufactures should be aware of the decline of the muscle car in the 1970's where fuel economy and emission standards nearly made the muscle car extinct. To sustain the current enthusiasm auto makers will need to examine and incorporate other fuel saving, low emission approaches like vehicle electrification. With Formula1 switching to hybrid powertrains and the recent release of high performance hybrid cars there is a new perception forming that is preparing the market for an electrified muscle car.

Modern Muscle Car Specifications

Automotive companies must make sure their cars meet certain design and technical specifications to meet the needs of the current American muscle car customer. The cars must look impressive as this is arguably the reason for the resurgence of the muscle car market. They are cars that look sharp and have a slight retro take on them to bring back nostalgia of the peak of the muscle car era. The goal of this study is to focus on the second pillar of the muscle car which is to have a strong powertrain that makes the car fun to drive and faster than most regular cars on the road.

The three automotive manufacturers of modern American Muscle Cars are Ford with the Mustang, Chevrolet with the Camaro and Dodge with the Challenger. The next few sections will look at the technical aspects of each of these vehicles so that a non-brand specific muscle car can be defined for the design targets of the proposed powertrain system.

Ford Mustang

The Ford Mustang is the only muscle car that has been in continuous production since its original introduction. From its introduction in 1964 the mustang has been a leader in muscle car class. Its perfect combination of style, performance and affordability made it a sure success. The mustang had record breaking sales and everything from the car's styling to the marketing was completely new. The Mustang was the first car in U.S. Automaker history to sell more than one million cars within 24 months. The car was created for younger drivers and with that in mind Ford made sure the price was low enough to accommodate [16]. This new cool car has continued to sell and still remains at the forefront of muscle cars as it was the first modern muscle car to mix retro styling with modern performance in the fifth generation Mustang. People loved the new more nostalgic muscle car and therefore the mustang has reignited muscle car glory [17].

Ford released an all new sixth generation Mustang for 2015. Some important updates were updated body styling, independent rear suspension, and three powertrain choices, including a turbocharged inline four cylinder engine. The vehicle technical specifications are shown in Table 2 below [18].

Table 2 – 2015 Ford Mustang Specifications

Model	**2015 Ford Mustang**		
	V6	**EcoBoost**	**GT**
MSRP	$23,600	$25,170	$32,100
Mass (lbs)	3526	3532	3705
Mass (kg)	1599	1602	1681
Fuel Economy			
MPG City	17	21	15
MPG Hwy	28	32	25
MPG Combined	21	25	19
Engine Parameters			
Displacement (L)	3.7	2.3	5
Max Power (hp)	300	310	435
Max Power (kW)	223.71	231.17	324.38
RPM at Max Power	6500	5500	6500
Max Torque (ft-lb)	280	320	400
Max Torque (Nm)	379.63	433.86	542.33
RPM at Max Torque	4000	4000	4250
Performance			
0-60 mph (sec)	5.7	5.3	4.5
0-100 mph (sec)	13.6	13	10.4
Quarter mile (sec)	14.1	13.6	13
Top Speed (mph)	155	160	164
Top Speed (kph)	249.45	257.49	263.93
Chassis & Tires			
Drag Coefficient	0.32	0.32	0.32
Estimated Frontal Area (m^2)	2.2	2.2	2.2
Tire Radius (m)	0.34544	0.3429	0.3429
Calculated Values			
kW/kg	0.140	0.144	0.193

Chevrolet Camaro

The Chevrolet Camaro was General Motors' reaction to the success of the Ford Mustang. Chevrolet did not have a car to compete with the Mustang so they rushed the design of the Camaro and was able to start selling it two years later in the fall of 1966. The 1967 the Chevrolet Camaro offered very similar advantages as the mustang with a very similar light weight, high performance and low cost design approach. The Camaro is the greatest competitor to the Mustang and with a high performance strategy the Camaro has done well through the years. The Modern Camaro came out with a retro modern styling and included independent rear suspension. [19]

The fifth generation Camaro is about to give way to the sixth generation. By 2015 Chevrolet has had a lot of time to improve upon the original release of the fifth generation Camaro and even reintroduced its high performance Z/28 badge. Table 3 below shows some of the technical features of the 2015 Camaro offerings.

Table 3 – 2015 Chevrolet Camaro Technical Specifications

Model	**2015 Chevrolet Camaro**			
	LT	**SS**	**ZL1**	**Z/28**
MSRP (USD)	$23,705	$33,505	$55,505	$72,305
Mass (lbs)	3719	3908	4120	3820
Mass (kg)	1687	1773	1869	1733
Fuel Economy				
MPG City	17	16	14	13
MPG Hwy	28	24	19	19
MPG Combined	20	19	16	15
Engine Parameters				
Displacement (L)	3.6	6.2	6.2	7
Max Power (hp)	323	426	580	505
Max Power (kW)	240.86	317.67	432.51	376.58

RPM at Max Power	6800	5900	6000	6100
Max Torque (ft-lb)	278	420	556	481
Max Torque (Nm)	376.92	569.44	753.83	652.15
RPM at Max Torque	4800	4600	4200	4800
Performance				
0-60 mph (sec)	5.9	4.5	4.4	4.4
0-100 mph (sec)	13.7	10.3	9.9	9.5
Quarter mile (sec)	14.5	12.9	12.7	12.7
Top Speed (mph)	113	156	161	172
Top Speed (kph)	181.86	251.06	259.10	276.81
Chassis & Tires				
Drag Coefficient	0.35	0.35	0.35	0.35
Estimated Frontal Area (m^2)	2.2	2.2	2.2	2.2
Tire Radius (m)	0.36322	0.36322	0.35433	0.35433
Calculated Values				
kW/kg	0.143	0.179	0.231	0.217

Dodge Challenger

The Dodge Challenger was originally the last vehicle to enter the smaller muscle car market of the major American automotive manufacturers. Built on a similar lightweight cost effective strategy, the first 1970 Challenger also offered nine powertrain options. Dodge never sold as many Challengers as Ford or Chevrolet sold their rival cars, but Dodge always had something a little different to offer than the other two which created a special place in the market for itself.

Dodge started selling the modern Challenger in 2008 after being motivated by a well-received showing of their concept during the 2006 North American International Auto Show. Similar to the other muscle cars in its class the Challenger offers a balance of retro-modern styling, high performance, and new suspension technology [20]. Table 4 shows the technical specifications of the 2015 Challenger.

Table 4 – 2015 Dodge Challenger Technical Specifications

Model	2015 Dodge Challenger			
	SXT	**R/T**	**SRT**	**Hellcat**
MSRP (USD)	$26,995	$31,495	$44,995	$58,295
Mass (lbs)	3825	4083	4239	4488
Mass (kg)	1735	1852	1923	2036
Fuel Economy				
MPG City	19	15	14	13
MPG Hwy	30	23	23	22
MPG Combined	23	18	17	16
Engine Parameters				
Displacement (L)	3.6	5.7	6.4	6.2
Max Power (hp)	305	375	485	707
Max Power (kW)	227.44	279.64	361.66	527.21
RPM at Max Power	6350	5150	6100	6000
Max Torque (ft-lb)	268	410	475	650
Max Torque (Nm)	363.36	555.89	644.01	881.28
RPM at Max Torque	4800	4300	4200	4000
Performance				
0-60 mph (sec)	6.1	4.9	4.2	3.6
0-100 mph (sec)	16	12.5	10.1	7.6
Quarter mile (sec)	14.7	13.5	12.6	11.7
Top Speed (mph)	156	165	181	199
Top Speed (kph)	251.06	265.54	291.29	320.26
Chassis & Tires				
Drag Coefficient	0.337	0.337	0.337	0.337
Estimated Frontal Area (m^2)	2.37	2.37	2.37	2.37
Tire Radius (m)	0.35814	0.35814	0.36449	0.36449
Calculated Values				
kW/kg	0.131	0.151	0.188	0.259

Combined Muscle Car

To continue with a powertrain selection, the vehicle technical specifications need to be defined for the target vehicle. Since the project is concerned with muscle cars in general each of the aspects of the three vehicles can be combined into one list of technical specifications for each major price point. Table 5 shows the combined values for all four price points of muscle cars. The goal for the electrified muscle car has been set very close to a combination of the high and super performance levels. The higher price point of the high performance muscle car variant will help justify and cover the increased cost of an electrified powertrain.

Table 5 – Combined Muscle Car Technical Specifications

Model	**Combined**				**Goal**
	Low	**Mid**	**High**	**Super**	**Electrified**
MSRP	$ 24,766.67	$ 30,056.67	$ 44,200.00	$ 65,300.00	$65,300.00
Mass (lbs)	3690	3841	4021	4154	4154
Mass (kg)	1674	1742	1824	1884	1880
Fuel Economy					
MPG City	18	17	14	13	25
MPG Hwy	29	26	22	21	30
MPG Combined	21	21	17	16	27
Engine Parameters					
Displacement (L)	3.6	4.7	5.9	6.6	< 3.6
Max Power (hp)	309	370	500	606	500
Max Power (kW)	231	276	373	452	373
RPM at Max Power	6550	5517	6200	6050	5000
Max Torque (ft-lb)	275	383	477	566	920
Max Torque (Nm)	373	520	647	767	680
RPM at Max Torque	4533	4300	4217	4400	3000
Performance					
0-60 mph (sec)	6	5	4	4	4
Quarter mile (sec)	14	13	13	12	12
Top Speed (mph)	141	160	169	186	200
Top Speed (kph)	227	258	271	299	320
Chassis & Tires					
Drag Coefficient	0.344	0.344	0.344	0.344	0.34
Estimated Frontal Area (m^2)	2.3	2.3	2.3	2.3	2.3
Tire Radius (m)	0.356	0.355	0.354	0.359	0.3556
Calculated Values					
kW/kg	0.138	0.158	0.204	0.238	0.2

3. Hybrid Architectures

At a basic level there are two ways of defining the power flow of hybrid powertrains. The first being a series power flow and the second a parallel power flow. Hybrid vehicles are not limited to these types of powertrains as many incorporate some combination of series and parallel power flow.

A series hybrid uses an electric motor to supply the tractive energy to propel the vehicle similar to a battery electric vehicle. An ICE or other fuel converter runs a generator to provide power to the motor and battery. Series hybrid power flow follows a single path, fuel to electric then electric to mechanical power [21]. A series powertrain is shown in Figure 1. Since the internal combustion engine is not mechanically connected to the wheels it can operate at peak efficiency independent from the speed of the vehicle.

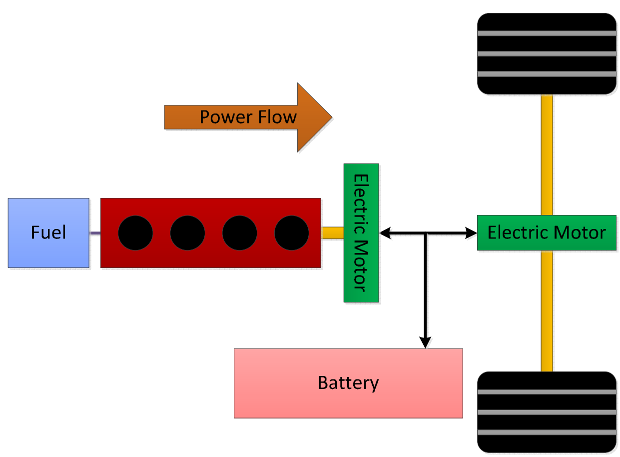


Figure 1 - Series Hybrid Powertrain

A parallel hybrid can use the engine or electric motor to supply tractive effort to drive the vehicle. Using a torque coupling the energy from the engine and electric motor can be used as tractive effort [21]. Any combination of torque split between the engine and electric motor can be used to provide the requested torque from the driver. Figure 2 is a diagram showing the power flow in a parallel hybrid. The internal combustion engine and motor are connected directly to the wheels though gear ratios so the engine has to run at some specific ratio to the wheels.

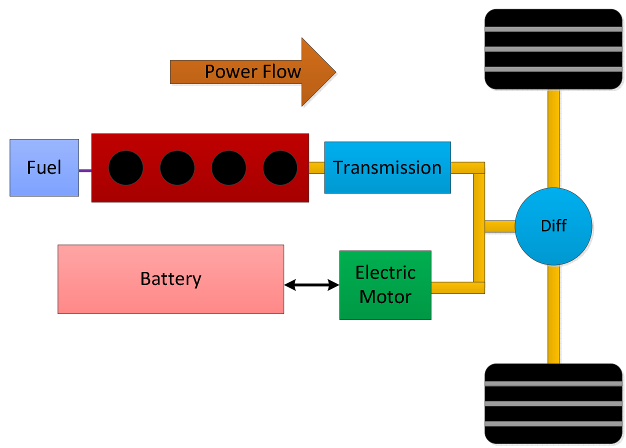


Figure 2 - Parallel Hybrid Powertrain

Based on these two basic principles many combinations of hybrid electric vehicle powertrains can be used to meet design goals of different vehicles. With a large variant of consumers in the automotive market certain structures of hybrid vehicles are better suited for different applications. There are hybrid vehicles that have been created for almost every segment of the vehicle market, from sub compact to highway trucks. An investigation into some of the current solutions of vehicle segments close to that of the American Muscle car can create a starting point when deciding on a powertrain for this segment. The three main motivations for electrification also represent market demand for those motivations of fuel efficiency, emission reduction or performance.

Powertrains for Fuel Economy

The power-split architecture has been used to greatly increase fuel economy of vehicles and is used in the most popular hybrid car the Toyota Prius as well as most of the other Toyota and Lexus brand hybrid cars. Ford has also licensed this technology from Toyota and incorporated it into the Cmax, Fusion Hybrid, Escape Hybrid, and Lincoln MKZ. [22]

Power-Split Powertrains

The power-split system uses a planetary gear set to split the transmission input from the internal combustion engine [23]. The planetary gear set splits the power from the engine power into the mechanical path and an electric path. By adjusting the portions of power transferred through these two paths, the system achieves a variable output torque and speed. This creates a great opportunity to increase the overall system efficiency [24].

A planetary gear set consists of an inner sun gear circled by a set of planet gears mounted on a carrier, all of which is enclosed with an outer ring gear. The entire assembly of the planetary carrier, ring gear, and the sun gear rotate concentrically. Figure 3, shows the planetary gear set assembly and block diagram representation where R is the ring gear, C represents the planetary carrier and S is the sun gear.

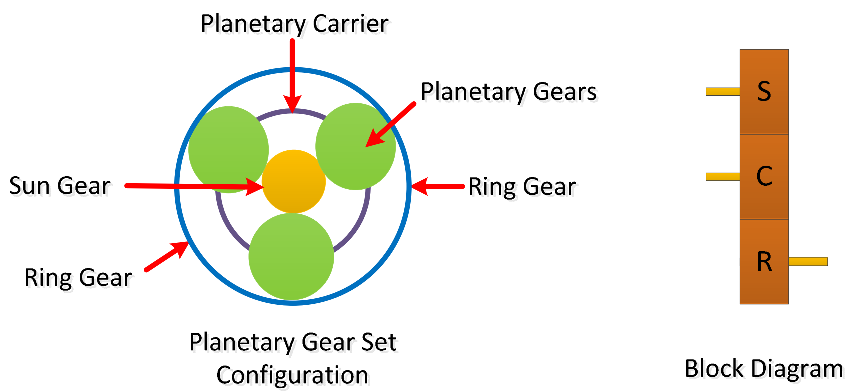


Figure 3 - Planetary Gear Set

Each planetary gear set has three mechanical connection points. The input from any two of the connections will define the output of the third one. A planetary gear set can be defined by the fundamental equations 1-3.

$$\omega_s + k\omega_r = (1+k)\omega_c \tag{1}$$

$$T_s = -\frac{1}{1+k}T_c \tag{2}$$

$$T_r = -\frac{k}{1+k}T_c \tag{3}$$

The angular speed and torque are represented by ω and T respectively. Each mechanical connection is shown using a subscript, where r refers to the ring gear, c the planetary carrier and s the sun gear. The gear ratio of a planetary gear system can be described by the ratio of the ring gear to the sun gear and is represented by k. There have been a variety of commercially available vehicle architectures based on the planetary gear set. The Toyota hybrid system (THS) was the first configuration and was used in the original Toyota Prius before 2004. The block diagram of the THS is shown in Figure 4.

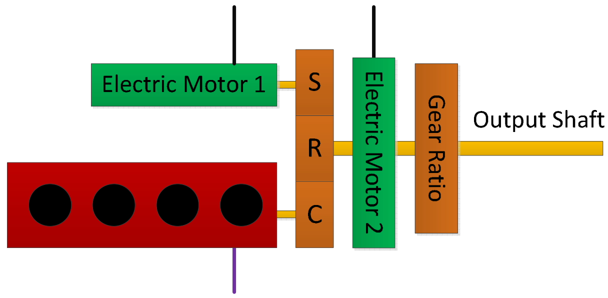


Figure 4 - Toyota Hybrid Drive (THD)

The internal combustion engine output shaft is connected to the planet carrier and the generator motor is directly coupled to the sun gear. The ring gear and tractive motor are coupled and combine to provide the output torque which powers the vehicle wheels. The traction motor supplements the power split torque and provides tractive effort for low speed operation and regenerative breaking. The energy that is input from the engine is split between the mechanical and electrical power flows. Depending on the operating point, most of the power directly transfers through the mechanical path to the transmission final output, while the remaining power transfers to the generator motor. The energy that is transferred to the electrical path goes to charge the battery or to power the traction motor depending on the current vehicle power request and the energy storage system's state of charge.

There are more current variations of the TSD system such as the Hybrid Synergy Drive (HSD). The new versions has been incorporated into many different Toyota and Lexus lineups as well as licensed to Nissan and Ford. The most significant change was the addition of a gear ratio between the traction motor and the planetary output. The addition of the extra gear ration helps increase the vehicles top speed. [24]. Figure 5 shows the HSD system and its block diagram.

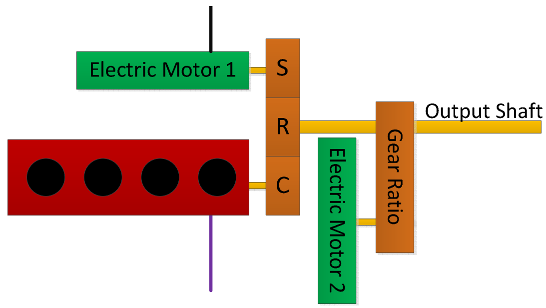


Figure 5 - Toyota Hybrid Synergy Drive (HSD)

By incorporating an electric motor on the axle of the vehicle that is not powered by the transmission all-wheel drive capability can be added as seen in the Lexus RX450h and Toyota Highlander. Along with this variation, other variations have been added to increase high speed and low speed efficiency [25].

The power-split powertrains has several different operating modes by changing the overall control strategy. The driving modes are described as follows:

1. Electric-only mode: At low speed operation or reverse the traction motor is used to provide all the tractive effort with the generator rotating in the opposite direction to ensure the internal combustion engine speed is zero.
2. Engine start mode: The generator motor is used to start the engine which can be done with the vehicle moving or stationary
3. Motor-assist mode: The traction motor assists the engine in proving tractive effort on accelerations.

4. Charging mode: The engine produces extra power over the driver request that is taken out at the power split by the generator motor to charge the battery.
5. Regenerative mode: the Tractive motor is uses in Generator mode during breaking to recuperate some the vehicles kinetic energy back into electrical energy.

Where the power split transmission has been used in previous available vehicles can give some insight on how well the architecture works on a variety of vehicle platforms. Table 6 shows vehicles offered in North America that use a power split style hybrid transmission.

Table 6 - Hybrid Vehicles with Power-Split Powertrains [26]

Vehicle class	Model	Engine size (L)	Engine power (kW)	Main electric machine power (kW)	Main electric machine torque (Nm)	Battery capacity (kW·h)	US production model years
Compact	Toyota Prius	1.5	57	50	400	1.3	2000-2009
	Lexus CT200h	1.8	73	60	206	1.3	2011-
	Lexus HS250h	2.4	110	105	270	NA	2009-2012
	Ford C-Max Hybrid	2	105	88	159	1.4	2013-
Mid-size	Toyota Prius	1.8	73	60	207	1.3	2010-
	Toyota Camry Hybrid	2.5	118	105	270	1.6	2007-
	Toyota Avalon Hybrid	2.5	116	105	270	1.6	2013-
	Lexus ES 300h	2.5	116	105	270	1.6	2013-
	Ford Fusion Hybrid	2	105	88	159	1.4	2010-
	Lincoln MKZ Hybrid	2	105	88	159	1.4	2011-
	Lexus GS450h	3.5	213	149	275	1.87	2006-
	Lexus LS600h	5	290	165	300	1.87	2008-
Large	Ford Escape Hybrid	2.5	99	70	NA	1.8	2005-2012
	Lexus RX400h	3.3	155	123	333	1.87	2006-2009

	Lexus RX450h	3.5	183	116	333	1.87	2010-
	Toyota Highlander Hybrid	3.5	172	123	333	1.87	2005-

The power-split powertrain allows continuously variable engine speeds because of the 2 degree of freedom in the planetary gear set transmission. By controlling the speed of the generator with respect to the speed of the ring gear a desired speed of the engine can be achieved which greatly helps in improving fuel economy. When looking at fast accelerations because the electrical system is integrated into the transmission, for the internal combustion engine to provide tractive torque the generator and traction motors also need to be active. This splits off mechanical energy out of the transmission and then transfers it back out through the traction motor.

The power-split transmission is neither a series hybrid nor a parallel hybrid. There is actually no disconnect and therefore is both always creating a series power flow and parallel power flow as opposed to just series or parallel operation.

Powertrains for Low Emissions

Electric Vehicle Powertrains

Electric vehicles (EVs) are generally simple powertrains compared to hybrid powertrains because they only use one energy source. EV powertrains typically only consist of an electric motor, a fixed gear reduction and a mechanical differential to move the power from the electric machines to the wheels as shown in Figure 6.

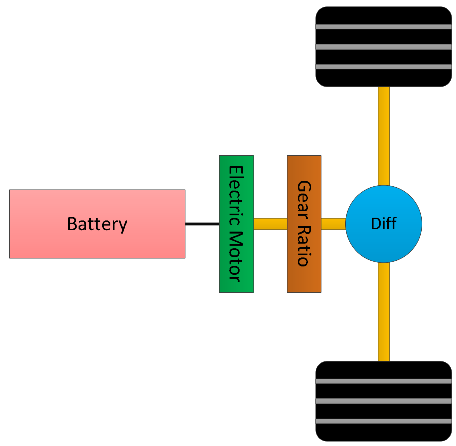


Figure 6 - EV Powertrain Configuration

The fixed gear reduction is used to assist in changing the motor power into higher torque and lower speed. A single gear reduction is used because they are robust and do not need as much maintenance as a multiple gear box. The maintenance on a single reduction is much less than a multi-gear transmission because the gears are in constant mesh and there are no slipping components such as clutches and synchronizers. The primary advantages to using an electric only powertrain are each component offers a higher efficiency when comparted to internal combustion engines and zero tailpipe emissions are produced. Other advantages include smooth operation with no noise and low overall vehicle maintenance. Table 7 shows all the electric vehicles currently for sale within North America.

Table 7 - Electric Vehicle Powertrain Models and Specifications [26]

Vehicle class	Model	Electric machine power (kW)	Electric machines torque (Nm)	Electric range (km)	Battery capacity (kW·h)	US production model years
Minicompact	Smart fortwo Electric Drive	30	120	101	16.5	2013-
	Scion iQ EV	47	163	80	12	2013
	Fiat 500e	83	147	140	24	2013-
Subcompact/co	Mitsubishi i-MiEV	47	180	100	16	2012-2014

mpact	Chevrolet Spark EV	97	443	132	21.3	2013-
	Ford Focus Electric	107	245	122	23	2011-
Mid-size	Nisan Leaf	80	280	121	24	2010-
	Honda Fit EV	92	256	132	20	2013-2014
Large	Tesla Model S	310	600	335/426	60/85	2012-
	Toyota Rav4 EV	115	296	166	41.8	2012-2014

For electric vehicles the primary concern is the rate at which they can be recharged. With conventional vehicles when whey run out of energy they can be filled up very quickly with a large selection and filling station availability. Electric vehicles take a much longer time to charge because batteries can only take energy in a certain rate and only so much electrical power can be transferred to the vehicle safely. The amount of range the vehicle receives per charge becomes very important because electric vehicles take much longer to recharge and drivers do not want to wait a long time beside their cars as it charges.

Powertrains for Performance

Parallel Hybrid Powertrains

The parallel hybrid architecture has been the powertrain of choice for many manufacturers as their first move into vehicle electrification. The parallel architecture consists of an electric motor placed in line with the internal combustion engine. It is referred to as a parallel configuration because the power is added up from both the ICE and the electric machine to the transmission independent of each other. Depending on the relative position of the electric machine and the engine, parallel hybrid powertrains can be categorized into 4 configurations, which are typically referred as P1 to P4 [27], shown in Figure 7.

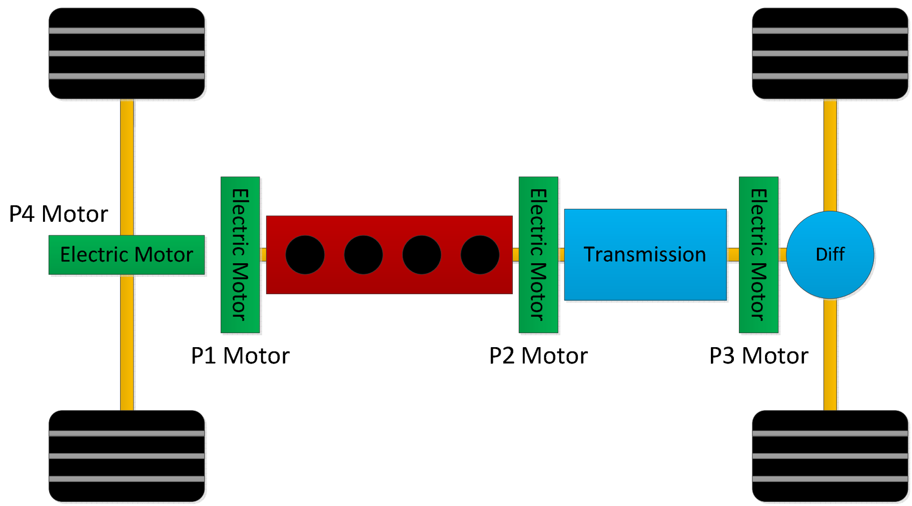


Figure 7 - Parallel Hybrid Motor Configurations

The mildest form and most popular of parallel hybrid is where electric machine is located before the engine in P1 configuration. The motor is generally referred to as an integrated starter generator (ISG) or belt starter generator (BSG) and it replaces the alternator and starter motors connected to the internal combustion engine with a larger single motor. This motor acts as both a starter motor for the engine and generator for powering vehicle accessories. With a larger motor it also allows the engine to shut off when the vehicle is stopped which prevents idling and saves fuel. It can also be used for light regenerative braking during vehicle deceleration and slight power assistance during acceleration. This architecture is used for lower levels of vehicle electrification and has been employed in almost every vehicle class.

Motors that are placed in the P2 position are close to the engine and used all the gears in the transmission. Motors placed in the P3 positon are after the transmission and are connected to the ground through a fixed gear ratio in the differential. The P4 configuration places the electric machine either directly at the wheels or on a different axle. When the electric machine is on a separate axle from the main drive axle, it is commonly referred to as a parallel through-the-road powertrain. The main advantages of the P4 motor are the performance benefits of an all-wheel drive (AWD) powertrain and electrical system isolation from the harshness of the internal combustion engine. A list of commercially available parallel hybrid vehicle can be found in Table 8.

Table 8 - Parallel Hybrid Powertrain Models and Specifications [26]

Vehicle class	Model	Hybrid level	Engine size (L)	Engine power (kW)	Engine torque (Nm)	Electric machine power (kW)	US production model years
Compact	Acura ILX Hybrid	Stop-Start	1.5	67	132	17	2013-
	BMW Active Hybrid 3	HEV	3.0	250	450	41	2012-
	Honda Civic Hybrid	Stop-Start	1.5	67	131	17	2012 -
	Honda CR-Z	Stop-Start	1.5	83	144	10	2011 -
	Honda Insight	Stop-Start	1.3	73	167	10	2000 - 2006 2010 - 2014
	Infiniti Q50/M35h Hybrid	HEV	3.6	269	290	50	2012-
	Volkswagen Jetta Hybrid	HEV	1.4	106	100	20	2013-
Midsize	Chevrolet Malibu Hybrid	Stop-Start	2.4	136	233	15	2008-2010, 2013-
	BMW Active Hybrid 5	HEV	3.0	223	406	41	2012 -
	Infiniti M / Q70 Hybrid	HEV	3.5	226	358	43	2012 -
	Buick LaCrosse Hybrid	Stop Start	2.4	136	233	15	2012 –
	Buick Regal Hybrid	Stop Start	2.4	136	233	15	2012 –
	Mercedes E400H	Mild	3.5	225	370	20	2013 –
	Nissan Altima Hybrid	Mild	2.5	118	220	30	2007 - 2011
Large	BMW Active Hybrid 7	Mild	3.0	235	450	15	2010 -
	Chevrolet Impala Hybrid	Stop-Start	2.5	146	252	15	2014-
	Mercedes S400HV	Mild	3.5	205	225	20	2012 - 2013
	Porsche Panamera S Hybrid	HEV	3	245	440	35	2012-

SUV / Truck	Audi Q5 Hybrid	HEV	2	155	350	40	2011-
	Chevrolet Silverado Hybrid	Stop Start	5.3	220	454	NA	2005 – 2007
	Infiniti QX60 Hybrid	HEV	2.5	186	329	15	2014-
	Nissan Pathfinder Hybrid	Mild	2.5	171	330	15	2014 –
	Porsche Cayenne S Hybrid	HEV	3	245	440	35	2011 –
	Volkswagen Touareg Hybrid	HEV	3	245	440	35	2011 -

Reviewing the list of parallel hybrid vehicles that are currently on the market it can be observed that more luxury vehicle makers have chosen the parallel hybrid powertrain over the power split architecture. The luxury vehicle market has always preferred car with nice styling and more performance than the average vehicle of the same size. Excluded from the list above because of their low production numbers and inaccessibility to the average consumer are some of the most notable parallel hybrids produced for performance driving. The very exclusive hyper car class has been taken over by a new breed of hybrids. McLaren, Porsche, and Ferrari have all created very high performance cars with concept showings from Lamborghini and Koenigsegg talking about electrified vehicles as well.

The McLaren P1 is a rear wheel drive car that has a 542 kW internal combustion engine and a 131 kW electric motor in the P2 position. The battery can hold 4.7 kWh of energy with plug incapability for some all-electric range driving. With the motor in the P2 position the electric motor can provide traction torque throughout the entire speed range of the car.

Very similar to the P1 the Ferrari LaFerrari is also rear wheel drive however the LaFerrari has electric motors at the P1 and P3 positions. The P1 motor is used mostly for starting and generating and the P3 motor is used for traction and regenerative braking. The engine is a large displacement 6.2 liter and produces 588 kW. With a smaller 2.4 kWh battery the LaFerrari does not have any all electric range or plug in capabilities.

The Porsche 918 Spider is an all-wheel drive vehicle and with the extra traction from the front wheels is a faster acceleration car than the P1 and LaFerrari. The 918 uses motors in both the P2 and P4 positions. With a strong electrical system and a 6.8 kWh battery pack the 918 can do 19 km of all electric driving. The currently available high performance electrified vehicles can be found in Table 9.

Table 9 - High Performance Hybrid Models and Specifications

Vehicle class	Model	Hybrid level	Engine size (L)	Engine power (kW)	Battery Capacity (kWh)	Electric machine power (kW)	US production model year
Super Car	McLaren P1	PHEV	3.8	524	4.7	131	2014-
	Ferrari LaFerrari	HEV	6.3	588	2.3	120	2014
	Porsche 918 Spider	PHEV	4.6	453	6.8	115 +93	2015

Series-Parallel Hybrid Powertrains

The series-parallel architecture is a multiple function alternative to the power-split powertrain which uses a planetary gear set to split the power flow of the internal combustion engine. It differs from the power split architecture because it lacks the electronically continuously variable transmission (eCVT) functionality provided by planetary gear sets. In a series-parallel powertrain the internal combustion engine can have a direct mechanical connection to the wheels or through the use of a clutch be completely disconnected from the wheels. A series-parallel powertrain must consist of at least two electric motors, one of the motors is always connected to the

ICE and the other always connected to the wheels. The motor connected to the engine acts as both a starter motor, a generator during series operation and can provide tractive effort during parallel operation. There is a clutch that separates the engine and generator motor from the main traction motor that is connected to the final drive. There are three main powertrain modes of operation are summarized below:

1. Electric-only operation: The clutch is open and the main traction motor provides all the tractive effort for the vehicle with power from the batter.
2. Series operation: The vehicle is driven the same as in electric mode however with the clutch open the engine is run spinning the generator and producing electrical energy for the battery or the tractive motor.
3. Series-Parallel Operation: The clutch is engaged and the engine provides power to the road in parallel with the electric motors. The motors can be placed in generating mode to push the engine operating point to a higher efficiency region.

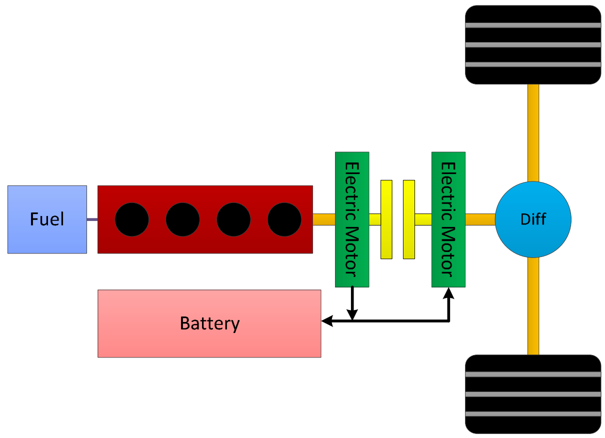


Figure 8 – Series-Parallel Hybrid

There are only a few vehicle models available on the market in North America that use the series-parallel hybrid architecture. Table 10 shows the vehicles that use a series-parallel powertrains. The series-parallel powertrain requires a higher level of vehicle electrification because it requires at least two motors and one of them must be fairly strong when compared to traditional parallel hybrids.

Table 10- Series-Parallel Hybrid Powertrain Models and Specifications [26]

Vehicle class	Model	Engine size (L)	Engine power (kW)	Electric machine power (kW)	Electric machine torque (Nm)	Battery capacity (kW·h)	US production model years
Mid-size	Kia Optima Hybrid	2.4	119	35 / 8.5	205 / 45	1.43	2011-
	Hyundai Sonata Hybrid	2.4	119	35 / 8.5	205 / 45	1.43	2011-
	Honda Accord Hybrid	2.0	105	124 / NA	306 / NA	1.3	2014-

4. Model Based Design

Vehicle simulation is critical to the vehicle development process. When initially imagining the vehicle concept it is important to know as early as possible in the design phase how the vehicle will perform. With electrified vehicles this is even more important as engineers can gain substantial amounts of data about very complex systems through simulations. Simulations allow designers to virtually design the car and test it in a flexible and relatively low cost environment. With recent advancements in the computer science and software fields there are many tools that can be used to simulate a full vehicle system.

The tool developed by the author in Simulink® is built upon the power loss technique. The power loss analysis can be used at multiple levels within the model from the top level full vehicle system down to individual components. For every system and component and energy balance can be created where the power in is equal to the power out plus the power lost due to in efficiencies within the system or component. Figure 9 shows how the power loss approach works at the most basic level. Within each component the power loss is calculated based on the dynamics of the specific system.

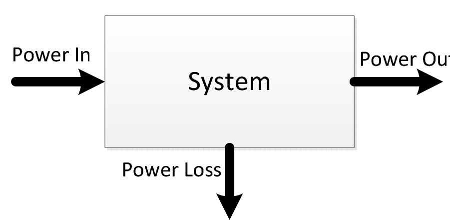
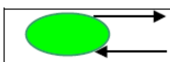
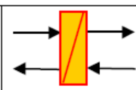
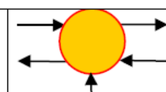
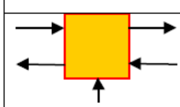
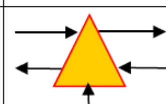
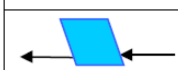
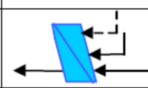
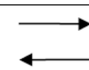


Figure 9 - Power Loss System Approach

As an alternate approach to power loss modelling, the University of Lille in France developed the Energetic Macroscopic Representation (EMR) modelling technique. This approach was developed to accurately model multidisciplinary systems. Drive control has become an important subject of learning for engineers and the required understanding of plant modelling has increasing with the possible addition of power electronics, automatic control, electrical machines, mechanics and industrial electronics. The EMR approach is based on action and reaction principles where subsystems are connected using the integral causality techniques [28]. The advantage of the EMR approach is that a control system can be developed by taking the inverse of the plant blocks contained in the system. The subsystems are developed based on how they interact with the other subsystems. These subsystems are categorized into sources, accumulating elements and converting elements as shown in Table 11.

Table 11 – Energetic Macroscopic Representation Elements [28]

	Source of energy		Element with energy accumulation		Electromechanical converter (without energy accumulation)
	Electrical converter (without energy accumulation)		Mechanical converter (without energy accumulation)		Mechanical coupling device (energy distribution)
	Control block without controller		Control block with controller		Action and reaction varaibles

The Energetic Macroscopic Representation method works very well when a powertrain architecture has been decided and a control system must be developed. For the powertrain architecture comparison study however, the power loss model can track system and subsystem losses with greater ease. When developing the components in the subsystems of the power loss model, the input and output variables can also follow the integral causality techniques because the product of the action and reaction is equal to the instantaneous power in or out.

Simulink Vehicle Modelling

The model used to simulate fuel economy over a large range of vehicle topologies was developed by a team at McMaster University and is constructed using Matlab® and Simulink® tools. The model has four major components driver controller powertrain and vehicle chassis as shown in Figure 10. The driver takes in a drive cycle input and sends accelerator and brake commands to the controller. The controller takes these driver requests and other vehicle information and sends commands to the vehicle powertrain plant model. The powertrain takes in the input energy to the system and the control commands and outputs wheel torque to the vehicle chassis. The vehicle chassis takes the wheel torque, simulates the vehicle loads and sends the vehicle speed information back to the driver.

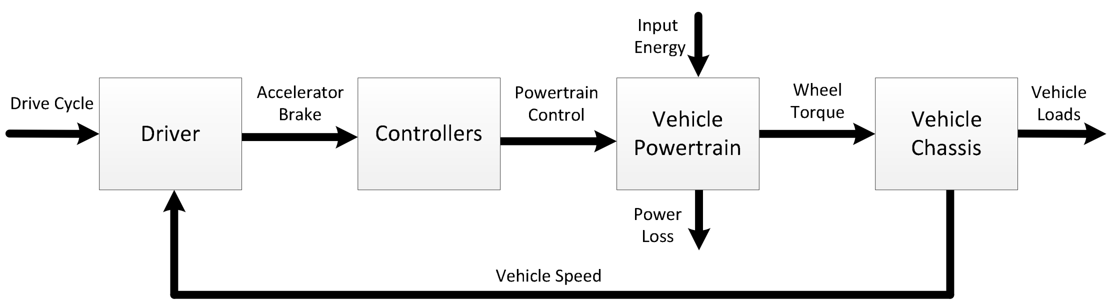


Figure 10 - Vehicle System Model Overview

To facilitate the structure within Simulink® busses are used to pass the signals from one system to the next. The busses allow signals to be added and removed from the lines without changing the overall structure. The model has also been designed with components in libraries and model referencing, this allows great flexibility for the user to change components to achieve better simulation performance.

Driver

The driver model is the main control in charge of the vehicle speed similar to the way a human operates a vehicle. The desired speed is an input to the model as a vehicle velocity verses time input plot

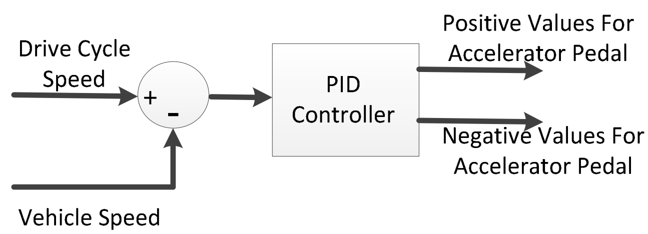


Figure 11 - Driver Model Diagram

Controller

The hybrid supervisory controllers are constructed using Stateflow diagrams and have the main purpose of ensuring all the components in the system are operating in the most energy efficient regions. Generally to increase the overall system efficiency it is most effective to focus on increasing the efficiency of the least efficient components within the system. Equation 4 shows the equation for the input power given the required output power and efficiency.

$$Pin = Pout/Eff \tag{4}$$

Using a simple experiment the approach to reduce the overall input energy by focusing on the least efficiency components can be explained. Figure 12 shows the input power required to produce 1 kW over a range of efficiencies from 10 to 100 percent. Examining the plot it can be determined that a 5 % increase in efficiency from 20-25% is a 1 kW decrease in input power whereas a 5 % increase in efficiency from 80-85% is only a decrease of 0.07 kW.

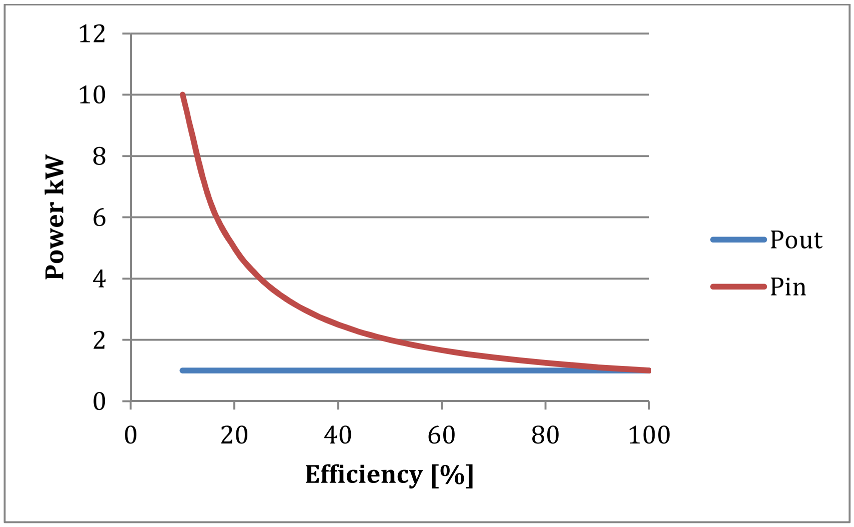


Figure 12- Effect of Efficiency on Input Power

To determine the components of greatest concern to the control system the peak and average efficiencies of all the major components can be compiled. Table 12 shows all the major components and their peak efficiencies. The internal combustion engine is the least efficient followed by the batteries and electric motors. The controller is then designed so that each of these components is operating closer to their peak efficiency regions.

Table 12 - Powertrain Component Efficiencies

Component	Peak Efficiency [%]	Average Efficiency [%]
Internal Combustion Engine	37	22
Electric Motor and Inverter	91	82
Transmission	96	96
Gear Reductions	98	98
Batteries	90	85

Within the model an efficiency map of the engine is created. The overall peak efficiency point can be determined easily on the map. However the road loads do not continuously require the output power that is given at overall peak efficiency point which requires the engine to operate away for the optimal spot. To determine the best operating points for a variety of power requests local peak operating points can be determined. Figure 13 shows the internal combustion engine peak efficiency points for the entire range of power requests.

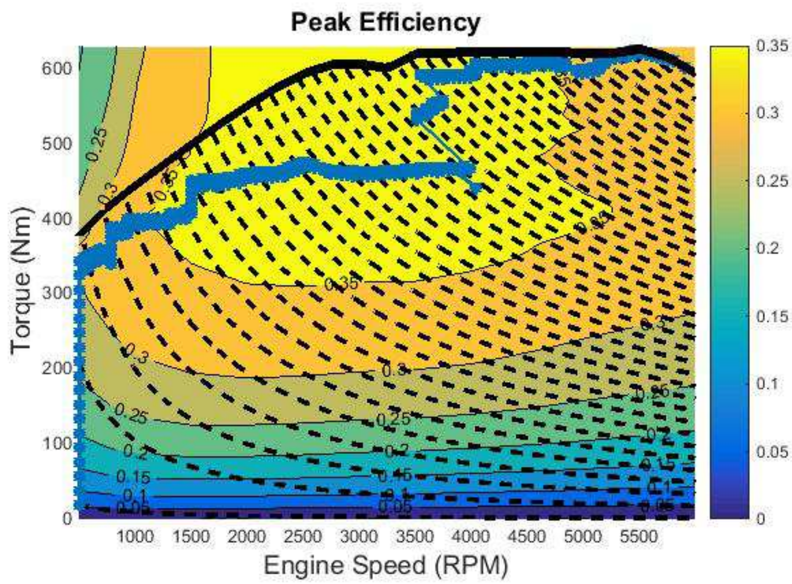


Figure 13 - Peak Efficiency Operating Points for Requested Power

Brake Controller

The brake controller is designed to achieve the most regeneration from the electric motors. If the braking request from the driver can be achieved by applying torque on the traction motors the mechanical brakes will not be used. If the braking torque request is larger than the motor can provide the motors will be set to regenerate the maximum torque possible and the mechanical brakes will supplement the rest of the required torque.

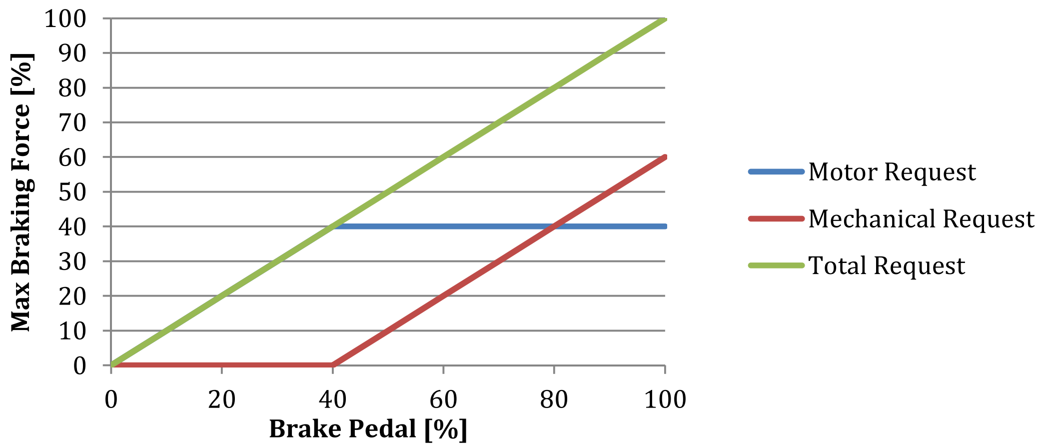


Figure 14 - Regenerative Braking Strategy

Powertrain Modelling

The tool was designed with the focus of being able to customize, create and replace any component with another. The powertrain system needs to be very versatile to be able to adapt with many different changes to architecture layout and component changes. Keeping with the main structure of the model the powertrain system incorporates busses and libraries to facilitate easy model customization.

For every change in architecture, the layout has been built up on the specific governing equations. The Controller model selects requested torque from each component plant then the torque is generated in each torque creating component then is passed through the model as the reactive speeds are fed back to the components. The ability to drag components anywhere within the powertrain and change where the torque is added to the system allows the user great freedom to explore and compare many different architecture layouts very quickly.

Internal Combustion Engine Model

One of the primary components in all hybrid electric powertrains is the internal combustion engine. The engine model is primarily based off of a generic engine fuel map, maximum torque curve and minimum torque cure. These maps are all based on torque request and current speed of the engine and are implemented into the model as look up tables. The internal combustion engine model data is based off of empirical data that was extracted from the commercially available Autonomie engine model. The engine efficiency map and maximum torque curve can be seen in Figure 15. The component model has also been built so that the maps can be scaled up or down allowing the user the freedom of changing the engine model to any engine size within the model.

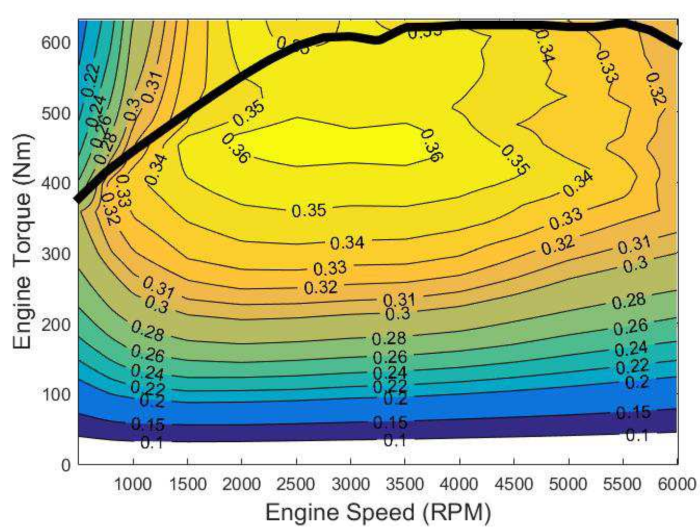


Figure 15 - Internal Combustion Engine Efficiency Map (373 kW)

Electric Motor Model

The Electric motors are very important torque producing components in an electrified powertrain. The electric motors are modeled in a very similar way to the internal combustion engine. The torque request and current speed is input to the component model and the torque and energy used is output. The efficiency map for the motor and inverter as well as the maximum torque curves were digitized from the YASA-400 datasheet by YASA Motors. The thermal limitation of the peak motor power is implemented using an integral that sums up the time above and below the continuous motor power rating and the peak power is limited according to the thermal limitation of the motor. By changing the motor and inverter efficiency map any motor can be added to the system. Like the internal combustion engine model the electric motor model can be scaled to any maximum torque, maximum speed, and maximum and continuous power. The motor efficiency map and peak torque curve that is used in the model is shown in Figure 16.

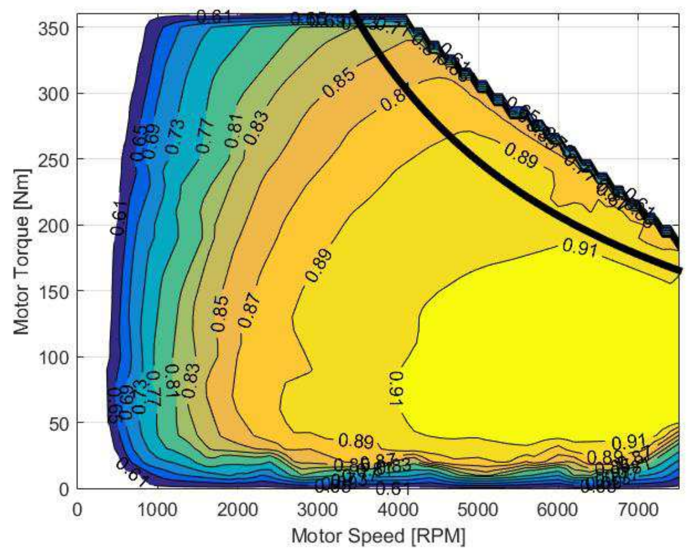


Figure 16 - Motor and Inverter Efficiency Map YASA-400

Battery Model

The battery provides energy to the electrical system of the vehicle and it is very important to model and analyze the effects of the battery on the system. There are many approaches that can be made to battery modelling and the Simulink® model is a great environment to explore them and their effects on the rest of the system. The library of battery models has many different model types from simple power loss to multiple RC equivalent circuits and thermal effects. With the MathWorks® built in parameter estimation tool a battery model can be fit to empirical data and implemented into the model. [29] To keep the overall fidelity lower in the model allowing faster simulation times the battery has been simplified to a single resistance circuit. This simplification greatly reduces the simulation time from a more complex multiple RC circuit and still provides reasonable indication of the battery losses in each architecture that is being compared.

Gearbox Modelling

The gears in each gear reduction and transmission within the vehicle driveline are also modelled as separate component systems. With advancements in manufacturing gear reductions have become very efficient overall and can almost be assumed to be perfect. For the architecture comparison study each gear ratio has a set to a typical gear efficiency of 98% [30]. Through the gears the output torque is calculated from the input torque and the input speed is calculated from the output speed. The gear ratio sets the amount that the torque and speed are multiplied. Normally a gear reduction in a transmission utilizes two gear ratios so the transmission is given an efficiency of 96%.

Chassis Modelling

The chassis model simulates the vehicle body and contains all the equations of motion for the vehicle. To run fuel economy simulations to keep the calculations simple and quick the car body is only modeled in one dimension. When considering more complex vehicle dynamics models can be created that include the vehicle suspension and individual tire models to better predict the how driver inputs affect and lateral movement and yaw of the car effect the performance of the car and vehicle drivability. These tests are out of the scope of this study so there is no major benefit of going into that much detail.

The chassis model is derived from the first principles of one dimensional longitudinal dynamics. From a very basic level the chassis can be approached as an inertial mass. Newton's second law can be applied to the vehicle mass and the velocity can be determined by taking the integral of the vehicle's calculated acceleration as shown in equations 6.

$$Force\ [N] = mass\ [kg]\ \times acceleration\ \left[\frac{m}{s^2}\right] \tag{5}$$

$$velocity\ \left[\frac{m}{s}\right] = \int acceleration \times dt \tag{6}$$

A free body diagram analysis can be used to determine the sum of the force acting on the vehicle mass. Figure 17 shows the free body diagram of the vehicle. The effort is pushing the car forward and is opposed by aerodynamic drag, rolling resistance of the tires and the force needed to overcome any grade in the road surface. Equation 7 shows how the net vehicle force is added based on the free body analysis.

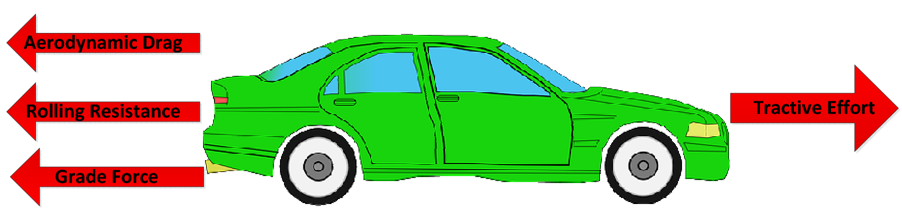


Figure 17 - Vehicle Free Body Diagram

$$Force = Tractive\ Force - Rolling\ Resistance - Aerodynamic\ Drag - Grade\ Force \tag{7}$$

With all the known forces acting on the body each one can be individually analyzed and defined. The tractive force is a function of the torque applied to the wheel and the wheel radius as shown in equation 8. The Aerodynamic drag force is a function of air density, the vehicle's frontal area, its coefficient of drag and current air velocity over the body as shown in equation 9. The rolling resistance is calculated based on the vehicle weight and the rolling resistance coefficient as shown in equation 10. Finally the grade force can be determined based on the vehicle weight and the gradient of the road as shown in equation 11. More complex definitions of these forces can be generated however these representations are commonly accepted representations of the vehicle body dynamics for one dimensional simulation. [31]

$$Tractive\ Force\ [N] = \frac{Torque\ [Nm]}{Wheel\ Radius\ [m]} \tag{8}$$

$$AerodynamicDrag\ [N] = \frac{1}{2} \times AirDensity \left[\frac{kg}{m^s}\right] \times FrontalArea\ [m^2] \times DragCoef\ [-] \times Velocity^2 \left[\frac{m}{s}\right]^2 \tag{9}$$

$$Rolling\ Resistance[N] = Vehicle\ Weight\ [N] \times\ Rolling\ Resistance\ Coef\ [-] \tag{10}$$

$$Grade\ Force\ [N] =\ Vehicle\ Weight\ [N] \times\ \sin(\text{atan}(Road\ Grade\ [\%])) \tag{11}$$

Within one dimensional vehicle modeling the vehicle a 2 axle approach can be taken to determine the dynamic weight distribution of the vehicle. By knowing the weight on each axle the tractive system can be analyzed to determine how much torque can be applied to each axle at any given time without locking or spinning the tires. The forces acting on a complex mass structure of a vehicle body can be simplified to forces acting on the center of gravity of the vehicle. Figure 18 shows a simplified vehicle body with the forces acting on the center of mass. To determine the longitudinal weight transfer between the two axles by a given tractive force, the moments about point O can be calculated. Knowing that at any given time the sum of all moments must be equal to 0, equation 12 can be derived. With the dynamic weight calculated it can be added with the static weight for that axle as in equation

13. To determine the weight of the secondary axle the weight on the first axle can be subtracted from the first axle as shown in equation 14.

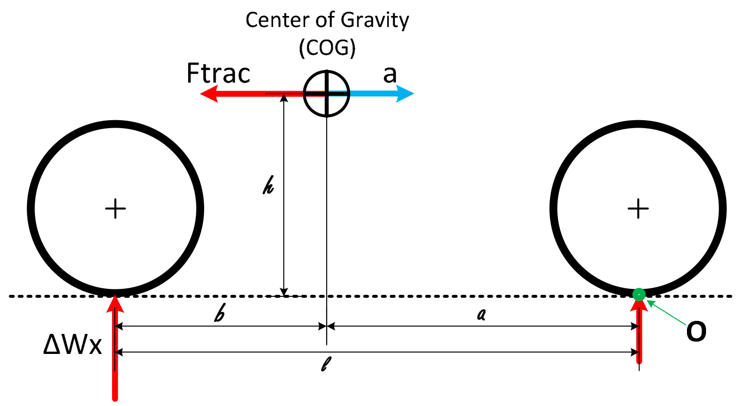


Figure 18 - Simplified Two Axle Vehicle

$$\Delta Wx = \frac{h}{l} \times Tractive\ Force\ [N] \tag{12}$$

$$Total\ Wx = Static\ Wx + \Delta Wx \tag{13}$$

$$Total\ Wo = (Static\ Wx + Static\ Wo) - \Delta Wx \tag{14}$$

With the dynamic weight on each wheel calculated the maximum tractive force for the front and rear axles can be calculated. To determine the traction limitation of the tires the weight on the axle is multiplied by the coefficient of friction as shown in equation 15. For further development of the model a more complex tire model can be applied, to determine the current slip ratios and variable longitudinal maximum forces required for a very smart traction control system these models will be necessary. For the scope of this project as a comparison study it is beneficial to keep the tire coefficient of friction constant so that the simulations can run quickly. Since the main advantage of adding tire complexity is to derive a better control system that can be applied to any of the selected architectures the effect it would have on the overall decision would very small.

$$Max\ Tractive\ Force\ = Total\ Axle\ Normal\ Force\ \times \mu_{tire} \quad (15)$$

Vehicle Testing Procedures

How the vehicle is tested in both the modeling and hardware environments is very important to the development and design processes. The tests need to be designed and conducted in a way that the generated results can clearly indicate if the design goals have been achieved. The testing procedures for this study need indicate how the vehicle compares to the design targets of the electrified American Muscle Car which is to increase fuel economy without decreasing performance.

Vehicle Testing Procedures for Fuel Economy and Emissions

The commonly used and accepted way to test and compare the performance of a vehicle with other vehicles is to run a driving cycle. A driving cycle is a standard velocity verses time trace that must be followed by the vehicle during a test. Common driving cycles used to test fuel economy and emissions are developed by the governing agencies. In the United States the Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), and US06 schedules are used. The UDDS cycle mimics typical city driving and the HWFET cycle follows as typical highway regime. These cycles do not have fast acceleration or braking sections so the US06 cycle is used to mimic more aggressive driving styles on a mixture of both highway and city. These drive cycles were developed by the Environmental Protection Agency (EPA).

The fuel economy labels posted for cars sold in North America use the five cycle weighting system developed by the EPA. The five cycle weighting system was developed to be a standard that could realistically predict fuel consumption for vehicles across a diverse field of powertrain architectures. The development of a standard test to predict fuel consumption for the majority of customers is a very complex problem. Fuel consumption is highly dependent the driving style of the driver, the environment the vehicle is operated in and the vehicle itself. A small variance in any one of these variables can have a large effect on fuel consumption. The EPA noticed that the early predictions of fuel economy were inflated and therefore developed the five cycle weighting system to incorporate more driving technique variances, outside environment impacts and variances in vehicle structures in order to better predict fuel consumption for the average drivers and vehicles on the road.

Each of the driving cycles helps to incorporate a different driving variable into the overall fuel consumption calculation. Each cycle and the main objective variables are described in Table 13.

Table 13 - 5 Cycle Test Procedures

Test Objective	Drive Cycle	Description
City Driving	FTP75	• Vehicle starts cold and runs the cycle • First 505 seconds are the same as the last 505 second
Highway Driving	HWFET	• Vehicle starts hot and runs the cycle
Aggressive Driving	US06	• Vehicle starts hot • Cycle with faster accelerations with faster highway speeds
Air Conditioning	SC03	• Vehicle starts hot • Ambient temperature 75°F (24°C) • Cycle is run with the Air-conditioning in use
Cold Weather	FTP	• Vehicle starts cold • Ambient temperature 20°F (-7°C)

Vehicle Testing Procedures for Performance

Owners of American Muscle Cars will expect their cars to perform at a greater level than the standard fuel economy tests can predict. To obtain an understanding of how the car will perform when it is driven aggressively different test need to be defined. Standard tests like acceleration (0-60mph) and top speed can give a good indication on how much a car is performance oriented. These tests work well for conventional cars where as long as there is fuel in the tank, the full vehicle performance is available upon request. Hybrid and plug in hybrid vehicles have a more complex power structure with varying peak and continuous power ratings, as well as, multiple sources of power that may need to be limited based on power usage and available energy.

To ensure that the proposed vehicle is not compromising on performance a race track drive cycle has been defined. The race track is a great place to compare vehicle performance and is an environment that some muscle car customers may actually run their car on. The track drive cycle was developed using Optimum Lap which is a lap simulator provided by OptimumG, a provider of vehicle dynamic solutions for many racing and commercial applications. To develop a drive cycle a vehicle and track need to be defined and then the simulation is run to create the drive cycle results.

The vehicle defined in Optimum Lap is based off of the generic muscle car defined in Chapter 2. The maximum torque curve of the engine was taken from the same engine data that was used for the Simulink® model in the baseline muscle car simulations. The gear ratios and all the other vehicle parameters like tire data and overall vehicle weight are also the same as what was used in the Simulink® simulations.

To decide on a baseline racetrack to simulate the car on it was desired to have a mixture of long straights and sharp turns so that vehicle has both large and small acceleration and deceleration sections. OptimumG offers a large database of racetracks all over the word from small go-cart tracks to large endurance racing tracks. The Circuit of Americas is a racetrack track in Austin Texas that hosts Formula 1 for the American Grand Prix. The track is 5.4 km long and has the desired combination of both long straights and with a variety of turns.

With the car and track confirmed the simulation is completed to create the results needed for the drive cycle. From the results shown in Figure 19 it can be seen that the top speed reached is 240 km/h and lowest cornering speed is 47 km/h. The result also shows a broad range of different accelerations and decelerations that provide a wide variety of operating points to ensure that the vehicles can operate in all performance conditions not just acceleration and top speed. The track shape and vehicle speed one each section is shown in Figure 20.

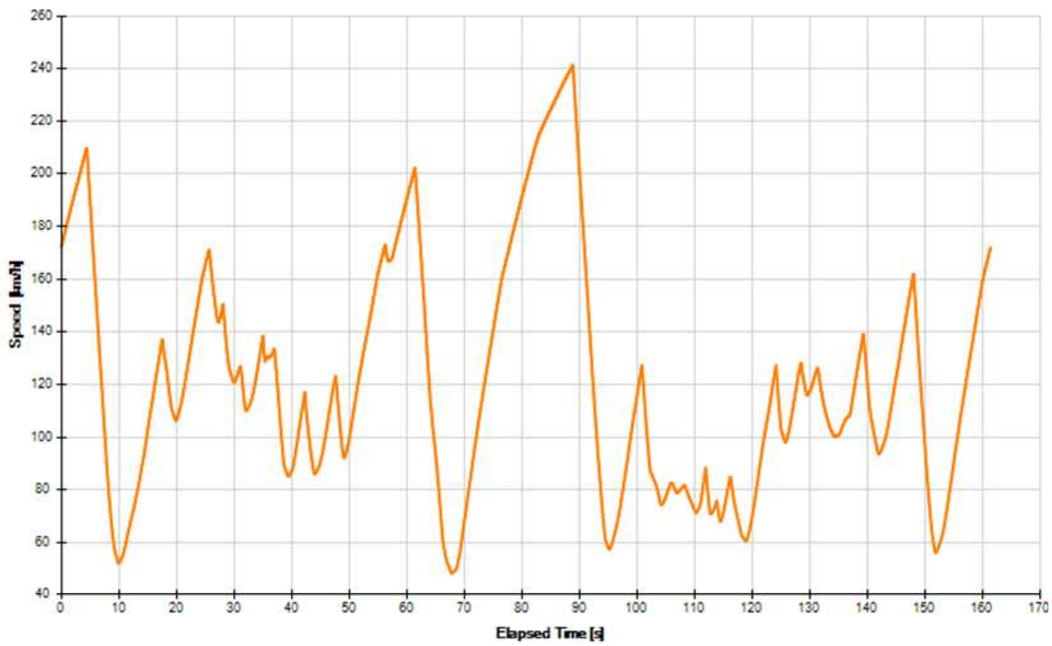


Figure 19 - Velocity vs. Time Drive Cycle of the Circuit of the Americas

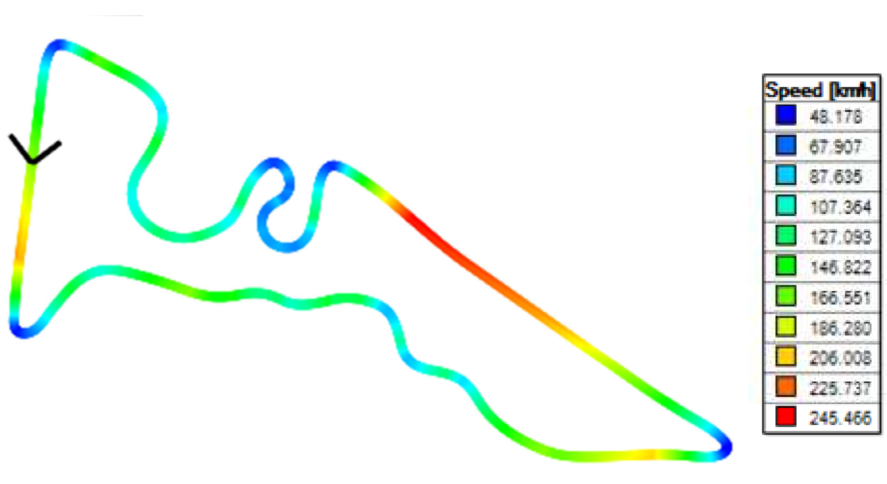


Figure 20- Circuit of the Americas with Vehicle Speed

The velocity time drive cycle will give an idea whether or not a vehicle will be able to keep up with the baseline vehicle but will not indicate if the vehicle's powertrain is powerful enough to complete the track faster than the baseline. The Optimum Lap simulator calculates the fastest speed that the vehicle can go around a corner. Between the corners the braking and acceleration distances are calculated based on the tractive power limits of the powertrain and traction limitations of the brakes. The calculation process is shown in Figure 21.

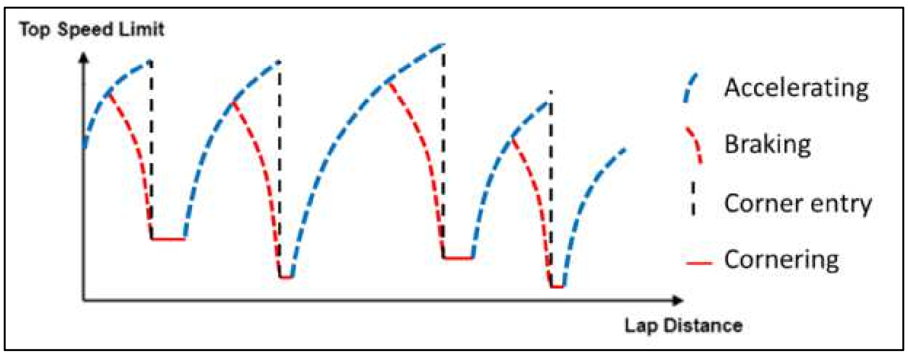


Figure 21 – Driver Calculation in Optimum Lap [32]

From the Optimum Lap simulator a speed verses distance drive cycle can be determined based on the lateral speed limitations of the car. With the vehicle's lateral limitations shown in Figure 22 a driver is developed in the Simulink® model that looks ahead from the vehicle's current position. Based off the traction limitations of the vehicle the driver applies the brakes before the corner so that the speed of the vehicle does not exceed the maximum corner speed. With this new driver based on track distance the potential lap time of each powertrain can be determined.

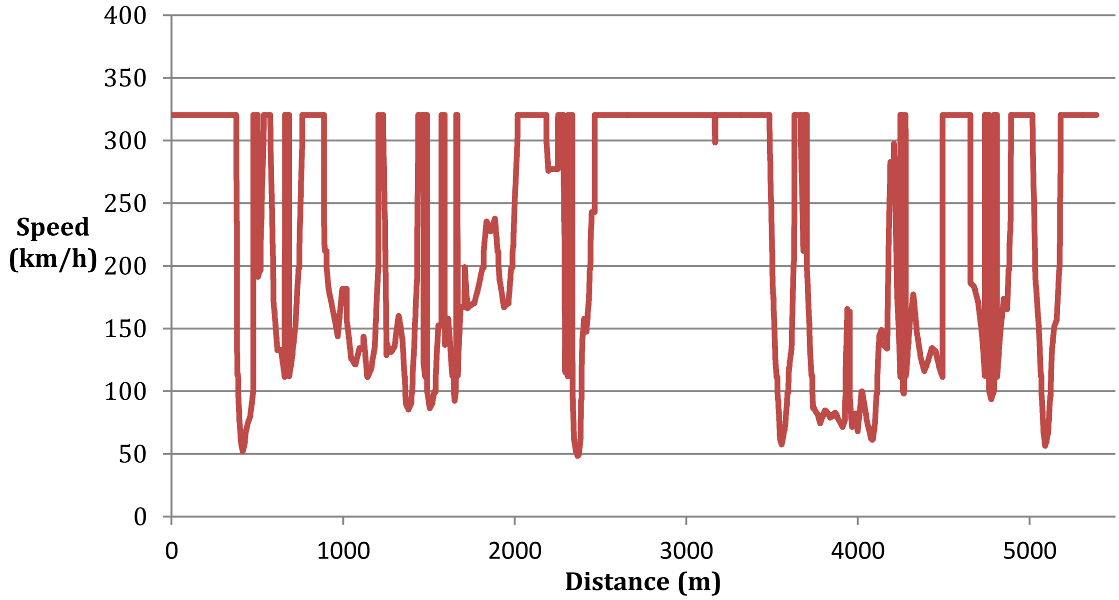


Figure 22 – Maximum Cornering Speed on the Circuit of Americas

Model Verification

With the model running drive cycle tests it needs to be verified to ensure that the calculated results are a good indication of how the vehicle will actually perform. The first check on the model can simply be a visual reality check. The check can be performed on components that have expected functions for example ensure that the speed into a gear reduction is higher than the speed out of the gear reduction. The second test can be an energy balance analysis where the energy into the system is compared to the energy out of the system plus the losses as shown in equation 16. The vehicle tractive is integral of the vehicle acceleration and tractive force as in equation 17. The full vehicle losses are the sum of the component losses in equation 18. This analysis can be performed on the entire system as well as each individual component. The ability to create models and trust the results takes a lot of work, very careful planning and experience.

$$Energy\ In = Tractive\ Energy + Losses \tag{16}$$

$$Tractive\ Energy = \int Tractive\ Force * Vehicle\ Acceleration\ \ dt \tag{17}$$

$$Losses = \ Engine\ Losses + Motor\ Losses + Drivelive\ Losses + Battery\ Losses + Mechanical\ Braking\ Energy \tag{18}$$

The energy balance analysis is completed on each of the vehicle powertrains to ensure that the simulation calculations are completed correctly. Table 14 shows the energy that went into the model, tractive energy used and the losses of each component.

Table 14 – Energy Balance of Vehicle Simulation Tool

Energy Balance in kJ	Baseline	Power-Split	Electric	Parallel	Series Parallel
Energy In					
Fuel	30635	271.1	0	37370	4398.8
Electricity	0	188.6	10232	9396	805.8
Tractive Energy	5279.4	573.6	6155.8	584.4	5831200
Losses					
Engine	23424	20483	0	27321	2932.6
Motors	0	380.0	1736.2	1451300	1362.4
Battery	0	238.2	1868.7	1673700	1544
Transmission	503.5	0	0	434.2	350160
Final Drive	334.5	323780	381.6	343.4	339880
Friction Brakes	1067.2	30186	517.4534	197.1184	1980.5
Difference Error	26.4	110.1	89.1	92.6	95.0
Percentage Error	0.5	1.9	1.4	1.6	1.6

Comparison with Commercial Software

George Box in a book about empirical modelling said, "Essentially, all models are wrong, but some are useful." [33] This statement is very true when it comes to vehicle system modelling. To figure out for each modelling scenario what would make the model or results useful and what would make it useless. Below is a list of all the simulation tool aspects that are required for a system level modeling design approach.

Table 15 - Modelling Tool Comparison

Goal	Simulink®	Autonomie
Custom powertrain configuration	Powertrain configuration defined by equations in Powertrain subsystem	Powertrain configuration defined by equations in compiled code
Custom Components	Component models built on look up tables initialized before simulation	Component models built on look up tables initialized before simulation
Testing Procedures	Velocity vs time testing procures entered using excel Model can be changed to accept different testing types i.e. velocity vs distance	Velocity vs time testing procures entered using import tool
Result Accuracy	Validated internally and compared to other commercially available software.	Most models verified with test data
Simulation Time	Single drive cycles in less than 5 minutes Can use Parallel processing	Single drive cycles in less than 5 minutes No parallel Processing
Debugging	All in on environment	Multiple environments to debug
Model Insight	Signals can be logged and plotted using Matlab tools and scripts	Good post processing with lots of logged signals

An EPA 5 cycle simulation test was run to ensure that the results from the Simulink® simulation tool compare with the commercially available software Autonmie. A conventional vehicle with the exact same parameters was defined for both simulation tools. The test results are shown in Table 16. Looking at the results it can be seen that both simulation tools predict the same fuel economy given the same vehicle. This verifies the Simulink® simulation tool results and because of the benefits it provides it will be used for the rest of the powertrain selection study.

Table 16 - Modelling Tool Result Comparison

Results – Simulink (mpg)						
FTP			**HWFET**	**US06**		**SC03**
Bag 1	Bag 2	Bag 3		City	Highway	
25.2	30.6	33.6	45.76	21.3	35.9	29.1
25.3	24.9	27.4				32.5
City			**Highway**			**Combined**
City FE	25.4		Highway FE	30.8		27.8
Results – Autonomie (mpg)						
FTP			**HWFET**	**US06**		**SC03**
Bag 1	Bag 2	Bag 3		City	Highway	
25.9	30.6	34.7	45.51	20.82	36.04	29.5
25.9	24.9	28.2				32.1
City			**Highway**			**Combined**
City FE	25.9		Highway FE	31.1		28.2

Simulation Limitations

The described simulation tool works well to produce useful results for desired testing procedures. Every modeling tool and approach has certain limitations and therefore it is important to examine the limitations of the modeling tool and testing procedures. Table 17 shows the limitations of the model and justifications for each limitation or assumption. There is a balance that has to be made between model complexity, simulation time and result accuracy.

Table 17 – Model Limitations

Limitation	Justification
Steady state component maps	Transient effects are very hard to test and create repeatedly results to obtain a transient map. The effects of transient spikes on the simulation results only effect the results by a very small amount
Constant tire friction	Model can be added that calculates tire slip and traction however this is more important for simulations that test traction control and more finite systems
No Steering Effects	Steering event can change the driveline efficiency and tire traction limitations. For the five cycle fuel economy test the vehicle is tested without steering therefore it is not required in the simulation.
No emission specific maps	Requires an emission map for each type of vehicle emission. By reducing the overall fuel consumption the overall emissions will be reduced.

5. Powertrain Comparison

This chapter examines multiple variations in powertrains to be considered for an American muscle car. Before simulations are completed certain vehicle parameters based on stead state operation can be calculated using the fundamental equations. The standard components that will be used for each of the vehicles in the architecture comparison will be described. The weight and specifications of an electrified muscle car will be determined using a weight analysis. Results from the simulations of each powertrain are discussed with respect to the vehicle technical specifications. To remain consistent with the American muscle car all the vehicle powertrains are rear wheel drive.

Vehicle Parameters

To meet the top speed goal of the electrified muscle car the powertrain must be able to provide enough power to overcome the high speed road loads. The top speed of a vehicle is the point where the maximum power the car can produce equals the power required to overcome the aerodynamic drag and rolling resistance. Using the equations discussed in Chapter 4 and vehicle specifications shown in Chapter 2 the resistance forces and required power can be calculated as shown in Table 18.

Table 18 - Required Power Calculations

Parameters		
Vehicle Weight + Driver	2034	kg
Rolling Resistance Coef	0.009	-
Aerodynamic Drag Coef	0.34	-
Frontal Area	2.3	m^2
Driveline Efficiency	0.94	-
Maximum Speed	200	mph
	322	kph
	89	m/s
Aero Force	3763	N
Rolling Resistance	180	N
Total	3943	N
Required Power	375	kW
	502	hp

With the required combined powertrain power defined the components for the vehicle are determined. To provide torque to the hybrid systems the powertrain will consist of two electric motors and an internal combustion engine. The selected electric motor is the YASA-400 because its high torque capabilities and power to weight ratio are desirable for a high performance vehicle. With a 400 volt battery system the motors will provide 90 kW of peak power each, totaling a combined 180 kW. Either a turbocharged four cylinder or naturally aspirated V6 internal combustion engine would provide enough power for the remaining 200 kW needed to meet the vehicle goals. For this study a four cylinder turbocharged engine will be chosen to reduce the overall system weight. The electrical energy storage unit will be sized to take advantage of plug in operation which greatly reduces the vehicle fuel consumption but is not oversized to limit overall powertrain weight. The specifications of the hybrid vehicle components are shown in Table 19.

Table 19 - Component Specification Table

Component Description	**Manufacturer and Model**	**Performance Specifications**
Internal Combustion Engine (ICE)	GM LTG 2.0L Turbo I4 Ford EcoBoost 2.3L Turbo I4	P_{peak}: 203 kW T_{peak}: 353 Nm Max. rpm: 7000 [34] P_{peak}: 230 kW T_{peak}: 434 Nm Max. rpm: 7000 [35]
Electric Machines	YASA Motors – YASA 400	Peak Pwr: 90 kW Cont. Pwr: 85 kW Peak Trq: 360 Nm Cont. Trq: 250 Nm [36]
Inverter for Electric Machines	Rinehart Motor Controller – PM 150 DXR (2x)	V_{dc} (max.): 360 V V_{Motor}(max): 250 V $I_{contiMotor}$; 450 Arms $I_{peakMotor}$: 450 [37]

In order to keep the architecture analysis a side by side powertrain comparisons all the hybrid architectures will consist of the same components for engine, electric machines, battery etc. Table 20 shows the weight analysis that was completed to determine the weight of the electrified vehicle. With this all the calculated data can be compiled to create final vehicle specifications that will be used for all the tested powertrains.

Table 20 – Hybrid Vehicle Mass Analysis

	Description	**Mass (kg)**
	Muscle Car Mass	1674
Added	LTG – Inline 4 Engine	150
	YASA-400 Electric Motor (2x)	48
	Rinehart Motor Controller (2x)	25
	Energy Storage System	120
	On-Board-Charger	7
	Electrical Components (HV cables, connectors, electronic distribution/busbars, battery cooling lines, motor cooling etc.)	40
Removed	Stock Engine (V6)	185
Total Weight		**1880**

Vehicle Simulation

Baseline Powertrain Simulations

Baseline vehicle simulations are run to ensure constancy between the simulations and the specified vehicle parameters. The baseline model constructed using the same specifications as the combined high performance muscle car defined in Table 5. The fuel economy results of the simulations are shown in Table 21 and the performance results are listed in Table 22. It is observed that the simulation results correlate well with the combined high performance muscle car specifications listed in Table 5.

Table 21 - Baseline Vehicle Fuel Economy Simulation Results

Charge Sustaining Results – Simulink (mpg)							
FTP				HWFET	US06		SC03
°C	Bag 1	Bag 2	Bag 3		City	Highway	
24	15.9	16.1	21.2	30.7	14.3	27.2	18.3
-7	12.9	13.1	17.3				

City FE	Highway FE	Combined FE
14.7	22.1	18.0

Table 22 - Baseline Vehicle Performance Simulation Results

Maximum Speed	196	mph
	315	kph
0-60	4.2	sec
0-100	9.4	sec
Lap Time	161.2	sec

Fuel Economy Powertrain Simulations

The power-split powertrain is commercially used for increased fuel economy vehicles. The vehicle and powertrain system were designed in the Simulink® tool with the basic equations of the planetary gear set similar to the one used in the first Toyota Hybrid Drive system. The components and vehicle parameters were set to the same as the rest of the hybrid electric vehicles in the comparison study. The simulation results are given in Table 23 and show that the fuel economy of the power-split hybrid is a great improvement over the baseline vehicle.

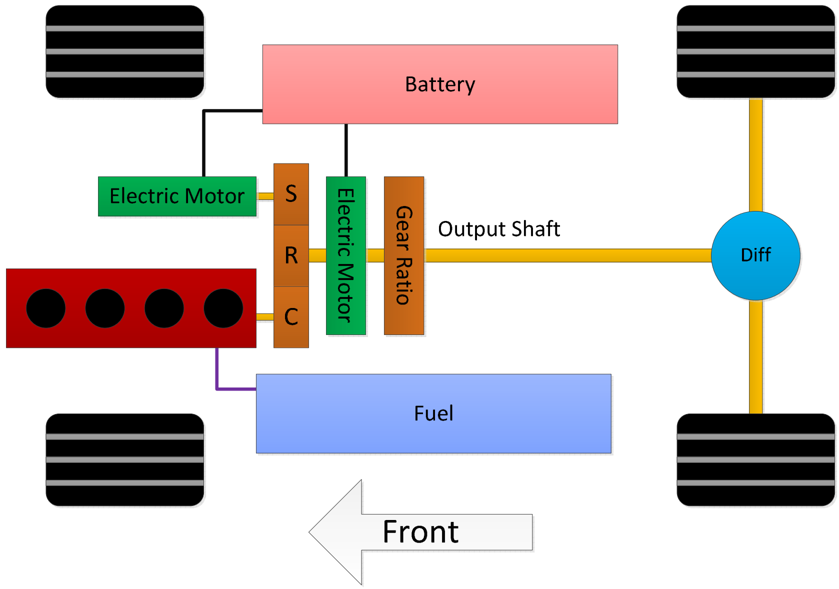


Figure 23 - Power-Split Powertrain Diagram

Table 23 - Power-Split Simulation Results

Charge Sustaining Results – Simulink (mpg)							
FTP				**HWFET**	**US06**		**SC03**
°C	Bag 1	Bag 2	Bag 3		City	Highway	
24	24.4	33.7	32.6	37.5	20.3	31.5	23.5
-7	19.9	27.5	26.5				

City FE	**Highway FE**	**Combined FE**
24.6	26.1	25.3

The electronic continuously variable transmission of the power-split transmission limits the powertrain from using all the potential torque of all three prime movers for tractive power at any given instant. Therefore, the performance of the power-split hybrid electric vehicle is a compromise from the baseline vehicle performance as shown in Table 24. The nature of the two degrees of freedom in the power-split transmission requires that motor 1 must be used to provide a reaction force to control the speed of the engine during acceleration therefore limiting it from providing tractive effort. Since the baseline vehicle can use all of its onboard torque production for tractive effort it will accelerate faster. These limitations carry over to the racetrack as well which explains the increased possible lap time.

Table 24 - Power-Split Simulation Performance Results

Maximum Speed		167	mph
		269	kph
0-60		11.1	sec
0-100		21.1	sec
Lap Time	**Hot Lap**	167.8	sec
	CS Lap	171.8	sec

Emissions Reduction Powertrain Simulation

A battery electric vehicle does not contain all the same components as the rest of the vehicle powertrains that will be tested. The internal combustion engine would be removed entirely. To ensure that the vehicles tested all have the same power level two more YASA-400s are added to replace the engine. A larger battery would need to be put in its place. A simple weight analysis is completed to determine the curb weight of the electric vehicle and is shown in Table 25. The battery weight is 544 kg which based on the battery weight of an 85 kWh Tesla Model S battery [38].

Table 25 - Electric Vehicle Weight Analysis

	Description	Mass (kg)
	Muscle Car Mass	1674
Added	YASA-400 Electric Motor (4x)	96
	Rinehart Motor Controller (2x)	50
	Energy Storage System (85 kWh)	544

	On-Board-Charger	7
	Accessories (battery housing, HV cables, connectors, electronic distribution/busbars, battery cooling, motor cooling etc.)	40
Removed	Stock Engine (V6)	185
Total Weight		**2226**

The calculated battery electric vehicle weight is combined with the chassis and component parameters to initialize the vehicle model in Simulink®. Since electric vehicles do not use any gasoline the mile per gallon equivalent is used to compare the fuel economy of electric and gasoline vehicles. The battery electric diagram that was used for the simulations is shown in Figure 24. Table 26 shows the simulations results for the fuel economy of the battery electric powertrain in the American muscle car.

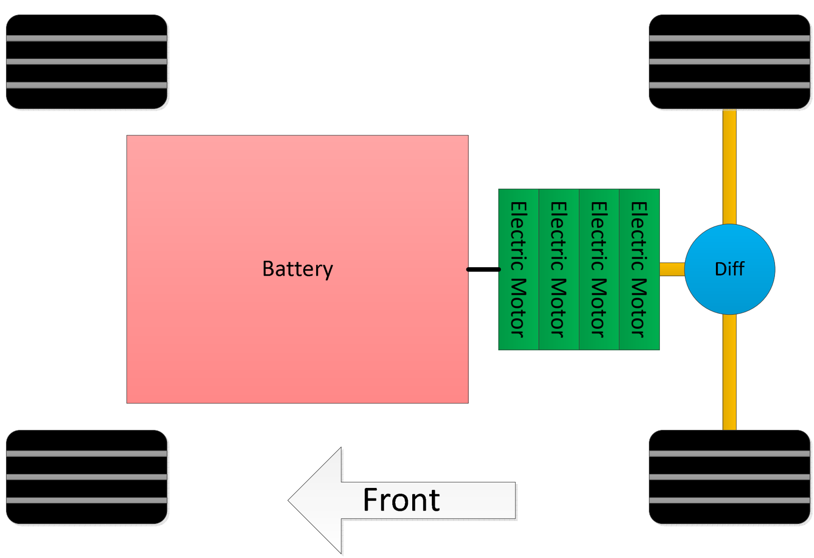


Figure 24 – Battery Electric Powertrain Diagram

Table 26 - Electric Powertrain Simulation Results

<table>
<tr><td colspan="8">Results – Simulink (mpge)</td></tr>
<tr><td colspan="4">FTP</td><td rowspan="2">HWFET</td><td colspan="2">US06</td><td rowspan="2">SC03</td></tr>
<tr><td>°C</td><td>Bag 1</td><td>Bag 2</td><td>Bag 3</td><td>City</td><td>Highway</td></tr>
<tr><td>24</td><td>52.6</td><td>68.6</td><td>86.1</td><td>101.45</td><td>45.40</td><td>73.96</td><td>47.58</td></tr>
<tr><td>-7</td><td>64.5</td><td>55.9</td><td>70.2</td><td></td><td></td><td></td><td></td></tr>
</table>

City FE	Highway FE	Combined FE
55.3	62.7	58.6

The equivalent fuel economy is very high compared to the baseline vehicle due to the higher efficiency of the electric components. The electric powertrain also does not burn any fuel and therefore does not produce any emissions on any of the drive cycles. With a similar peak power level and ability for all the electric motors to provide traction the maximum speed is close to the conventional vehicle. The rest of the performance results are shown in Table 27.

Table 27 – Electric Vehicle Performance Simulation Results

Maximum Speed	194	mph
	312	kph
0-60	5.7	sec
0-100	10.7	sec
Lap Time	158.6	sec
Racing Range	30.6	km
	5.7	Laps

Performance Powertrain Simulation

For the third vehicle electrification motivation of performance improvements a parallel hybrid electric vehicle and series-parallel hybrid electric vehicle will be tested in simulation.

Parallel Hybrid Powertrain

The parallel hybrid vehicle architecture can produce lots of tractive effort as the torques from the engine and electric motors are combined at a torque coupler. The electric motors are both placed in the P3 position after the transmission. This allows the transmission to shift into neutral, which disconnects the engine from the driveline and allows the vehicle to operate in electric only mode. Figure 25 shows a diagram of the parallel powertrain used for the simulations. The simulation results for the fuel economy of the parallel powertrain are shown in Table 28 and the performance results are in Table 29.

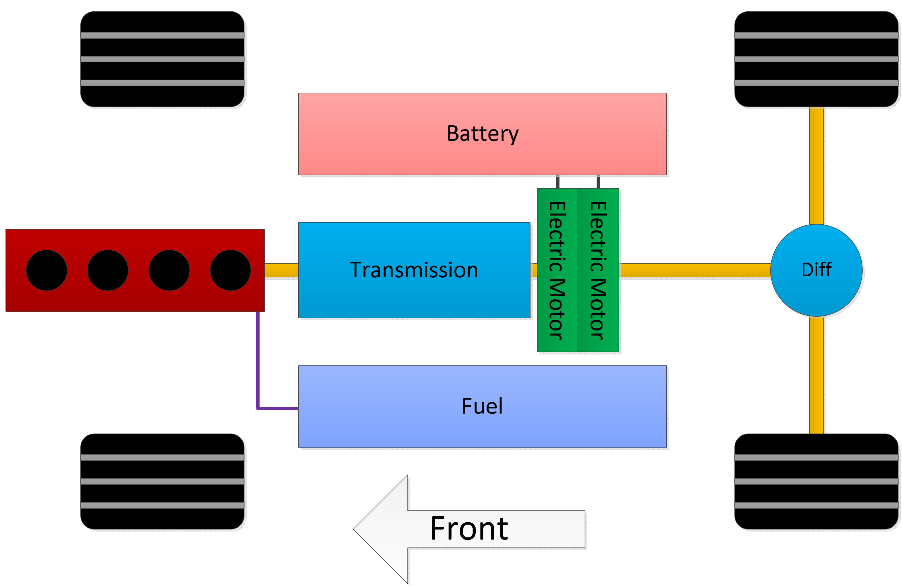


Figure 25 – Parallel Hybrid Powertrain Diagram

Table 28 – Parallel Hybrid Simulation Results

Charge Sustaining Results – Simulink (mpge)							
FTP				**HWFET**	**US06**		**SC03**
°C	Bag 1	Bag 2	Bag 3		City	Highway	
24	21.7	23.4	28.9	35.9	22.7	29.0	24.6
-7	17.7	19.1	23.6				

City FE	Highway FE	Combined FE
20.9	24.4	22.5

Table 29 - Parallel Hybrid Performance Simulation Results

Maximum Speed		193	mph
		311	kph
0-60 mph Time		4.4	sec
50-70 mph Time		1.7	sec
Lap Time	**Hot Lap**	168.5	sec
	CS Lap	156.2	sec

Series-Parallel Hybrid Powertrain

The series-parallel powertrain has the added functionality of being able to select series or parallel operation. The additional functionality helps where a parallel hybrid works best for highway and a series hybrid is developed more for stop-and-go city use. The electric motors are both placed in the P2 position with one on the engine side of the clutch and the other on the transmission side as shown in Figure 26. With all the torque producing components placed before the transmission the gears can be shifted in any driving mode. This gives the system motor potential operating points to select from which can help improve fuel economy and performance. The clutch between the motors is used to switch from electric/series mode to parallel mode. Table 30 shows the fuel economy results and Table 31 shows the performance results for the series-parallel hybrid powertrain.

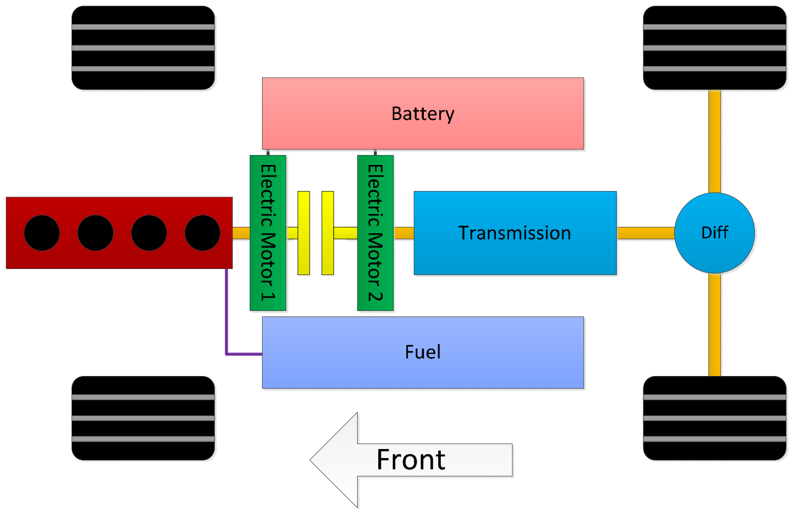


Figure 26 – Series-Parallel Powertrain Diagram

Table 30 – Series-Parallel Simulation Results

Series-Parallel Simulation Results – Simulink (mpg)							
FTP				**HWFET**	**US06**		**SC03**
°C	Bag 1	Bag 2	Bag 3		City	Highway	
24	20.6	29.8	27.5	34.7	24.1	30.2	21.2
-7	16.8	24.3	22.4				32.6

City FE	**Highway FE**	**Combined FE**
22.1	24.6	23.3

Table 31 – Series-Parallel Hybrid Performance Simulation Results

Maximum Speed		193	mph
		311	kph
0-60 mph Time		4.1	sec
50-70 mph Time		1.7	sec
Lap Time	**Hot Lap**	154.6	sec
	CS Lap	164.4	sec

6. An Architecture Proposal

With the analysis of each of the powertrain architectures, the data can be compared with the design goals of the vehicle to propose an appropriate architecture for an American muscle car. A selection matrix is used to determine how well the vehicle architecture meets the design criteria. There are three input elements to the selection matrix, the objectives, the objective weighting and the results for each powertrain. The objectives and weighting are created to ensure the selected vehicle meets the original design goals. The quantitative results are taken from the simulation results and the qualitative results are based on information about each powertrain.

Selection Matrix

The objectives of the American muscle car are described previously as qualitative vehicle functions and parameters. From the discussion qualitative objectives and weighting scale can be determined. Table 32 shows the weighting factor for each of the objectives. The weighting factors represent the design goal of maintaining or increasing performance while reducing vehicle's fuel consumption with considerations concerning cost, emissions, rate of energy refilling, and driver feel. The weighting factors are given in percent so that when applied to each of the powertrain results all the vehicles scores will range from 0-1000 with 1000 being a perfect score.

Table 32 – Vehicle Objectives and Weighting Factors

0-60 mph Acceleration	50-70 mph Acceleration	Driver Feedback	Track Performance	City Fuel Economy	Highway Fuel Economy	Vehicle Emissions	Cost	Energy Refill Rate
16	8	6	16	15	12	8	10	9

The powertrain results are determined from the simulations and information about each powertrain. A summary of the simulation results is given in Table 33. The qualitative results are determined on what the customer of an American muscle car expects from their vehicle. Driver feel is how well the car operates compared with what the drive is accustomed to using. There are certain reactions that are expected from the car when it is given different inputs. When pressing the accelerator pedal they hear the engine rev up at a given relationship to the vehicle speed and they like to have control over when the gears shift to match their personal driving style.

Table 33 – Summary of Simulation Results

	Baseline	**Electric**	**Power-Split**	**Parallel**	**Series Parallel**
City (mpg)	14.7	55.3	24.6	20.9	22.1
Highway (mpg)	22.0	62.7	26.1	24.4	24.6
Combined (mpg)	18.0	58.6	25.3	22.5	23.3
Maximum Speed (mph)	196.0	194.0	167.0	193.0	193.0
0-60 mph(sec)	4.6	5.6	9.3	4.4	4.1
50-70 mph(sec)	3.6	2.1	3.7	1.7	1.7
CS Lap (sec)	161.2	158.6	171.8	168.5	164.4
Hot Lap (sec)	161.2	158.6	167.8	156.2	154.6

With all the results and objectives obtained the selection matrix can be populated. Table 34 shows the completed selection matrix for all the vehicle powertrains including the baseline vehicle. All the raw scores are multiplied by the weighting factor to obtain the weighted score. A total powertrain score is determined by summing all the weighted scores for each vehicle.

Table 34 – Powertrain Selection Matrix

Objective	Total Weight (%)	Baseline		Power-Split		Electric		Parallel		Series Parallel	
		Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
0-60 mph Acceleration	16	8.9	142.4	4.4	70.4	7.3	116.8	9.3	148.8	10	160
50-70 mph Acceleration	8	4.7	37.6	4.6	36.8	8.1	64.8	10	80	10	80
Driver Feedback	6	10	60	3	18	5	30	8	48	7	42
Track Performance	16	9.4	150.4	9	144	6.2	99.2	9.7	155.2	9.9	158.4
City Fuel Economy	15	2.7	40.5	4.5	67.5	10	150	3.8	57	4	60
Highway Fuel Economy	12	3.5	42	4.2	50.4	10	120	3.9	46.8	3.9	46.8
Vehicle Emissions	8	3.1	24.8	4.3	34.4	10	80	3.8	30.4	4	32
Cost	10	10	100	6	60	2	20	5	50	4.5	45
Energy Refill Rate	9	10	90	10	90	3	27	10	90	10	90
Total	**100**	62.3	**687.7**	50	**571.5**	61.6	**707.8**	63.5	**706.2**	64.2	**714.2**

From the table above, the series-parallel powertrain has the best score and is the best candidate to meet all the design goals of an American muscle car. The parallel and electric powertrains also make an improvement on the baseline conventional powertrain, whereas the power-split powertrain even though it has a small improvement on fuel efficiency its low performance capabilities make it the least desirable powertrain. To gain greater insights into the selection matrix results the mean performance and fuel economy scores are calculated and each vehicle's deviation from this mean can be analyzed. The results of Table 35 show that power-split performance is low and the series parallel has a significant performance advantage. Observing the deviation in the fuel economy results it can be seen that the electric vehicle has the greatest advantage and the baseline has the worst fuel economy score, whereas the hybrid vehicles all perform similarly.

Table 35 – Selection Matrix Scoring Deviation from Mean

	Baseline	Power-Split	Electric	Parallel	Series Parallel
Performance Deviation from the Mean	22.8	-98.4	-56.8	59.6	72.8
Fuel Economy Deviation from the Mean	-73.9	-28.9	168.8	-34.7	-31.3

Series-Parallel Hybrid Electric Vehicle

Following the analysis it can be seen that the series-parallel hybrid is the most appropriate candidate to be selected for an electrified American muscle car. The results show that an electrified muscle car can increase fuel economy while exceeding the baseline performance targets. To ensure that powertrain choice is a proper fit for the vehicle study on the control system, energy storage system and overall cost is completed.

Supervisory Controller Mode Selection

With multiple powertrain modes and multiple torque producing components a control strategy is developed to ensure that the vehicle meets the driver torque request, ensure the state of charge of the energy storage system is stable and the powertrain is operating efficiently. Practically, the supervisory controller selects the hybrid mode based on the vehicle's speed, state of charge (SOC) of the HESS and the driver's torque request. Table 20 illustrates how each hybrid mode is selected, as predefined set points for Low, Medium, and High SOC (SOC_{Low}, SOC_{Med}, SOC_{High}) and similarly vehicle speed is given as $Speed_{Low}$, $Speed_{Med}$, $Speed_{High}$. During Charge Depleting Mode the vehicle's SOC will be above SOC_{High} and, therefore, only electric operation will be requested. While in Charge Sustaining Mode, the vehicle may operate as either a series or parallel hybrid.

Table 36 – Hybrid Mode Selection Matrix

	Charge Sustaining Modes			
	$SOC < SOC_{Low}$	$SOC_{Low} < SOC < SOC_{Med}$	$SOC_{Med} < SOC < SOC_{High}$	$SOC_{High} < SOC$
$0 – Speed_{Low}$	Series Mode	Electric Mode	Electric Mode	Electric Mode
$Speed_{Low} – Speed_{Med}$	Series Mode	Series Mode	Electric Mode	Electric Mode
$Speed_{Med} – Speed_{High}$	Parallel Mode	Series Mode	Series Mode	Electric Mode
$> Speed_{High}$	Parallel Mode	Parallel Mode	Parallel Mode	Electric Mode

Since only the P2 electric motor provides tractive power during the Series and Electric Hybrid Modes, the vehicle will switch to the Parallel Mode if additional torque is requested.

Electric Mode

In Electric Mode, the clutch is disengaged and only the rear P2 motor provides tractive power. To maintain a linear torque response to the driver's request, the pedal position (expressed as a percentage) is multiplied by the maximum torque the vehicle is able to deliver, and subsequently, divided by the rear P2 motor's maximum torque. This process is illustrated in Equation 19. In the event that the driver requests more torque than the rear P2 motor can provide, the vehicle will switch to the Parallel Mode in order to gain access to the torque produced from the P1 motor and from the internal combustion engine.

$$\text{Motor2} = \text{Pedal Position} * \left(\frac{(\text{ICEMaxTorque} + \text{Motor1 Max Torque} + \text{Motor2 Max Torque})}{\text{Motor2 Max Torque}}\right) \tag{19}$$

The control of strategy for the transmission in Electric Mode is based on the operating speed of the rear P2 motor. The transmission shifts up into a higher gear when the motor's speed exceeds 6000 RPM and is shifted down when the speed drops below 3000 RPM.

Series Mode

Similar to Electric Mode, the Series Mode will see the vehicle's clutch disengaged and the rear P2 motor is the only motor providing tractive power. The motor torque request and transmission shift strategy are the same as that used in Electric Mode. A thermostatic control strategy is used for both the ICE and the front P2 motor. The front P2 motor is first used to start the ICE and bring it up to speed. Once the engine is up to speed, a PID controller is used to govern the front P2 motor's torque to insure that the ICE speed and throttle position are held constant.

Parallel Mode

Within the Parallel mode there exist three sub-modes. Each sub-mode is used to produce low, medium, and high tractive power, respectively. In the low-torque parallel mode, the ICE operates at its peak efficiency point and the front P2 motor acts as either a generator or provides torque so that the driver's request is met. If the front P2 motor has reached its peak torque output, the clutch is reengaged and the rear P2 motor begins to produce torque in Medium-Torque Parallel Mode. If the front P2 and rear P2 motors are both applying peak torque, the ICE torque request is increased past its peak efficiency point to its peak torque point in High-Torque Parallel Mode. Figure 27 illustrates how the torque is split between the front P2 motor, rear P2 motor, and the ICE and how together, they add up to the driver's linear torque request.

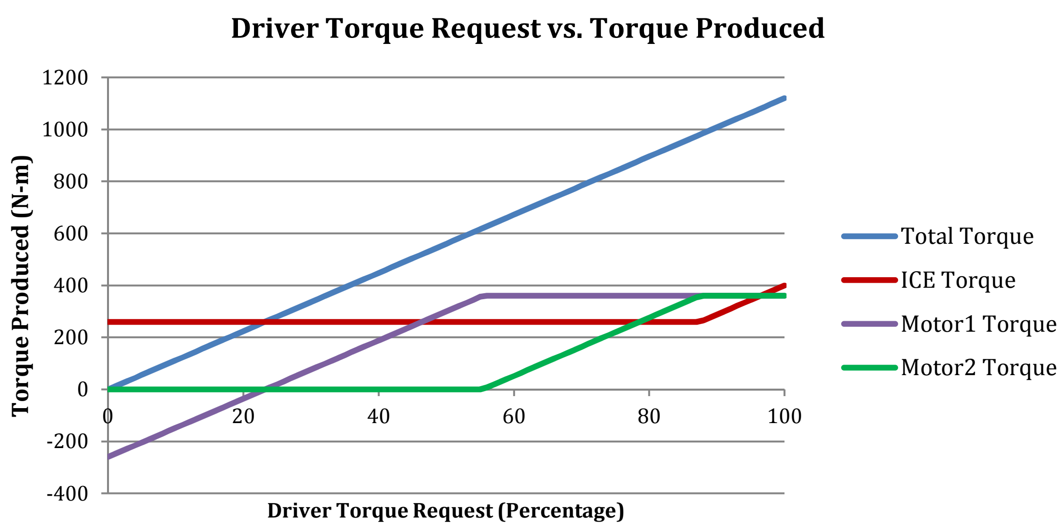


Figure 27 - Driver Torque Request vs. Torque Produced

Energy Storage System

The electrical energy storage (ESS) on a hybrid vehicle is a key component in how successful that vehicle becomes. Without a proper ESS the motors will not be able to perform to their full potential and the whole powertrain system will suffer and therefor the ESS needs to meet the demands of the hybrid system. The simulations that were completed in for the powertrain selection process used a generic electrical energy source and the charge was always balanced for each drive cycle.

Automotive manufactures have made batteries of various sizes based on the level of hybridization they designed into their vehicle. A large battery pack is expensive but can offer the series parallel hybrid a few advantages such as more usable electrical power and all electric ZEV range.

The energy storage system must be able to produce the amount of electrical power that the hybrid system is requesting. To determine a typical maximum load power the vehicle is simulated using the most aggressive test of the race track drive cycle. The power demand from the battery can be seen in Figure 28. The series-parallel is a higher level of electrification and therefore needs a high power battery. The results show that the battery power required is 235 kW output and 150 kW input.

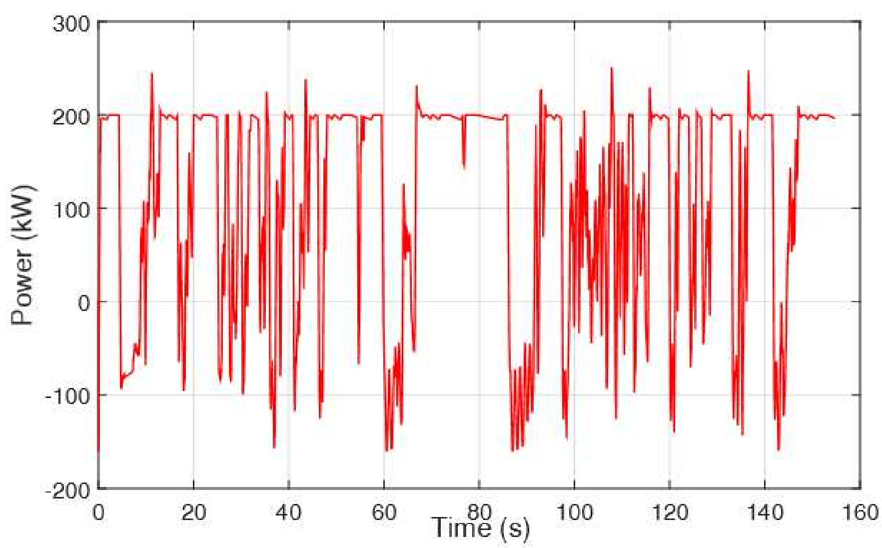


Figure 28 - Battery Power Load (kW)

A larger battery will be able to offer the vehicle a certain range of all electric operation which can be used to greatly reduce the overall fuel economy and emissions of the vehicle. By offering an all-electric range people who commute could travel their commute mostly or all electric then only use the engine when going on longer trips.

To build up a battery pack for this vehicle the first concern is the power requirements because if a plug in electric range is desired it can be added at any max power. A123 Systems offers a lithium ion cell that has a power density of 4 kW/kg [39]. To meet the power demand of 235 kW, 60 kg of cells would have to be used and would combine to have 11.5 kWh of onboard electrical storage. With 60kg of cells this leaves 60kg for packaging, cooling, conductors and a battery management system.

Charge Depleting Results

With a relatively large battery pack the vehicle could be charged up and run on electric only power for a certain range. To determine the charge depleting range simulations are done with the battery SOC starting at 100% then simulating the city and highway drive cycles until the SOC reaches the charge sustaining level.

Table 37 – Charge Depleting Series-Parallel Results

Series Parallel Simulation Results – Simulink (mpg)							
FTP				**HWFET**	**US06**		**SC03**
°C	Bag 1	Bag 2	Bag 3		City	Highway	
24	79.7	116.5	106.4	113.0	61.4	81.8	69.8
-7	65.0	94.9	86.7				

City FE	**Highway FE**	**Combined FE**
79.8	55.1	68.7

Charge Depleting Range	43 km

The EPA and Society of Automotive Engineers (SAE) have completed research to determine how much fuel the charge depleting range saves the average customer. To do so they created a utility factor (UF) that is a function of the charge depleting range shown in Figure 29. The UF represents the time that an average driver will spend in charge depleting mode. Once the UF is determined for the vehicle a weighted combination of the charge depleting fuel economy and charge sustaining fuel economy can be determined for the vehicle. Table 38 shows the utility factor weighted fuel economy for the selected series-parallel plug-in hybrid electric muscle car.

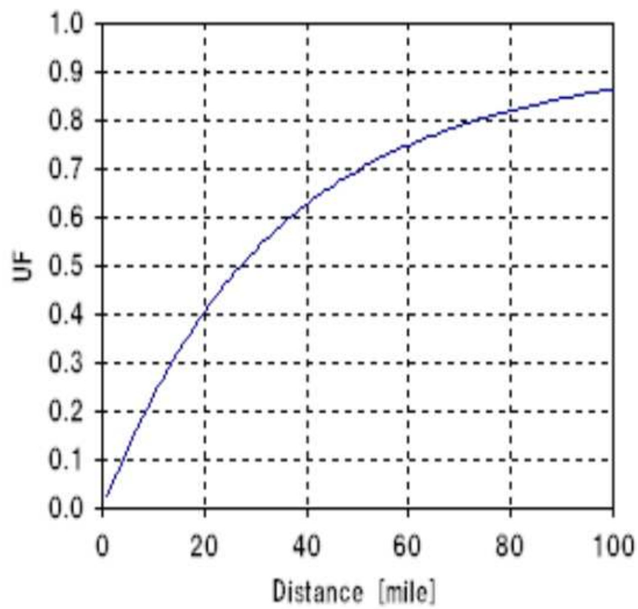


Figure 29 – Utility Factor [40]

Table 38 – Utility Factor Weighted Fuel Economy

Charge Sustaining Fuel Economy				
City FE		**Highway FE**		**Combined FE**
22.1		24.6		23.3
Charge Depleting Fuel Economy				
City FE		**Highway FE**		**Combined FE**
79.8		70.6		68.7
Charge Depleting Range	43 km	**Utility Factor**		0.52
UF Weighted Fuel Economy				
City FE		**Highway FE**		**Combined FE**
52.9		48.7		51.0

7. Conclusion

An electrified powertrain in an American muscle car can improve both the fuel economy of the vehicle and the overall vehicle performance. The model based design process has shown to accurately predict the expected fuel economy and performance of a variety of powertrains. The results of the study show that the most appropriate electrified powertrain for the American muscle car is the series-parallel hybrid architecture. With motors in the P2-P2 position the vehicle has a well-rounded powertrain that will perform well for daily driving and provide power when required on a racetrack. Including a smart control system and a large battery which allows a charge depleting range will greatly increase the effective fuel economy of the vehicle.

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