

The UW EcoCAR2 Vehicle Development Process and Vehicle Level  
Torque Control Strategy Documentation

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**Abstract**

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The transportation sector accounts for 28% of total US energy consumption, and 93% of this energy comes from petroleum resources (Energy Information Administration, 2014). If the effect of energy use for the transportation industry go unchecked, the associated emissions represent one of the biggest threats to our global environment. To reduce energy consumption used by transportation simply by traveling less or shipping less goods would hinder commerce and slow economic growth. It becomes important then to find an engineering solution to the environmental impacts of personal transportation in order to allow commerce and economic growth to continue uninhibited.

The EcoCAR2 competition is a three year long collegiate level automotive engineering competition in which fifteen universities across North America to reduce the environmental impact of personal automobiles without sacrificing the consumer acceptability of the vehicle (Argonne National Laboratories, 2014). It is the first competition of its kind designed to create automotive technology that can penetrate the mass market and have significant and lasting environmental impact reductions. The technical goals allow for modifications to the power train of the vehicle and control strategy innovations to reduce greenhouse gas emissions, criteria emissions, petroleum energy consumption, and total energy consumption.

The phrase “electrified vehicle” includes mild Hybrid Electric Vehicle (HEV), strong HEV, Plug-in Hybrid Electric Vehicle (PHEV), and fully electric vehicles (EV). These types of vehicle powertrains are one

technology that can potentially improve upon all of the technical goals of EcoCAR2. The stronger the electrification of a vehicle, the better the improvement upon the competition's four main technical goals. However, with stronger electrification typically comes higher cost and increased emissions, both mostly due to the high voltage battery pack that is typically a NiMH (small capacity) or lithium chemistry. There are very few additional technologies that universally improve upon all of these criteria without causing detrimental effects on consumer acceptability.

Hybrid vehicles consist of two or more torque producing components, typically an electric motor and a petroleum internal combustion engine. The driver interface for hybrid vehicles, however, still only has a single accelerator pedal. There is a need for a supervisory control strategy that controls the torque output of each component. This supervisory control strategy is responsible for commanding the vehicle drivetrain as a system to match the driver's intended torque demand, while optimizing to minimize emissions and energy consumption.

This thesis outlines the vehicle development process utilized by the University of Washington EcoCAR2 team over all three years of the EcoCAR2 competition. The UWEC2 team came up with a Parallel Through the Road (PTTR) PHEV that can operate as an EV for the first 50 miles after being charged off of the grid. This very heavy reliance on grid electricity for propulsion addresses all four of the primary technical goals of the competition. Once the battery pack is depleted, the vehicle will turn on a 1.7L turbo diesel engine operating on B20 to drive the vehicle as a HEV for the following 350 miles in a charge-sustaining fashion. Biodiesel will reduce the criteria emissions and petroleum energy consumption of the charge-sustaining mode. These modes of operation combined with several other advantages of the PTTR architecture provide a very good baseline for the UWEC2 team to compete at year three competition of EcoCAR2.

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# A. Glossary of Terms

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<b>505</b>	505 vehicle drive cycle
<b>AVTC</b>	Advanced vehicle technical competition
<b>B20</b>	Bio-Diesel, with a blend of 80% petroleum, 20% bio-fuel
<b>BAS</b>	Belted alternator/starter
<b>CD</b>	Charge Depleting (mode of operation)
<b>CS</b>	Charge Sustaining (mode of operation)
<b>DFMEA</b>	Design Failure Mode Effects Analysis
<b>DOE</b>	Department of Energy
<b>DPF</b>	Diesel particulate filter
<b>E85</b>	Petroleum mix with 85% ethanol, 15% petroleum
<b>E10</b>	Petroleum mix with 10% ethanol, 90% petroleum
<b>ECM</b>	Engine Control Module
<b>EPO</b>	Emergency Power Off
<b>EREV</b>	Extended range electric vehicle
<b>ESS</b>	Energy Storage System
<b>FTA</b>	Fault Tree Analysis
<b>GHG</b>	Greenhouse gas
<b>GVWR</b>	Gross Vehicle Weight Rating
<b>HEV</b>	Hybrid electric vehicle
<b>HIL</b>	Hardware in the loop
<b>HVIL</b>	High Voltage Interlock Loop
<b>HWFET</b>	Highway Fuel Economy Test
<b>ICE</b>	Internal Combustion Engine
<b>LOTO</b>	Lock Out / Tag Out
<b>MPG</b>	Miles per gallon
<b>MSD</b>	Manual safety disconnect

<b>PEU</b>	Petroleum energy use
<b>PHEV</b>	Plugin hybrid electric vehicle
<b>PTTR</b>	Parallel Through The Road
<b>SOC</b>	State of charge
<b>USO6</b>	Fuel economy drive cycle
<b>UF</b>	Utility factor
<b>WTP</b>	Well to pump
<b>WTW</b>	Well to wheel

# A - Production Vehicle Baseline Modeling

The UW EcoCAR2 team plans to design a vehicle in the virtual world that closely matches the completed prototype in year two. Control strategy algorithms and overall vehicle performance can later be modeled with this virtual vehicle. This section describes the modeling performed for the conventional baseline vehicle, the 2013 Chevy Malibu with a 2.4L 133.6kW gasoline engine. The vehicle that will be donated is the BAS+ version of the vehicle, but it is important to evaluate the design choices of the base vehicle to get an understanding of the overall vehicle platform.

A baseline study is important for demonstrating the effect that a new technology has on fuel economy and emissions. The 2013 Chevy Malibu stock vehicle simulations will provide a solid reference with which to make comparisons and improvements. Simulating the stock vehicle will give the UW team insight into where improvements can be made and how changing the existing architecture will improve the performance, fuel economy and reduce green-house gas emissions.

Briefly, power flows within the conventional vehicle as follows: Chemical energy is released as mechanical and thermal from the engine, then the mechanical energy is transferred through the transmission, drive shaft and final drive arrives at the wheels and propels the vehicle forward. Alternatively, mechanical engine power flows through the alternator and stored in the 12 V battery for consumption via the starter motor or vehicle accessories.

## A.1.1 - Autonomie Introduction

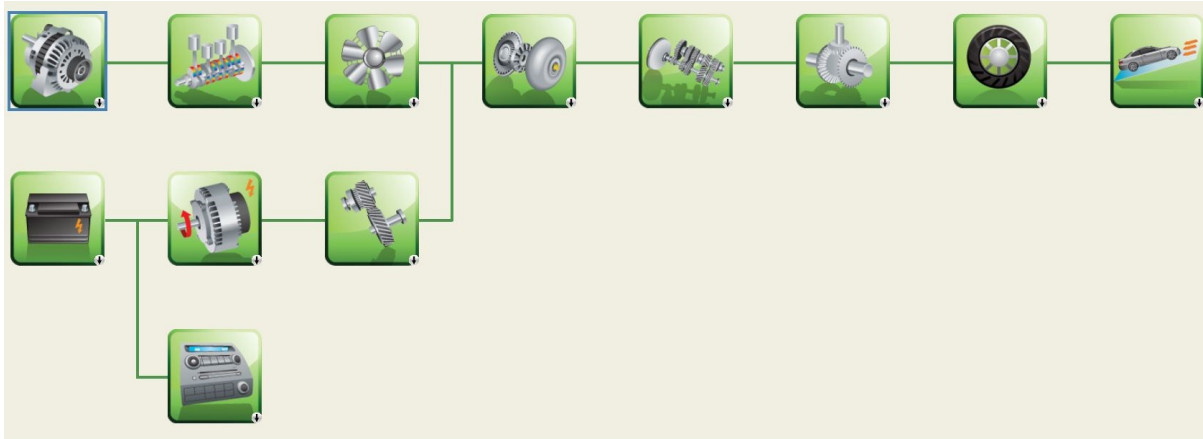
In an effort to address the shortcomings of conventional vehicle technology, the U.S. Department of Energy (DOE) has encouraged the development of Plug-in Hybrid Electric Vehicles. In response, Argonne National Laboratory (ANL) partnered with General Motors (GM) to meet the demand of the consumer while reducing net energy consumption, greenhouse gas emissions and overall petroleum energy usage. To best analyze and compare the vast combinations of possible hybrid vehicle powertrain systems, ANL developed the

Power Train Systems Analysis Toolkit (PSAT) which is a compilation of hybrid modeling software and individual component specifications. Building on PSAT, ANL developed a graphic user interface titled Autonomie. Because of its simplicity of use, extensive pre-existing architecture and component database, and power to make comparisons, the UW EcoCAR2 team used Autonomie to analyze three possible PHEV hybrid architectures. (Freyermuth, Fallas, & Rosseau, 2007)

The EcoCAR2 competition provides a donated vehicle plant model for the stock 2013 Chevy Malibu. This model was utilized for the baseline vehicle modeling exercise, whereas custom plant models were created for hybrid architecture modeling later on in this document.

In year one the UW team chose to use the provided Autonomie software and files to model the base Malibu. It was believed that the plug-and-play capabilities of the software will prove essential for future reports to evaluate the large variety of hybrid powertrain architectures. By becoming familiar with the features of the software early, it became a powerful tool that was used when work began on the modeling for Report #2. A sample high-level power flow diagram, as implemented in Autonomie, is shown in Figure 1 below.

The Autonomie software offers a very powerful modeling/simulation tool for vehicle architecture exploration in the convenience of a GUI. Autonomie considers everything from road load forces, to mechanical and electrical accessories, to empirically-obtained efficiency maps for every component, to the lag time of a virtual driver, giving the user almost full control over all aspects of the vehicle. Because Autonomie is built on MATLAB and Simulink, the user is also given full control over the Simulink solver options and can use many built-in functions to implement customized Autonomie processes and studies. The UW team recognized Autonomie's computing power and simplicity of use and will use Autonomie to simulate the stock vehicle and proposed vehicle architectures.



**Figure 1. Power flow diagram of the conventional vehicle within Autonomie**

Simulations using Autonomie are performed as follows: select vehicle, confirm components, setup drive cycle, then run the simulation. Autonomie makes simulation setup very convenient for the user and builds the model within Simulink automatically. Next Autonomie presents the results of the vehicle's performance such as electrical consumption, fuel consumption, average efficiencies etc. to the user for analysis. For more in depth analyses, Autonomie also provides signal vs. time plots for each component and all of the data is stored in a MATLAB data file. In the case of this report, parametric studies of engine size and vehicle weight were performed using Autonomie to better understand the design decisions made by GM for the baseline vehicle.

## **A.1.2 - Autonomie Parametric Studies**

In order to understand the design choices made for the 2013 Chevy Malibu base vehicle, a parametric study was performed on engine size and weight while recording the resulting effects on performance and fuel economy. The vehicle model was run through a set of drive cycles that were provided to give an accurate representation of North American drivers today.

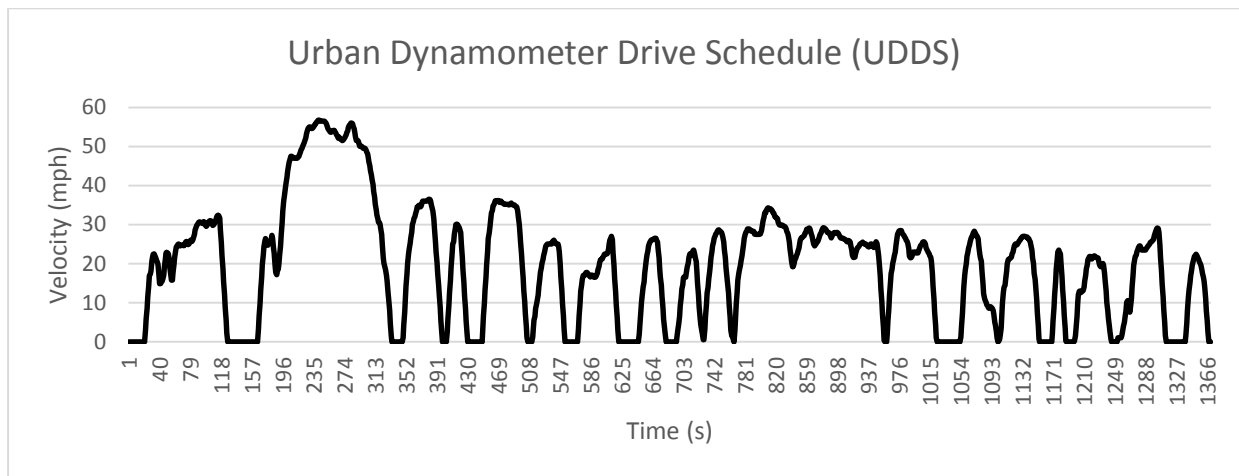
The EcoCAR2 blend is 57% highway (blue) and 43% city cycles (red) as documented by the EPA in their initial proposals for 5-cycle testing (Argonne National Labs, 2011). The assigned weights of each cycle are to take into account all kinds of drivers. Specifically, the City and HWY portions of the US06 drive cycle

represent very “aggressive” driving styles (darker color), while the HWFET and 505 represent fairly “light” driving styles (lighter color).

In order to ensure that fuel economy comparisons are meaningful, the trace quality of the modeled vehicle is important. As engine power or vehicle weight is varied, large trace misses would result in a saturation of engine power, leading to results that would be inadequate for comparison with accurately traced results. A trace miss of 5% or more on a single cycle was considered excessive for this report, and will be referred to as having “poor trace quality”.

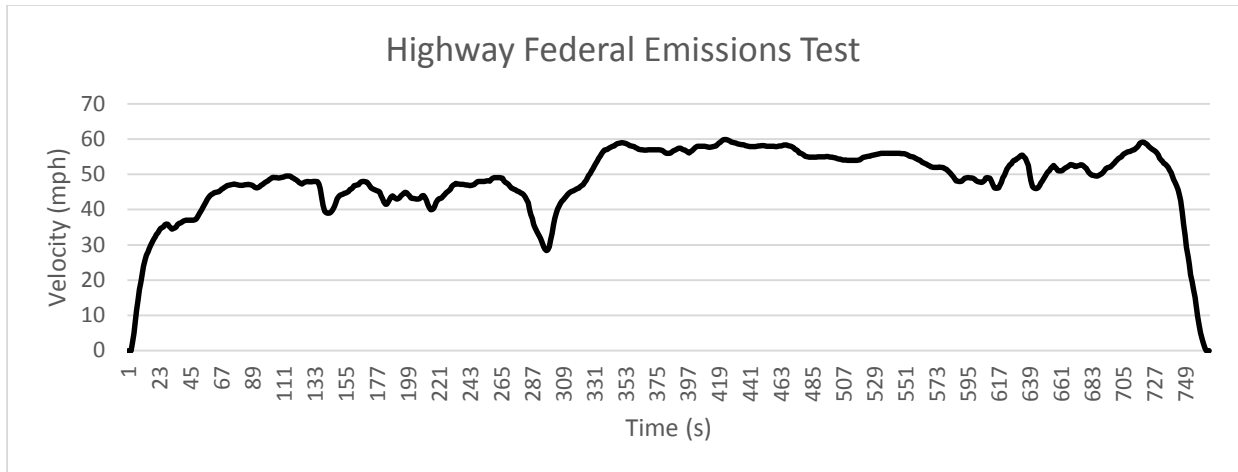
### A.1.2.1 - Drive Cycle Descriptions

The four cycles prescribed for modeling in the EcoCAR2 modeling and simulation events are the Urban Dynamometer Drive Schedule (UDDS), Highway Federal Emissions Test (HWFET), and US06 city and highway portions. The velocity trace of these cycles is shown in Figure 2, Figure 3, and Figure 4 below. These cycles are designed to represent the statistical driving habits of a typical American driver.



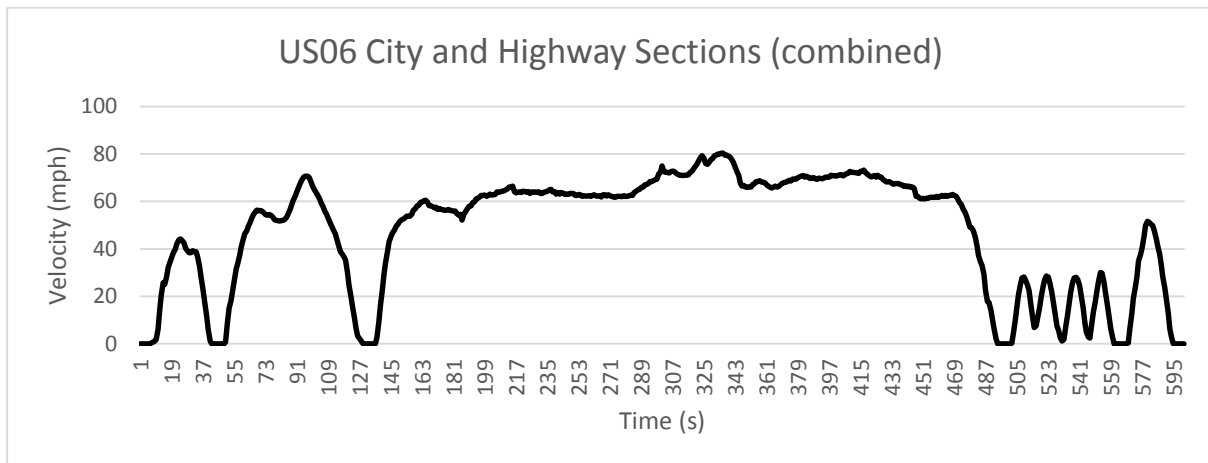
**Figure 2: UDDS Velocity Trace**

The UDDS velocity trace is a relatively tame drive cycle that represents low speed, low power demand city driving.



**Figure 3: HWFET Velocity Trace**

The HWFET velocity trace is another tame drive cycle with one low power demand acceleration up to highway speeds, relatively steady state speeds for about 10 minutes, then a deceleration.



**Figure 4: US06 Velocity Trace**

The US06 is a very rigorous drive cycle with heavy accelerations, very high speeds, and a very large power demand acceleration at 70mph to 80mph. Also very heavy braking demands.

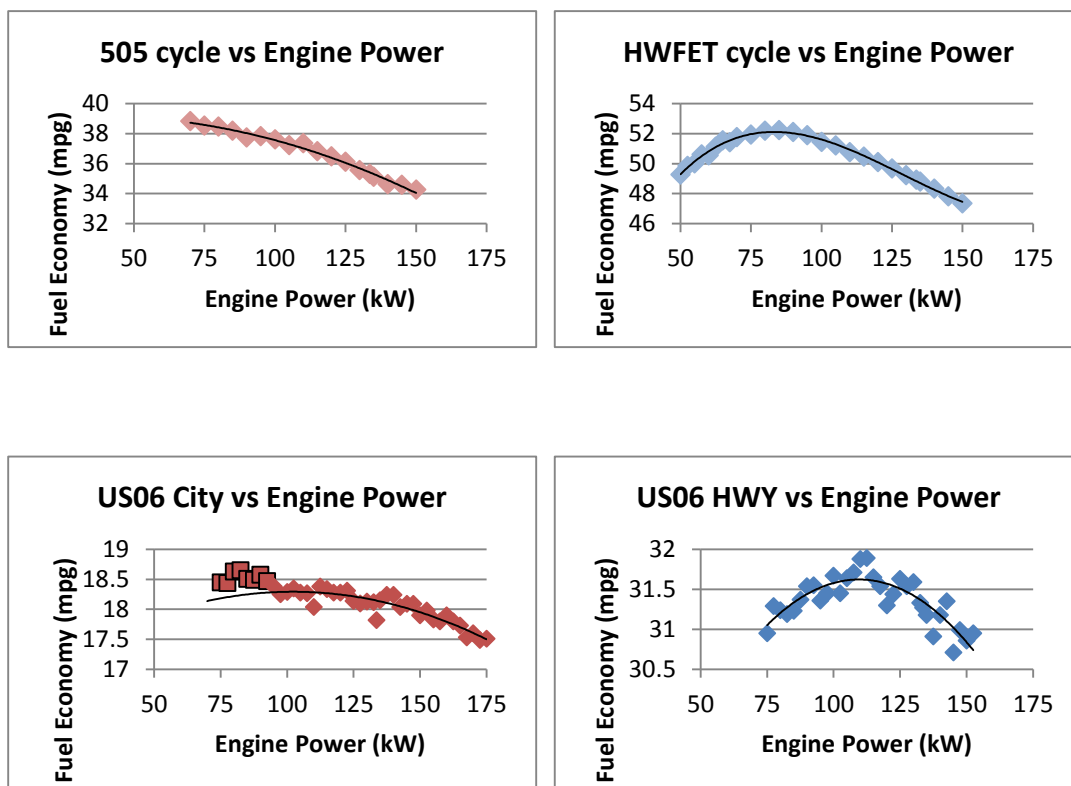
### A.1.2.2 - Engine Size Parametric Study

Varying the engine size in a vehicle will impact fuel economy, performance, noise, available space and more. For this report, only the effects on fuel economy and performance were focused on. The engine size was varied using a linear power scaling file in Autonomie, which accounts for engine parameters that

would change as a result of varying the max power, such as weight and rotational inertia. The engine power was scaled in increments of 5kW from 70kW to 150kW to get a good understanding of the effects of engine power during each drive cycle. The lower bound was based off of where any of the constituent cycles experienced poor trace quality. The upper bound was set where all cycles experienced very little 2mph trace miss (<~1%). For some cycles (US06), a higher resolution of 2.5kW was used due to a large amount of noise.

### **Engine Size Effect on Fuel Economy**

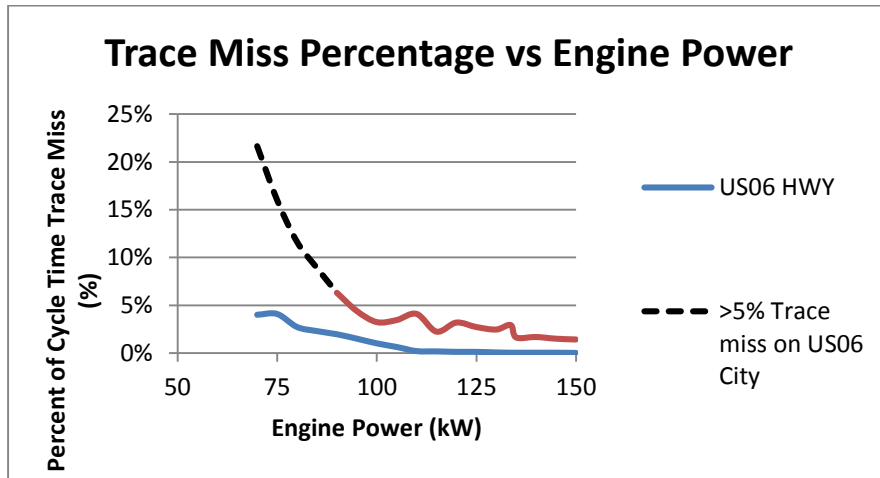
Figure 5 below shows the data for each of the four cycle's over various engine powers.



**Figure 5. Fuel economy results for different engine powers**

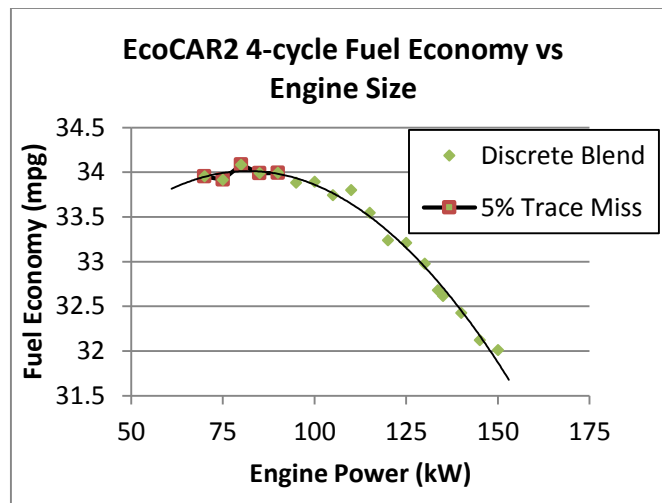
The 505 and HWFET drive cycles do not result in any trace misses from the simulated engine powers. The largest trace misses were experienced by the US06 City cycle followed by the US06 HWY cycle. Shown

on Figure 6 below is the trace miss data as a percentage of total cycle time for both US06 City and HWY cycles.



**Figure 6. Cycles with Trace misses at different engine powers**

It is important to note that trace quality was poor on the US06 City cycle when engine power went below 95kW. Lower engine power results for the blended cycle will be shown, however 95kW will be the lowest engine power considered for recommendation. Figure 7 below shows the resulting fuel economy versus max engine power over the EcoCAR2 4-cycle blend.



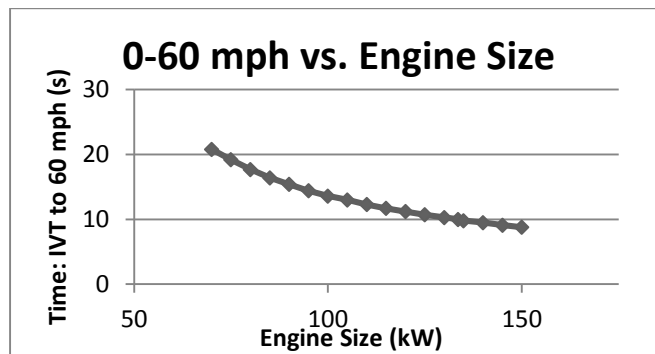
**Figure 7. Blended fuel economy results for different engine powers**

Figure 7 shows a distinct region where an optimal fuel economy of ~34 miles per gallon can be achieved over the EcoCAR2 4-cycle blend. According to the model, engine sizes from 75kW to 100kW will provide

this maximum, however factoring in the trace quality of the US06 cycles suggests that a 100kW engine is the most effective size. Knowing that the base vehicle engine is 133.6kW, it is apparent that fuel economy is not the only design consideration for the vehicle.

### **Engine Size Effect on Performance**

For this report, performance was defined as four main categories, 0-60 acceleration time, 50-70 time, gradeability and drive cycle trace quality. Varying engine size will directly affect acceleration performance. According to the EcoCAR2 VTS (Argonne National Laboratory, 2011), the competition requires a maximum of 11.5 seconds for a 0-60 acceleration test, while the design target is 9.5 seconds. Figure 8 below shows the results of the acceleration study.

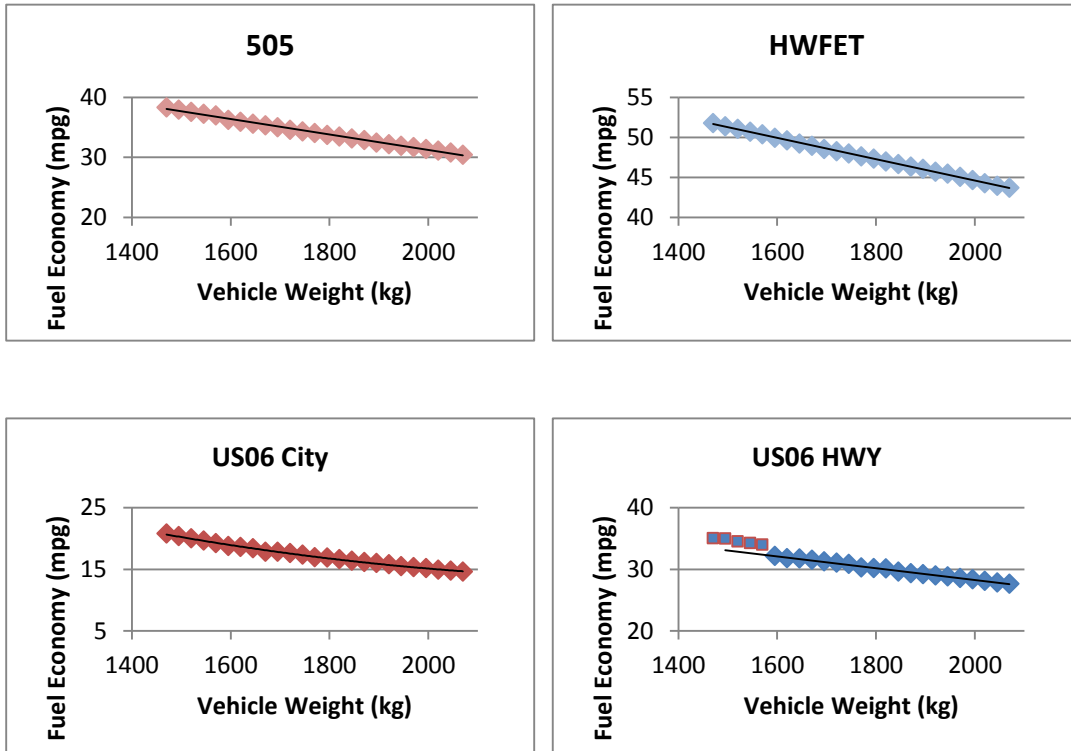


**Figure 8. Initial Vehicle Movement to 60 mph Time relative to Engine Power**

It is expected that increasing total vehicle mass will cause gradeability to decrease and 50-70 time to increase. Also increasing available engine power will cause gradeability to increase and 50-70 times to decrease.

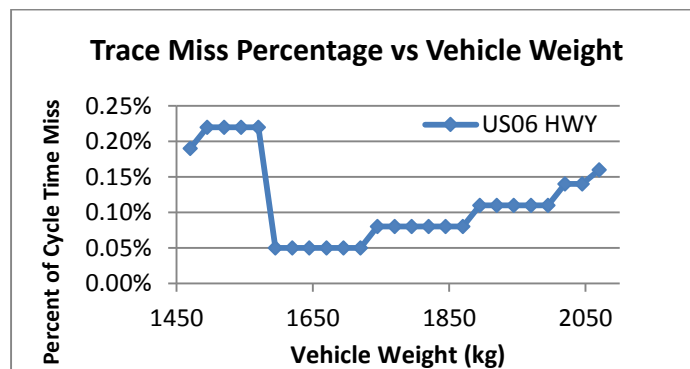
### **A.1.2.3 - Vehicle Weight Parametric Study**

Varying the weight of a vehicle has a significant impact on fuel economy and performance characteristics. The vehicle weight range modeled was chosen to explore all realistic mass values for a fully converted PHEV with a lower bound just below stock vehicle weight and an upper bound at 2100kg. This weight range provides an adequate description of all probable vehicle weights within the EcoCAR2 VTS of 2250kg. Shown below in Figure 9 is the data for fuel economy from all four cycles.



**Figure 9. Fuel economy results at different vehicle weights**

No trace misses greater than 5% of the cycle time were experienced during this study, however an irregularity was noted in the US06 HWY cycle data under 1600kg (highlighted above). It was expected that trace quality would only improve as vehicle weight was lowered due to the corresponding decrease in energy required to alter vehicle speed, however Figure 10 below shows that below 1600kg a small but unexpected drop in trace quality was seen.

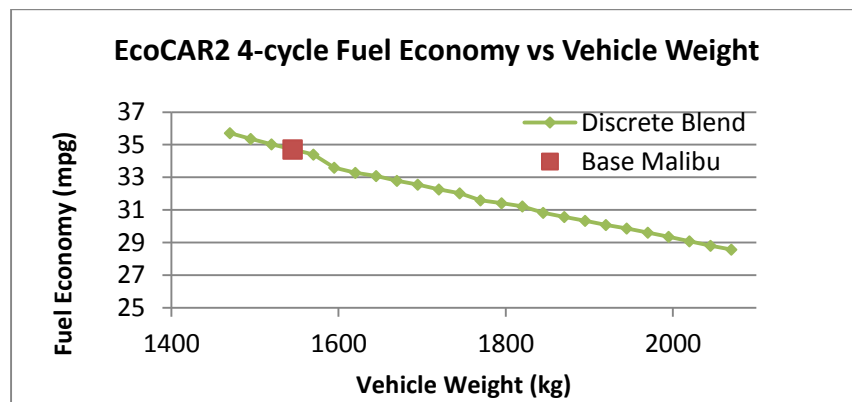


**Figure 10. Irregular trace characteristics of US06 HWY cycle**

The discontinuity in trace quality during the highlighted fuel economy range suggests a problem with the model. The cause of the unexpected trace performance is unknown, but the irregular data has been removed from further calculations and has been replaced with the trend-line over the rest of the US06 HWY data.

### **Vehicle Weight - Effect on Fuel Economy**

Figure 11 below shows the EcoCAR2 4-cycle fuel economy over the described weight range.



**Figure 11. Blended fuel economy results at different vehicle weights**

The strong linear correlation between vehicle weight and MPG over the EcoCAR2 4-cycle blend shows just how important vehicle weight is to fuel economy. Decreasing vehicle weight by only 200kg increases fuel economy by over 2 mpg, significant when compared to the maximum effective gain of 1 mpg by varying engine power.

### **Vehicle Weight – Effect on Performance**

Varying the vehicle weight has a definite impact on the performance of a vehicle. By decreasing weight, the energy required to accelerate a vehicle is lessened, causing a lighter vehicle with the same drivetrain to exhibit better performance. Figure 12 demonstrates this effect.

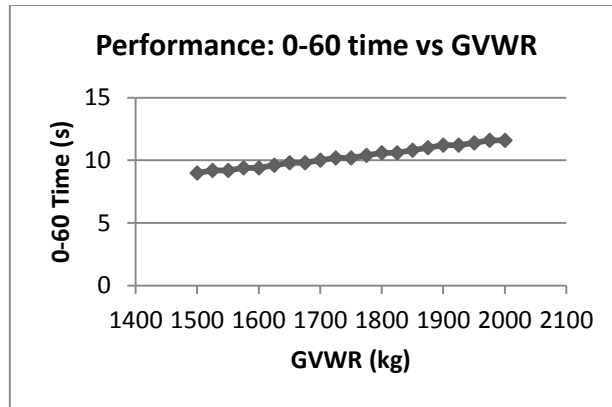


Figure 12. Performance while changing GVWR

### A.1.3 - Parametric Study Analysis

To understand the effect that varying engine power on individual cycles has on the EcoCAR2 blend, Figure 13 below shows plots of each cycle’s fuel economy results normalized to the fuel economy of the base vehicle’s engine power. To reduce the amount of noise from individual data points (especially from US06 cycles), only the trend line has been plotted for each cycle.

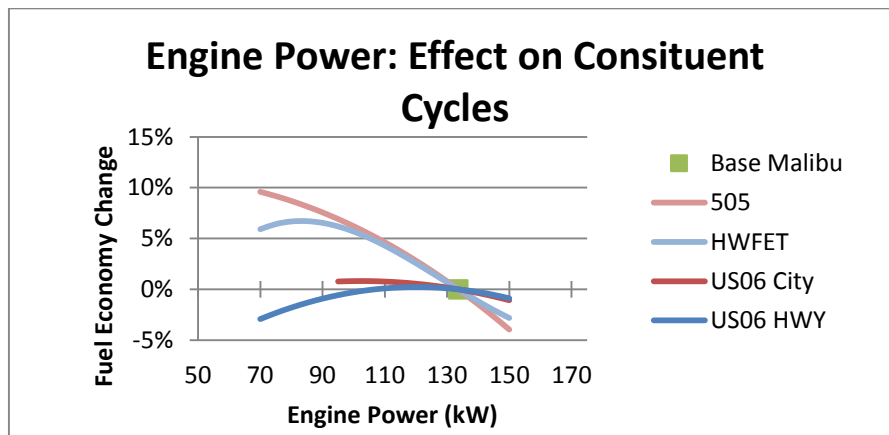
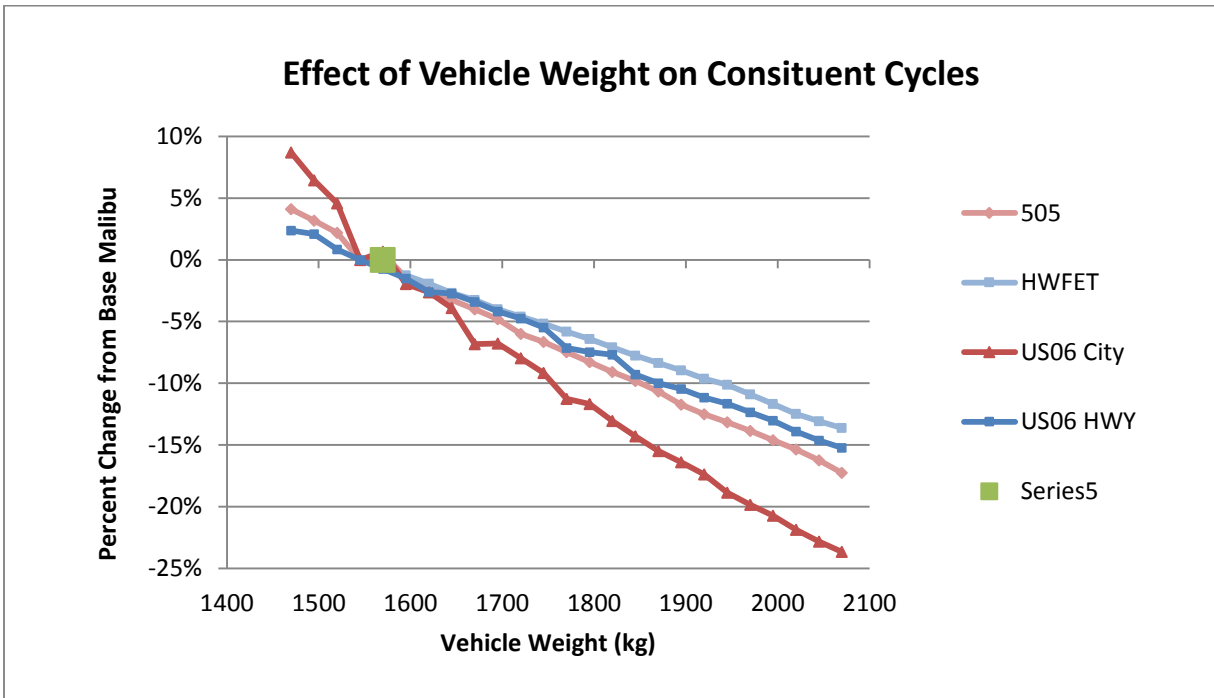


Figure 13. Effect of engine power on fuel economy over each drive cycle

For the light cycles it is clear that a smaller engine would provide better fuel economy, while for the aggressive cycles the stock engine provides close to maximum fuel economy. Viewed strictly from a fuel economy stand-point, this suggests that the design choices made for the vehicle are based on the assumption that the US06 cycle is the best representation of drivers from the Malibu’s target market.

Similar to the method above, Figure 14 shows plots of each cycle's fuel economy results normalized to the fuel economy at base vehicle weight.



**Figure 14. Effect of GVWR changes on fuel economy over each drive schedule**

The most significant reductions in fuel economy are seen in the US06 City cycle followed by the 505 city cycle. This is because of the large amount of braking energy required to run city cycles. City cycles by nature will experience a larger total amount of braking energy, but conventional gasoline vehicles have no way to capture it. Future reports will evaluate the effectiveness of any efforts made to regenerate this energy.

### A.1.4 - Stock Acceleration Performance Comparison

The Malibu Autonomie model was run through an acceleration procedure in an attempt to duplicate the GM-reported 0-60mph time of 8.2 seconds from Initial Vehicle Movement.

Initial Autonomie acceleration tests with no modified parameters resulted in 0-60mph time of 10 seconds, which is well above the EcoCAR2 VTS table's claim of 8.2s. In the acceleration procedure, the model is

thrown into maximum throttle from idle. This differs from real-world acceleration testing methods, where the driver testing an automatic transmission vehicle may use a technique called brake torquing: “With the left foot pressed securely on the brake holding the car in place, the right foot squeezes down on the accelerator and the car is launched by releasing the brake pedal.” (Webster, 2008) To simulate this testing method, an attempt was made to increase the idle RPM of the engine before the test initiation.

To modify the engine idle speed, it was first necessary to make the parameter “eng.plant.init.spd\_idle” visible and modifiable in the Autonomie GUI by changing the eng.plant a\_model XML file. Once made modifiable, a parametric study was run investigating spd\_idle’s effect on 0-60 times. According to the engine hot efficiency map, the highest torques are seen in the 200-650rad/s speed, so it was also necessary to modify a saturation block in the torque coupling’s transient calculation block to allow idle speeds over 310rad/s.

After performing a parametric study in which spd\_idle was varied from 80 to 525 rad/sec, some interesting control problems were encountered. Up until ~400rad/sec the results were as expected with a decreasing 0-60 acceleration test time, but further values resulted in an interesting problem displayed in Figure 15 below.

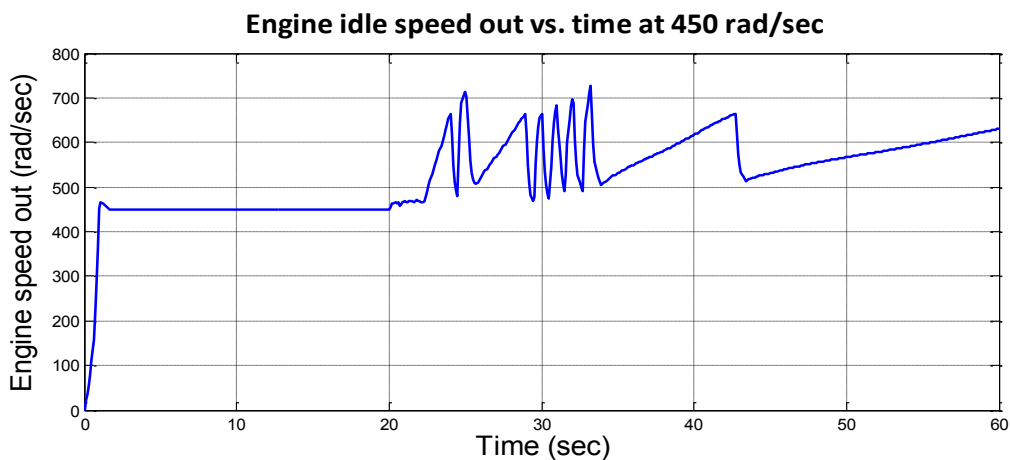


Figure 15. Engine speed out results on 450 rad/sec

The phenomenon shown above is a result of the in-gear RPM of the engine attempting to drop below `spd_idle`, shifting to compensate, and then realizing that it is not in the correct gear to provide the requested power. This erratic shifting pattern, not typical for a maximum throttle request, provided erroneous acceleration information and voided our attempt at simulating a brake-torqueing acceleration test.

## **A.1.5 - Baseline Vehicle Modeling Conclusion**

Reflecting on the fuel economy study, the optimal engine size was suggested to be 100kW. With respect to competition constraints, the design target of 9.5 seconds would require an engine size of 140kW. With these two numbers in mind, it becomes obvious as to why an engine size of 133.6kW was the engine selected for the Malibu 2013. Combining the conclusions derived from both studies, we can comment GM may have placed a greater emphasis on performance than fuel economy during the design of the Malibu.

In terms of weight, reducing GWVR results in improved both performance (trace quality and 0-60 acceleration test times) and fuel economy (mpg). Other considerations must be evaluated before light-weighting any parts of a vehicle, such as safety, noise insulation, or cost.

# **B - Vehicle Architecture Selection Process**

Hybrid electric powertrains vary widely in the arrangement of their torque producing components, specifically with respect to the relationship between the petroleum and the electric powertrains. These hybrid “architectures” were explored through a brief lit search to determine the strengths and weaknesses of each. Three distinct architectures were explored in depth to determine which would have the greatest chance of success with our team in the EcoCAR2 competition. The three architectures explored in detail were Series, Parallel Through The Road (PTTR), and PTTR with a Belted Alternator/Starter (BAS).

From the literature research, vehicle modeling, emissions and energy consumption simulation, and careful fuel selection, the final selection was narrowed down to what is known as a Parallel Through The Road Plug-in Hybrid Electric Vehicle (PTTR PHEV). With a diesel engine on one axle and electric traction motor on the other axle, the PTTR architecture outperforms the series architecture in performance, emissions, and energy consumption categories due to its parallel nature and to its ability to provide mechanical tractive power directly to the road during steady state speeds.

## **B.1 - Fuel Selection**

The UW EcoCAR2 team has considered a number of different fuels to power its EcoCAR. Considerations include the level of support, the fuel efficiency, and the eco-friendliness when compared against other fuels. We began our analysis with WTW impacts and the GREET model. Next, we considered the local level of support available for each fuel type. Then, energy consumption efficiencies and likely future extraction impacts were taken into account. Finally, the UW team selected B20 and electricity as the two sources constituting propulsion power for the UW EcoCAR. The UW EcoCAR2 team believes a B20 hybrid electric vehicle best address the needs of the consumer in terms of performance while minimizing environmental impact.

## **B.1.1 - Fuel Literature**

The following literature was found to develop an initial opinion of the benefits and drawbacks of each of the competition-approved fuels for EcoCAR2.

### **B.1.1.1 - Progress and Recent Trends in Biodiesel Fuels (Demirbas, 2008)**

Demirbas analyzes the issues and benefits of B20 fuel are stated in detail, beginning with the special properties of biodiesel fuel that give it a competitive edge in the market. Biodiesel is favored by German car manufacturers for its high combustion efficiency due to its high oxygen density of 11% by weight. This property eases the combustion process of biodiesel by homogenizing the oxygen of the biodiesel molecules with the oxygen molecules in the air. This results with B20 producing 93% more energy per gallon than is required to manufacture it while E85 is only 23%. In addition, a high oxygen level enables diesel to better lubricate a vehicle's components.

The paper later includes several benefits and downfalls of using B20 as a fuel source. Air pollutant emissions are significantly reduced by utilizing biodiesel rather than petroleum. Statistically speaking, "for soybean-based biodiesel at this concentration, the estimated emission impacts for percent change in emissions of PM, HC, and CO were 10.1%, 21.1%, and 11.0%, respectively." Consumers would emit 10-20% less particulate matter by using biodiesel over petroleum diesel. Another important benefit is that the methyl esters within biodiesel give the fuel lubricating properties. This means that the fuel will reduce the friction between engine components, therefore replacing the role of oil.

### **B.1.1.2 - Background on Flexible Fuel Vehicles and E85 (Green Energy Network, 2006)**

This paper suggests that E85 may be a poor fuel choice mainly for economic and environmental reasons. The two major economically viable feedstock crops for ethanol fuel are currently corn and sugar cane.

Ethical considerations must be made whether or not North America's corn-based food supply will be impacted by using E85 as a fuel. Utilizing corn as a fuel source rather than for food production will significantly increase the cost of growing corn, forcing more farmers to switch to corn and reducing the supply of other important farm-based products. According to the paper, if the automobile industry were to consume an additional 8 billion gallons of ethanol then food expenditures would increase \$10 billion per year.

However, the paper finds that using either E85 or B20 as fuel reduces the environmental impact of automobiles. The primary issue with E85 fuels is that they are very soluble in water. According to the paper, there have been many cases of both storage tanks leakage and spills due to traffic accidents which resulted in water supply contamination with E85. Large releases of E85 can significantly increase the pH level of water supplies and devastate nearby ecosystems.

### **B.1.1.3 - VT Report 5 from EcoCAR: The NeXt Challenge (Lynn Gantt, 2009)**

This paper, published by Virginia Tech in the EcoCAR 1 competition, outlines their architecture selection and vehicle design process. It has a section devoted to the fuel selection process, where they quantitatively compare E10, E85, B20, gaseous hydrogen, and grid electricity as viable fuel sources. In the following plots, they graphically plot the WTW petroleum energy use and CO<sub>2</sub> emissions of the different fuel choices:

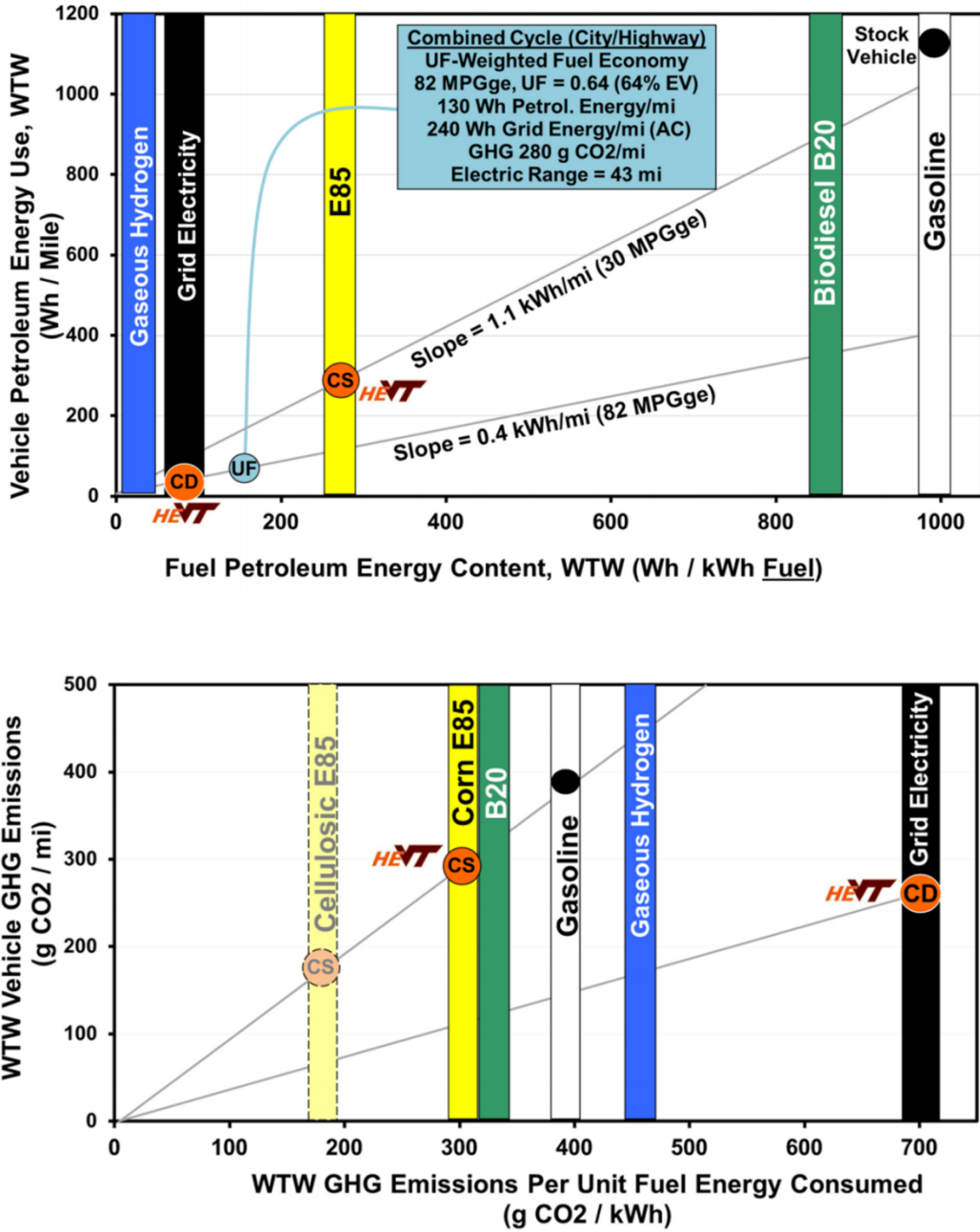


Figure 16. Virginia Techs plot of WTW petroleum usage and CO<sub>2</sub> emissions (Lynn Gantt, 2009).

Their analysis concluded that E85 was the best fuel choice due to the large petroleum usage reductions associated with using a fuel that is 85% biofuel. They found hydrogen to be an initially attractive fuel choice; once on-board storage density and integration difficulty were taken into account, however, they eliminated

gaseous hydrogen as a choice. They concluded that B20 is less effective at reducing petroleum usage and CO<sub>2</sub> emissions due to its lower concentrations of bio-sourced fuel.

## **B.1.2 - EcoCAR2 Approved Fuel Options**

### ***E85: Corn Based Ethanol mixed***

Based on GHG emission models, E85 is considered to be a very environmentally friendly fuel. In particular, according to the GREET model, it offers the potential for the lowest WTW GHG emissions per kWh; however, E85 has a considerable number of drawbacks. One drawback is its volumetric energy density and specific energy relative to B20 and E10. Being lower in energy content, it is expected that, for a given quantity of fuel, vehicles powered by E85 will have a lower vehicle range. Secondly, E85 is relatively unavailable in Washington State. There are very few fuel stations in the region that support E85, this means University of Washington facilities would have to install a fuel depot on campus which would add complexity and cost. Lastly, E85 has many political controversies surrounding it. Using corn to produce ethanol requires valuable farm land and impacts food prices around the world. Water usage and its environmental value are not taken into account in the GREET models and are difficult to quantify. Though cellulosic ethanol would be more environmentally favorable, the technical obstacles to making it in an economically viable manner are still unresolved. Ultimately, the disadvantages of E85 may potentially outweigh the savings in GHG emissions.

### ***B20: Petroleum Based Diesel Mixed with Bio fuel (Algae, Soy)***

B20 bio-diesel offers the greatest energy density among petroleum based fuels available for EcoCar2. Diesel engines also offer higher efficiency when compared to regular gasoline or blended ethanol options. The University of Washington plans to partner with local biodiesel company Propel or a student organization to obtain B20. Maintenance cost for B20 based engines will be comparatively lower than other petroleum or blended ethanol engines. A major disadvantage to B20 is the high level of NO<sub>x</sub> emissions it creates, with the requirement that a urea injection system be installed in order to bring the emissions down to a reasonable level. Diesel/B20 engines also are considerably heavier, because of the higher amount of metal

needed to safely contain the higher compression ratios. Presently, B20 doesn't offer the lowest WTW, but as the bio-diesel fraction increases from its current level of 20 percent, net GHG emissions are expected to decline.

Furthermore, as concentrations of biodiesel increase in a bio-diesel blend Figure 17 below shows the effect on the criteria emissions and particulate matter. The increase in NOx can potentially be dealt with via the on-board urea injection aftertreatment system – something that is already a necessity on new diesel vehicles.

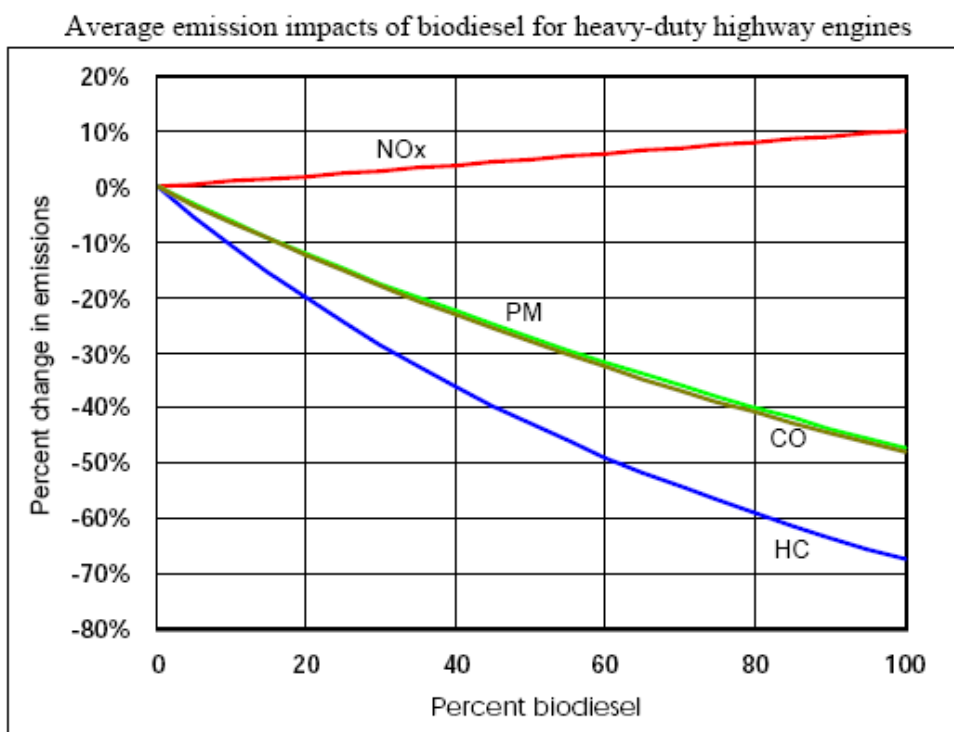


Figure 17: Bio Derived Diesel's effect on Criteria Emissions and Particulate Matter

### ***Grid Electricity***

Utilizing electricity is essential to reducing the production of GHG's. Although the GREET model suggests that electricity produces a very large quantity of GHG's upstream (WTP), it produces no PTW GHG's. The PTW emissions are a key consideration: because of the much higher efficiency of electric drive trains the overall GHG emissions may end up being lower depending on the region. With energy conversion

efficiencies taken into account, WTW GHG emissions from electricity are approximately equal to those produced by petroleum fuels. Furthermore, the US government, environmentalist groups, and consumers are advocating an energy grid which sources energy from renewable sources. Based on current trends, the environmental concern and continuing advancement of battery technology, electrically powered vehicles will surpass conventional vehicles. In Washington State, electricity is primarily hydroelectric and therefore doesn't create any GHG's. Unfortunately the scoring process for EcoCar2 uses blended average grid electricity which removes this local advantage that University of Washington naturally has.

### ***Gaseous Hydrogen***

UW rejected the use of hydrogen as a fuel source for several reasons. Low volumetric energy density, lack of facilities support, lack of donated fuel cells, and difficulty of integration were all major issues. While hydrogen offers an attractive fuel possibility for the future, at this point for the EcoCAR2 competition the difficulties associated with integrating the system into the stock Malibu significantly outweighed the benefits of low petroleum usage and emissions; this is especially true given the UW's status as a new school in the EcoCAR2 competition and our desire to have a functioning and polished vehicle in Years 2 and 3.

### **B.1.3 - Well-to-Wheel (WTW) Impacts**

Placing a number on a specific fuel's impact on the environment is important when it comes to making fuel comparisons. In order to quantify fuel impact, the entire life cycle from derivation to consumption of fuel must be considered. Termed well-to-wheel (WTW) impact, this represents the net impact of fuel on the environment. WTW impact can be conveniently split into two paths, well-to-pump (WTP) and pump-to-wheel (PTW). PTW impact can be measured empirically for each fuel, but in order to estimate the WTP greenhouse gas emissions (GHG) and energy consumed during fuel development, transportation, and storage, Argonne National Laboratory (ANL) has developed the GREET model.

The GREET database defines WTP impact constants on a "per kWh of fuel consumed" basis, which enables empirical consumption results from a vehicle (simulated or real) to be the only input for a WTW calculation. Using ANL's hybrid modeling software, Autonomie, the energy consumption of the vehicle can

be simulated for each energy source (electricity, diesel, etc.). Using the results from Autonomie, the WTP impact can be estimated from the GREET model, and the PTW impact can be estimated from the Eco CAR 2 emissions data for each fuel. The WTW impact is simply the combination of the WTP and PTW impacts. We then used these WTW results to compare our hybrid architectures during the selection process. See Equation 1: WTW CD GHG's, Equation 2: WTW CS GHG's, and Equation 3: WTW Total GHG's. Also see B.2.3 - Fuel Economy Simulations.

#### Equation 1: WTW CD GHG's

$$GHG_{WTW,CD} \left[ \frac{g}{km} \right] = EC_{CD,electricity} \left[ \frac{kWh}{km} \right] * GHG_{WTW,CD,electricity} \left[ \frac{g}{kWh} \right] * (UF)$$

#### Equation 2: WTW CS GHG's

$$GHG_{WTW,CS} \left[ \frac{g}{km} \right] = EC_{CS,actual\ fuel,SOC\ corrected} \left[ \frac{kWh}{km} \right] * GHG_{WTW,CS,actual\ fuel} \left[ \frac{g}{kWh} \right] * (1 - UF)$$

Equation 3 is the sum of the well to wheel GHG emissions for the charge depleting and charge sustaining weighted emissions.

#### Equation 3: WTW Total GHG's

$$GHG_{WTW} \left[ \frac{g}{km} \right] = GHG_{WTW,CD} \left[ \frac{g}{km} \right] + GHG_{WTW,CS} \left[ \frac{g}{km} \right]$$

## B.1.4 - Fuel Comparison

### ***GHG Emissions***

The WTW GHG value for each fuel type is a measure of how much CO<sub>2</sub>, CH<sub>4</sub> (methane), and NO<sub>2</sub> is produced, from the initial extraction of the fuel to the final propulsion of the vehicle, in terms of mass emitted per unit of energy produced. The UW EcoCAR2 team used data from the 2008 GREET model to estimate WTW GHG emissions. The exact values depend on many factors, including engine design and catalytic converter temperature. The three greenhouse gasses are converted to a single value with the weighting in Equation 4.

#### Equation 4: GHG emissions weighting

$$GHG = CO_2 + 21 \times CH_4 + 310 \times N_2O$$

The largest producer of GHG's is electricity, which is based on a national average of GHG emissions created by the production of electricity. In many regions of the United States coal is used to generate electricity, which results in large amount of GHG emissions. In Washington State however, electricity is generated from GHG free hydroelectric dams. The primary source of commercially available H<sub>2</sub> is from steam reforming of CH<sub>4</sub>, which in large GHG emissions from the CO (converted to CO<sub>2</sub> for safety and air quality) byproduct. The remaining fuels utilize some percentage of organic material, which absorbs GHG's from the air, to reduce their net GHG emissions. Naturally E85, the fuel produced from the highest percentage of organic material, has the lowest emissions. Figure 18 displays the results of this calculation.

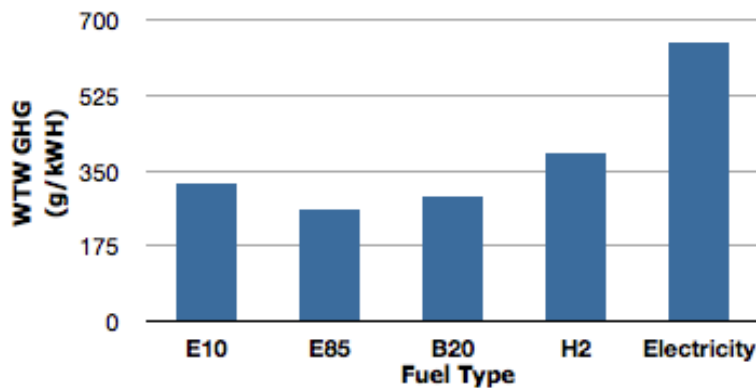


Figure 18. Plot of WTW GHG emissions for each of the competition fuels

### ***Petroleum Usage***

The WTW PEU value for each fuel is essentially a percentage of that fuel's energy that is derived from petroleum. Theoretically this value could be greater than 1. For example, pure gasoline is 100% petroleum, but additional petroleum is required to refine and transport gasoline. WTW PEU has larger energy independence implications than WTW GHG's because petroleum is the only significant energy source that is currently imported to the United States.

H<sub>2</sub> and electricity have very low WTW PEU values because they are generated largely from natural gas and coal. The other three values are directly related to the quantity of organic material they contain. Intuitively, the less petroleum in the fuel, the less petroleum it will take to produce them. Figure 19 shows the WTW PEU for each of the fuels considered for the EcoCAR2 competition.

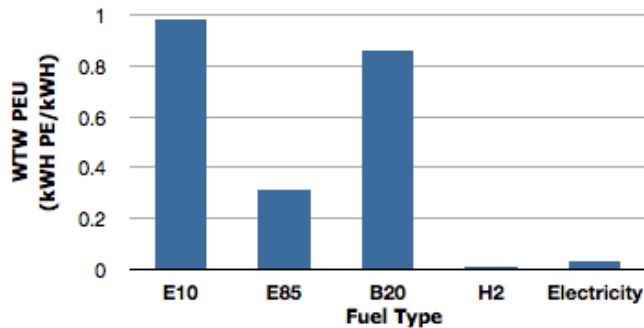


Figure 19. WTW PEU for each of the competition fuels

## B.1.5 - Fuel Selection Matrix

The advantages and disadvantages for each fuel are summarized in a decision matrix presented below in Table 1. The seven categories represented are a subset of the possible decision categories; it would not be possible, nor advisable, to include all possible decision categories. The included categories represent the most important categories to The University of Washington team. Electricity is included only to show the categories that it will assist the vehicle architecture with.

Table 1. Fuel Selection Matrix

	Weight	Diesel (B20)	Ethanol (E85)	Gasoline (E10)	Hydrogen	Electricity
Range	10%	5	3.5	4	4	
Fuel Economy	25%	5	2.5	4	3	5
GHG Emission	25%	5	4	4	4.5	
Petroleum Usage	15%	3	4	2	5	5

<b>Experience</b>	5%	4	4	4	0	5
<b>Facilities</b>	20%	5	4	5	0	5
<b>Total Score</b>	100%	<b>4.65</b>	3.575	3.9	3.025	3.25

A full description of how each category was scored can be found in the Section D.2 -Fuel Selection Matrix Assumptions of the Appendix.

It is important to note that fuel economy and greenhouse gasses were weighted significantly higher than petroleum usage. This is primarily because we believe that misrepresented in this category, as future technology advances and availability increases will push the biodiesel concentration to higher levels.

To reduce emissions even further for the diesel fuel option, we plan on installing a urea injection system to minimize NOx emissions. This will be in addition to the catalytic converters that come standard with the diesel engine. Greenhouse gasses and smog causing emissions will be reduced, and the results will be further documented in the following reports.

## B.1.6 - Fuel Selection Conclusion

In reference to the fuel decision matrix, B20 diesel fuel was selected to power the UW EcoCAR along with electrical power. Even though E85 and Gaseous Hydrogen are the best choice in terms of GHG emissions, B20 is expected to be more competitive in this area once higher concentrations of biodiesel are shifted to. Heavy emphasis on grid electricity usage will complement the biodiesel fuel by decreasing petroleum energy consumption, and it is also an energy carrier that our school is familiar with. If regional considerations are also made, Washington State's energy generation profile is highlighted by almost 80% fully renewable (70% hydro, 6% nuclear (Administration, 2009)) so the greatest reliance on grid electricity is desired. For these reasons, both B20 and electricity will power the UW EcoCAR.

## **B.2 - Powertrain Modeling, Simulation, and Analysis**

The modern Internal Combustion Engine (ICE) is not very efficient outside of its optimal torque and RPM range. In the case of traditional vehicles, where the engine supplies all the torque to the wheels, the output of the engine has to constantly vary to accommodate the driver's changing demands, especially in the case of "in-city" and "stop and go" driving. Additionally, engines that are operated in a very transient manner tend to emit significantly more criteria emissions that the EcoCAR2 competition is concerned with.

Plug-In Hybrid Electric Vehicles (PHEV's) provide large efficiency advantages over conventional vehicles by introducing one or more electric motors to a vehicle's drivetrain. An example of a production PHEV is the 3rd generation Toyota Prius, which uses the Toyota Hybrid System (THS), a complicated torque coupling mechanism which allows the engine and motor to apply power to the drivetrain independently. This allows the engine stay in a more efficient range and uses the electric motor, which is highly efficient across a wide torque range, to handle changing power demands. PHEV's can also recharge the battery by using the motor to brake using "regenerative braking." Rather than waste braking energy as heat through standard hydraulic brakes, the regenerated energy from braking can be used to propel the vehicle during its next acceleration event.

### **B.2.1 - Architecture Introduction**

Three architectures were chosen for analysis in this report based on preliminary simulations and basic energy flow calculations. Before coming to an architecture decision, each was simulated using Autonomie simulation software described in A.1.1 - Autonomie Introduction above. The goal was to generate a comparable set of results which would reveal a distinct architecture that would out-perform the others in terms of energy consumption, performance, and feasibility.

The three architectures are versions of what are considered standard PHEV architectures that have been designed, built, and tested by other parties. Our designs, however, exhibit unique component selections and implementations are therefore still relevant to explore. First considered was a series architecture with a large electric generator to match the ICE power output. The second architecture analyzed was a Parallel Through The Road (TTR) configuration with the electric motor on the rear half shafts and the ICE in the front of the vehicle. The final architecture proposed is a PTTR with a belted alternator/starter (BAS) for load leveling on the engine and for recharging the main traction battery pack in certain situations.

### B.2.1.1 - The Series Powertrain Architecture

As part of the UW team’s architecture selection process, the series architecture family was considered in detail. The distinguishing feature of the series hybrid is a decoupling of the ICE speed from the wheel speed. This means propulsion power comes solely from the energy storage system and the electric machine. In broad terms, the series architecture will require an internal combustion engine, an electric machine to convert mechanical power to electrical power, a large battery pack to store the electrical energy, a second electric machine to convert the energy stored in the battery back into mechanical power and a drivetrain to transfer the power to the wheels. A schematic diagram of a series hybrid is shown in Figure 20.

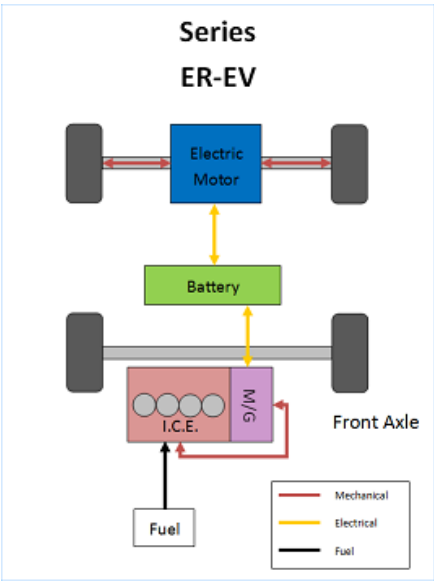
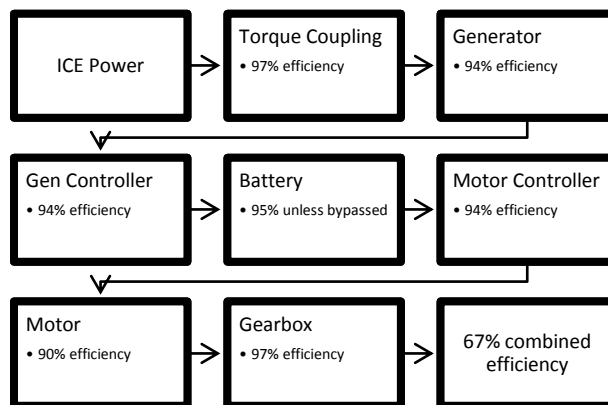


Figure 20. Energy Flow Diagram of Series Architecture

### B.2.1.1.1 High Level Power Flow Diagram

Before modeling the series architecture, a few characteristics were noted based on research and an intuitive understanding of how the series architecture should operate. Because the engine is decoupled from the wheel speed, the generator can load the engine such that the engine operates in its most efficient region. This feature is considered the ultimate advantage of the series architecture; however, this feature also leads to its drawback: the power out of the ICE must be converted from mechanical to electrical and back into mechanical power. With each conversion a loss in overall power path efficiency is expected, as well as the weight, cost, and complexity of extra electrical components.

A high level efficiency calculation of the series architecture's power path during charge-sustaining mode is shown in Figure 21 below to illustrate this drawback.



**Figure 21. High Level Series Efficiency Diagram**

It is important to note that there are seven total components through which the ICE power out must be converted before it is transferred to the wheels.

### B.2.1.1.2 Control Scheme

When implemented with a Rear Traction Motor (RTM) of high enough power, the Series architecture can function as a fully electric vehicle throughout its CD range. In CS mode, the engine will be operated only at peak efficiency to balance the ESS SOC at a predetermined level. When the SOC goes too low, the engine begins to generate. Once the ESS reaches an upper bounds, the engine will turn off. This is otherwise known as thermostatic control.

In the case of a high power request at low SOC, the engine will turn on to maintain SOC. Furthermore, if the power request exceeds the peak efficiency generation, the engine will be allowed to increase throttle up to the generator's peak power to meet the demand. These strategies are summarized in Table 2 below.

**Table 2. Series Architecture Control Strategy**

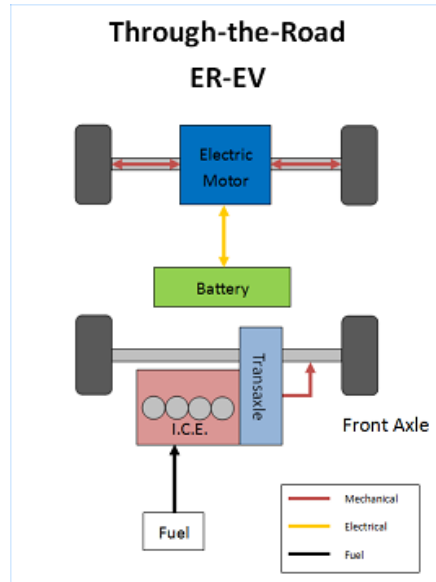
<b>Operation Mode</b>	<b>Throttle Request</b>	<b>Engine State</b>
CD	Any Throttle Request	All-Electric
CS	Normal Throttle Request	Thermostatic Control
	High Throttle Request	Engine on to match demand

### **B.2.1.2 - The Parallel Through-The-Road (PTTR) Powertrain**

#### **Architecture**

The second architecture considered by the UW EcoCAR team is a Parallel Through the Road (PTTR) hybrid, also known as a Series-Parallel architecture. It was used by several teams in the original EcoCAR and Challenge X competitions. It offers an attractive choice due to its high performance capabilities, all-electric mode, ease of implementation, and the ability to mitigate powertrain failures with a limp-home mode using either the front or rear axle propulsion systems.

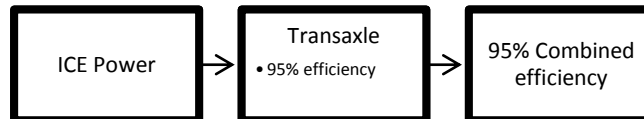
As seen in Figure 22, the TTR hybrid powertrain is comprised of two independently-powered axles, avoiding the need for a mechanical power coupling such as the THS. Due to packaging concerns, the internal combustion engine and transmission system powers the front axle and an electric machine powers the rear axle. In this hybrid scheme, the engine and rear traction motor are coupled through the wheels, which have the same rotational velocity to match the linear road velocity without slipping. Thus, the power systems are only linked through-the-road, giving this architecture its name.



**Figure 22. Energy Flow Diagram of TTR Architecture**

### B.2.1.2.1 High Level Power Flow Diagram

The power path for internal combustion engine for the through the road architecture maintains only a 5% loss from the engine output to the wheel (Figure 23). This is specifically for charge sustaining and does not demonstrate the electric motor load leveling capabilities.



**Figure 23. High level TTR Efficiency Diagram**

Compared to the series high-level power flow analysis results of a 95% transfer efficiency from the ICE power to the axles this appears to be a significant advantage; however, the impact of higher-efficiency Series ICE operating regions must be explored before coming to a conclusion.

With a high powered RTM, the TTR architecture can function as a fully electric vehicle throughout its CD range. During CS mode the vehicle will be initially propelled by the RTM, but once above a certain speed will be driven by the ICE with slight regeneration on the rear axle to maintain SOC. The strategy required

to drive this vehicle will be partially thermostatic, but will also incorporate load-following characteristics to minimize the losses associated with regenerating electrical energy “through the road”.

When there is a high power or traction demand from the driver, the vehicle will switch into performance mode and provide wide open throttle (WOT) on the ICE and RTM in parallel. This combined WOT mode results in a massive performance boost over the Series architecture with an identical RTM. The control strategy for TTR is summarized in Table 3.

**Table 3. TTR Architecture Control Strategy**

<b>Operation Mode</b>	<b>Throttle Request</b>	<b>Engine State</b>
CD	Normal Throttle Request	All Electric
	High Throttle Request	Engine on
CS	Normal Throttle Request	Engine on based on SOC / velocity
	High throttle request	Engine on

**B.2.1.2.2 Through the Road Hybrid Literature**

***Optimization and Testing of a Through the Road Parallel, Hybrid-Electric, Crossover Sports Utility Vehicle (Mehr, Michalak, Erlie, & Bower, 2009)***

The University of Wisconsin Hybrid Vehicle Team modified a 2005 Chevrolet Equinox with a TTR powertrain configuration. A GM 1.9L diesel engine was selected for use because it met the requirements for the largest continuous power demand the vehicle experiences.

The emissions equipment consisted of a stock close-coupled direct oxidation catalyst (DOC) which “reduces approximately 90% of the emitted CO, HC, and the soot soluble organic fraction.” The DOC is followed by the DPF and the urea injector. Thermocouples are placed in the exhaust stream to “ensure

urea is only injected when the SCR catalysts have reached their operating temperature of 225°C.” The NOx sensors are ECM brand and provide the hybrid controller with information on how much urea mass is needed to reduce the NOx output.

Test results indicate Wisconsin was able to reduce NOx emissions down to less than 0.1 grams per mile. However during highway driving, “the platinum in the DPF coating converted ammonia into NOx” and made it “hard to meet emissions targets.”

### ***Implementation of an Electric All-Wheel Drive System (Arnett, Rizzoni, Heydinger, & Guenther, 2008)***

Ohio State University designed an eAWD system for their 2005 Chevrolet Equinox that had a through the road powertrain architecture. Ohio State cannot use current traction control solutions that “utilize brake based, or engine torque reduction methods between the wheels of one axle” due to the fact that the “through-the-road configuration lacks a mechanical linkage between the front and rear axles.” Instead, wheel slip is controlled through one axle if the other axle loses traction.

For front wheel assistance, the control strategy goes through the “Engine Start mode” where, when the engine is at an appropriate speed, it delivers 85% of the torque request. Since the ICE is located at the front, having most of the torque come from it “minimizes the propensity of the vehicle to ‘fish-tail’.” For rear wheel assistance, if the front wheels lose traction, the eAWD will reduce the torque from the ICE by 15% and have the electric motor in the back deliver that torque instead. During maximum power request the eAWD will activate and deliver maximum power from both the ICE and the electric motor (based on its state of charge).

Test results on a basalt tile surface with a low-coefficient of friction successfully showed that the eAWD fulfilled its requirement of “increasing vehicle stability by managing wheel spin.” Ohio State concluded that this system is “robust and effectively replaces the viscous coupling of the stock vehicle.”

## ***Development and Implementation of a Control System for a Parallel Hybrid Powertrain (Mathews, Walp, & Molen, 2006)***

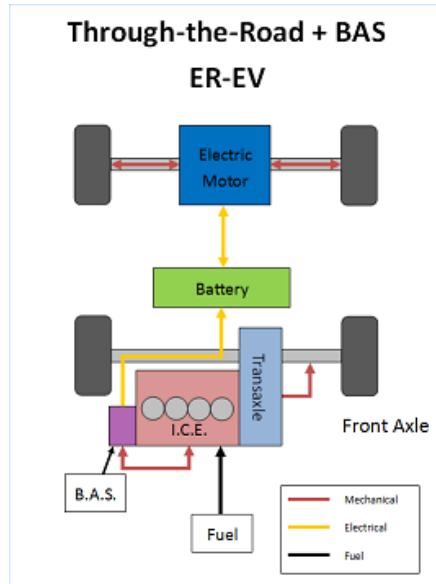
This paper describes a control strategy for a modified 2005 Chevrolet Equinox that contains a PTTR diesel-electric hybrid powertrain. Using an off the shelf controller from the MPC555 family as the main HEV controller, Mississippi State University split vehicle operation into four modes: ICE-only, blending, braking, and invalid.

The ICE-only mode is the operational strategy of conventional vehicles. In blending mode, MSU further defines three distinct powertrain operating states which are when the vehicle is accelerating, decelerating, and cruising. In acceleration, the electric motor (EM) provides additional torque to the ICE output. During deceleration regenerative braking is used to charge the high voltage battery. In cruising, the ICE operates alone with the EM regenerating charge at a low level dependent on the battery SOC.

Actual on-road results show that accelerations from 0-60 exceed model predictions. However the MPG (combined EPA) is less than predicted due to external factors that were not considered in the predictions.

### **B.2.1.3 - The PTTR + Belted Alternator Starter Powertrain Architecture**

The TTR hybrid gains an efficiency boost when a Belted Alternator/Starter (BAS) is added to the engine, as diagrammed in Figure 24. Although the drive-train remains largely the same, the BAS replaces the standard alternator and starter of the combustion engine. The standard TTR hybrid system is only able to charge the battery while the motor can apply a negative torque, i.e., when the vehicle is moving. The TTR+BAS allows the battery to charge through the BAS while the engine is idling and the vehicle is stopped because a single BAS unit is designed to generate much higher power and voltage than a typical alternator. (Rassem, Lequesne, Chen, Ronning, & Xue, 2001) The BAS also allows the engine to charge the battery without having to overcome the efficiency losses of going from the engine through the transmission, through the front wheels, through the back wheels, and finally into the motor. The BAS can also do running starts/stops (Jayabalan & Emadi, 2003) easily and it can load the engine to facilitate heating of the catalytic converter to its fully functioning state. (Boyd, 2006)



**Figure 24. Energy Flow Diagram of TTR+BAS Architecture**

The control logic for the TTR+ architecture, shown in Table 4, is only slightly different than TTR because it allows for idle regeneration.

**Table 4. TTR+ Control Strategy**

Operation Mode	Throttle Request	Engine State
CD	Normal Throttle Request	All Electric
	High Throttle Request	Engine on
CS	Normal Throttle Request	Engine on based on SOC
	High Throttle Request	Engine on

#### **B.2.1.3.1 Belt Alternator Starter (BAS) Literature**

The UW is considering the use of a BAS system on the TTR hybrid architecture to improve fuel economy and emissions levels by driving the engine into more efficient operation levels. The following papers focus on the benefits of implementing BAS systems on various hybrid powertrains.

#### ***Belt Driven Starter and Power Generator (Rassem, Lequesne, Chen, Ronning, & Xue, 2001)***

Research from Delphi Research Labs on a belt-driven starter-generator is outlined and presented in this paper. A prototype BAS was built and tested on a small European engine. The introduction focuses on three different packaging options with an alternator-starter: chain driven, gear driven, and belt driven. This paper concludes that a BAS is the best packaging option because of its low cost, no need for lubrication, more freedom in packaging, and very low noise. It also requires the least amount of engine, transmission, and vehicle modifications.

Mathematical models follow the introduction, and the parameters of their research are presented. Their test results follow, and the advantages of a BAS are explained. The relationship between maximum cranking speed and temperature is discussed. When temperatures fall, the maximum cranking speed also falls, due to a higher voltage drop on the battery. However, they found that at  $-20^{\circ}\text{C}$ , the engine cranked up to 400 RPM in .45 seconds thanks to a BAS, which fulfilled the cranking requirements of their research.

To conclude, the authors of the paper claim that they successfully created a BAS system that increases efficiency, especially in cold weather conditions. Because of the high power generating potential of a BAS, it can also supplement engine torque if needed. It can provide transient torque smoothing as well as power boosting. Smooth start up and restarts increase stability and reliability by decreasing start up times. When the motor is not yet to optimal efficiency levels, the BAS will help control engine speeds.

## ***42V Alternator Starter Systems (Rassem, Lequesne, Chen, Ronning, & Xue, 2001)***

This paper from the Illinois Institute of Technology acknowledges the increasing electrical power demand in today's vehicles, and suggests the use of a 42V Alternator Starter that can be belt driven. A Belt Alternator Starter (BAS) offers silent operation, more packaging options, and increased efficiency. Most cars have both an alternator to charge the on-board batteries and a starter to start the motor. A BAS is a single machine that performs the function of both, while providing high power efficiently and reliably.

The discussion moves to the benefits of a BAS system. BAS systems have efficiency greater than 90% during power generation because of its increased size and capacity. A BAS can double the torque output of a conventional starter motor, which dramatically decreases starting times. Present starter motors used for cranking up the engine rotate from 100-150 RPM. In contrast, the authors claim that a BAS can crank the motor up to 400 RPM, leading to a start time of .1s compared to 2-2.5s. Decreased starting time leads to reduced fuel consumption and lower emissions. The BAS cranks up the engine before ignition occurs to decrease hydrodynamic friction and fuel wastage. Ignition occurs when the engine has reached idle speed, allowing for complete combustion of fuel. Being of high power capacity, the BAS prevents the engine from falling below its ideal operating speed.

The discussion ends by presenting alternative applications of a BAS, beyond those of starting and generating power. This technology can also be used for start-stop, regenerative braking, engine dampening, and acceleration support. Several configurations of the BAS outlined in the conclusion.

## ***Hybrid Electric Vehicles Using a BAS (Boyd, 2006)***

A paper by Steven J. Boyd, "Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations" (Boyd, 2006) analyzes Virginia Technical Institute's HEV using a BAS system. It starts out by explaining how a BAS has to be a small and lightweight motor, be able to use the engine to charge the battery, and able to provide power directly to the drive system. A BAS is used to provide peak torque for engine starting

and continuous operation. Because it is belt-driven, a high-speed motor with speed reduction to the engine can be used.

Boyd expands on the BAS system by evaluating other operational modes. During normal driving conditions, the BAS generated power to charge the batteries, and does not need to supply any additional torque to the engine. When the BAS is needed to assist the engine under more demanding situations, torque output from the BAS boosts vehicle performance by avoiding engine operation at especially high or transient loads, while adding power to the wheels. The BAS is inherently more efficient for load leveling.

The advantages of a BAS are further emphasized towards the end of the report, when vehicle emissions are considered. Cold start emissions are where the majority of emissions are created. The best strategy for reducing cold start emissions is to control the engine speed so it reached optimal operation temperature as fast as possible. The BAS can have complete control of the engine load during start up, independent of driver demand. This approach makes sure that the engine runs at its most efficient state during warm-up.

## **B.2.2 - Component sizing**

Changing the specifications of major components within each architecture will have varying effects to the vehicle. We are limited in what we can use in our architecture simulations because of what we are able to source, however it is important to get a good understanding of the effect of component sizing on consumption and performance.

### ***Engine***

Because all of the three proposed architectures incorporate a large RTM that can satisfy all power requests over the EcoCAR2, it is desirable to minimize the size of the engine so that during CS mode its peak efficiency operating point satisfies the average power request while the RTM handles changing throttle demands. Additionally, there is a lower limit on engine size for the gradeability event such that the peak output power of the engine must maintain a 3.5% grade at a continuous power rating.

In an effort to obtain a smaller engine, we reached out to companies that build 1.1L Turbo diesels with a peak power of ~50kW, but were unable to obtain support for the engines.

### ***RTM***

Although our RTM can satisfy all power request during the EcoCAR2 4-cycle blend, we still must consider the effect of using the motor for very high power requests. Ideally, a motor that can exceed the power demands of highest density would be used to ensure that it is operating at peak efficiency as much as possible, however we were limited to what we could source from suppliers.

### ***ESS***

The University of Washington team hopes to take regional considerations into account regarding electricity use. Because Washington State power generation is almost 80% renewable (Administration, 2009), it is desirable to utilize as much grid electricity as possible.

### ***Transmission***

Rather than trying to source a more efficient transmission (dual-clutch, CVT, etc.), the University of Washington team decided to take advantage of the simple integration of the donated GM gearbox which mates with the donated GM 1.7L engine.

## **B.2.3 - Fuel Economy Simulations**

In order to provide a quantitative comparison between the three proposed architectures, architectures were simulated using Autonomie over the EcoCAR2 four-cycle-blend described in Report 1. With some post-processing, all consumption and emissions results can be directly compared between the architectures.

### B.2.3.1 - CD mode/range

Each of the three proposed architectures operates in EV mode throughout the entire CD range. Therefore to calculate each architecture's CD range, the electrical consumption over the EcoCAR2 4-cycle blend was used and extrapolated to our maximum available electrical energy from the ESS.

### B.2.3.2 - CS mode/range

During CS mode, each of the three proposed architectures use significantly different control strategies and therefore display very different results. Because electrical energy is effectively maintained at a steady state level, the effective range of each architecture is described simply by its fuel consumption per mile traveled.

To get the most accurate results out of the CS simulations, effort was taken to minimize the effect of the  $\Delta$ SOC correction factor equation. To do this, each architecture was run on the EcoCAR2 4-cycle blend nine times. This lowered the electrical energy consumption rate to <5Wh/mi, down from <75Wh/mi.

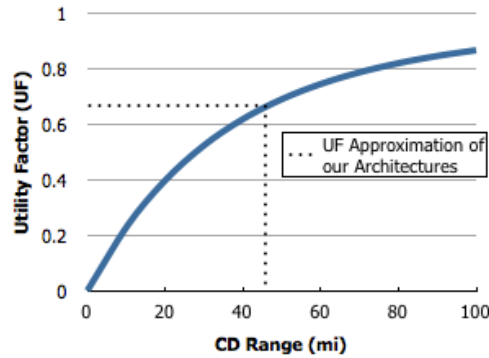
The remaining electrical consumption was accounted for via the SOC Corrected fuel consumption equation from the EcoCAR2 Non-Year-Specific Rules. The excess energy is accounted for by the usage or credit of fuel consumption, where 0.25% represents the typical efficiency of converting fuel energy to stored electrical energy. The effect of this factor is meant to be very small.

$$FC_{SOC-corrected} \left[ \frac{kg}{km} \right] = \frac{Mass_{fuel}[kg] + \frac{EC_{electric,CS}[Wh]}{0.25}}{LHV_{fuel} \left[ \frac{Wh}{kg} \right]} \cdot \frac{1}{Cycle\ distance[km]}$$

### B.2.3.3 - Utility Factor Calculation Process

Because PHEV's are characterized by two distinct modes of operation, Charge Depleting (CD) and Charge Sustaining (CS), to estimate the net energy consumption per unit distance of a PHEV, drivers who operate the vehicle only in CD mode must be weighed against drivers who drive further and operate the vehicle in both CD and CS mode. The Society of Automotive Engineers has developed a method of calculating this

weighting factor, termed “Utility Factor” (UF). In paper SAE J2841 (J2841, 2005), the UF curve, based on the 2005 National Household Travel Survey, is a function dependent on the CD range of a PHEV.



**Figure 25. Utility Factor as a function of CD Range**

Using our calculated CD range and Equation 5, the predicted UF for each architecture is summarized in Figure 25 and Equation 5.

**Equation 5: Utility Factor Calculation**

$$UF = 1 - e^{-\left[ C1 \cdot \left( \frac{x}{D_{norm}} \right) + C2 \cdot \left( \frac{x}{D_{norm}} \right)^2 + \dots + C6 \cdot \left( \frac{x}{D_{norm}} \right)^6 \right]}$$

Where  $D_{norm} = 399.9$

$C1 = 10.52 \quad C2 = -7.282$

$C3 = -26.37 \quad C4 = 79.08$

$C5 = -77.36 \quad C6 = 26.07$

**B.2.3.4 - 20-40-100 Utility Factor Method**

In order to simplify the scoring process, the EcoCAR2 organizers will be using a 20-40-100 utility factor weighing method. This method is a stepwise approach to performing the utility factor statistical approximation that is more predictable for the schools to design their control strategies for. In this method, the first twenty miles count three times towards the total energy consumption of the vehicle, the first forty

miles count twice, and the first 100 miles of a drive count once. The total energy consumption per kilometer of driven distance is given by the following equation, where A B and C are the 20 mile trip, the 40 mile trip, and the 100 mile trip respectively.

$$\text{Energy Consumption} \left[ \frac{\text{Wh}}{\text{km}} \right] = \frac{(\text{Fuel} + \text{AC Elec.})_A[\text{Wh}] + (\text{Fuel} + \text{AC Elec.})_B[\text{Wh}] + (\text{Fuel} + \text{AC Elec.})_C[\text{Wh}]}{A + B + C [\text{km}]}$$

To obtain the scored consumption for these results, the vehicle will be driven on a single 103 mile trip, where the first 20 miles will be A, the first forty miles will be B, and the entire 103 mile trip will be C. AC Electrical consumption will be calculated based on DC electrical consumption during the event, and the charging efficiency after the event.

## B.2.4 - Results and comparison

Based on the results from Autonomie, comparisons can be made between the three proposed architectures. The results are summarized in Table 5.

**Table 5. Quantatative Results for Each Architecture**

Metric	Series	TTR	TTR+
Mass (kg)	1948	1966	2001
Acceleration 0-60 (s)	8.4	7.1	7.2
Acceleration 50-70 (s)	3.8	3	3
Gradeability (% in CS mode)	7.4	8.9	8.9
CD Range (Miles)	44.8	44.6	44.2
CD Fuel Consumption	0	0	0
CS Fuel Consumption	677	686	560
UF-Weighted Fuel Energy Consumption (Wh/km)	234	238	196
UF-Weighted AC Electrical Energy Consumption (Wh/km)	138	138	139
UF-Weighted Total Energy Consumption (Wh/km)	372	376	335
UF-Weighted WTW PEU (Petroleum Energy Usage)	205.9	209.2	172.9
UF-Weighted WTW GHG Emissions (Green House Gas Emissions)	157	158.3	146.6

In reference to Table 5, the TTR+BAS architecture out-performs the other two proposed architectures in multiple fields. Most notably, the TTR+BAS stands out in the following fields: UF-weighted fuel consumption, UF-weighted GHG emissions, and UF-weighted WTW PEU. The UW EcoCAR2 team considered these areas as vitally important in reaching goals set by our own team and by the organizers of EcoCAR2.

The TTR+BAS addresses our team goals in that it demonstrates the lowest GHG emissions as well as minimal energy consumption and a comparable charge sustaining range to the other vehicles. It also maintains higher consumer acceptance in its performance numbers when compared to the other two architectures and provides a limp-home mode with either motor providing power to the wheels.

While the results of our Autonomie simulations are valuable, we realize that they are not very accurate. For example, the TTR architecture shows much higher consumption than it should because it is operating with a supervisory controller which was not designed for this architecture. It is expected that the actual results for UF-weighted fuel consumption, UF-weighted GHG emissions, and UF-weighted WTW PEU will be somewhere between the results from the Series architecture and those from the TTR+BAS architecture.

### **B.2.4.1 - CD/CS range and Constituent Drive Cycles in the EcoCAR2**

#### **Blend**

The different control strategies of each architecture cause significantly different results on each of the EcoCAR2 constituent drive cycles. A closer look will be taken at the effect of each drive cycle to determine the advantages and disadvantages of each architecture.

The difference in charge-depleting range between each architecture is very small due to the similarities in their rear drivetrain. Because of the identical drivetrains, the differences in CD range are only a result of the overall vehicle weight.

## **Series**

The series architecture achieves the greatest all-electric range due to it being the lowest in weight of the three proposed architectures. When charge-sustaining mode begins, however, the series design becomes less attractive. Even though the architecture allows the engine to run at peak efficiency at all times, the two additional energy conversions in this architecture end up causing it to consume almost 20% more energy during CS mode.

The effect of each individual drive cycle on the series architecture is negligible due to the wide efficient operating zone for the RTM. Low speed accelerations like those seen in the US06 City cycle are the only point where this architecture experiences a drastic loss of efficiency.

## **TTR**

Through-The-Road offers good acceleration results and an improvement in overall fuel consumption relative to the series vehicle. Looking closer at the effect of each individual drive cycle reveals that the TTR engine exhibits much lower efficiencies due to the fact that it's RPM is restricted by the vehicle's current speed. During city cycles the TTR results are significantly lower than the TTR+BAS, however on highway cycles (HWFET and US06 HWY) the two architectures are comparable.

One thing to note is that the current TTR controller expects that there be a small BAS motor on it to perform load-leveling. While modeling TTR, the BAS was simply scaled down to 1W and the controller was not re-programmed to use the RTM for load leveling. This means that in the control scheme, the vehicle is only regenerating electrical energy from braking energy, rather than load-leveling the ICE. In order to provide a more accurate comparison to TTR+BAS, the controller should be re-programmed to enable the RTM to provide engine load-leveling.

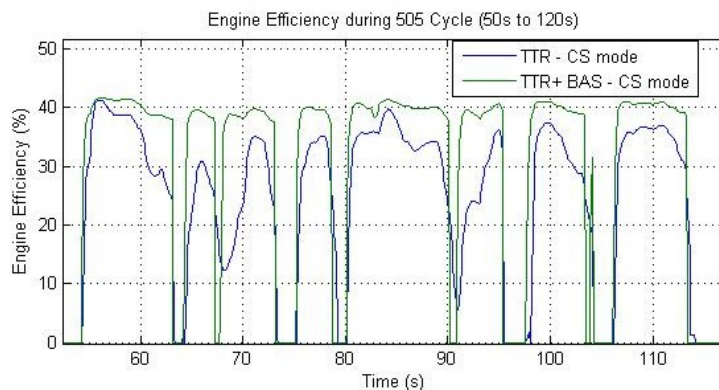
## **TTR+BAS**

TTR+BAS offers all of the benefits of the TTR architecture plus a load leveling BAS motor that is able to spin up the engine, load the engine to bring it to a more efficient state, perform idle regeneration, and possibly provide additional propulsive power during a high-throttle request.

By using a BAS, we can move the light regeneration required to load-level the ICE off of the RTM and connect it directly to the engine. Not only does this avoid the losses associated with transferring power “through the road”, but it also enables the generating electric machine to operate at a much more efficient point in its operating range. After a brief parametric exploration of BAS sizing, 10kW appears to be an optimal balance of weight vs. load leveling benefit.

The effect of adding the BAS to a TTR architecture over each drive cycle is very apparent. During city cycles (505, US06 City), the BAS is able to provide very effective load leveling on the engine throughout the quickly changing throttle requests. The improvement in engine efficiency is displayed by an excerpt of the 505 drive cycle results shown in Figure 26 below.

The Autonomie simulation results exhibit that adding a 10 kW BAS causes a reduction in fuel consumption of about 3% compared to TTR. During highway cycles (HWFET and US06 HWY), the contribution from the BAS is very small because the engine is consistently loaded at a level throttle. During these cycles, the detriment to fuel consumption that occurs due to the increase in overall vehicle weight actually outweighs the gains of engine load leveling.



**Figure 26. Effect on Engine Efficiency by adding a BAS to TTR**

### **B.2.4.2 - Regenerative Braking**

It was mentioned in report 1 that the effect of capturing wasted braking energy during city cycles would be analyzed. In each simulation, braking energy is regenerated through the RTM. Because this component

and mating gearbox is identical in all architectures, the effectiveness of regenerative braking is similar. Generally, with heavier vehicles it is more essential regenerative braking to avoid wasting energy as heat during deceleration.

### **B.2.4.3 - Performance**

#### ***Acceleration***

Upon inspection of the acceleration results, we can see TTR and TTR+ perform very similarly. This is expected because the only difference between TTR and TTR+ is the weight of the BAS system. It is notable that the series architecture is by far the slowest architecture. Because all of the architectures have identical RTMs, TTR and TTR+ have much more power at the wheels because of the additional axle being powered by the ICE. In terms of performance alone, the TTR and TTR+ are favored over the series architecture.

#### ***Gradeability***

In the same way as the acceleration results, TTR and TTR+BAS both exhibit a similar maximum gradeability of 8.4%, due to the limiting factor being the maximum power that the ICE can create at 60 mph road speed. The result of the RPM limiting causes the maximum power from the ICE to drop to approximately 73 kW.

Gradeability for the series architecture during CS mode is limited by the RTM's continuous power rating of 60 kW, giving the series a maximum gradeability of about 7.4%.

In CD mode, the gradeability of the series architecture is unchanged. TTR and TTR+BAS are both able to use the RTM to assist the ICE in CD gradeability tests, resulting in a gradeability of in excess of 12%, which is well over the production vehicle gradeability.

## **B.2.5 - Publication (EVS26, Los Angeles) - Analysis of Dual and Quad Axle Mounted Motor Drivetrain Performance**

This paper explores the benefits in terms of efficiency, performance, safety and features that a drivetrain using dual and/or quad inboard axle-mounted motors has over that of a single-motor electric drivetrain. Several methods for improving efficiency by taking advantage of the possibilities of axle-mounted motors are explored and presented as an inventory of possible power request scenarios. It is argued that axle-mounted drivetrains can provide a number of safety and convenience features over that of a single-motor electric drivetrain while maintaining or increasing electrical efficiency.

To adequately compare axle-mounted drivetrains with single-motor drivetrains, a standard certification cycle that includes cornering must be developed. With potential gains of up to 25% overall drivetrain efficiency, this is the most vital future research presented by this paper for verification of concepts presented.

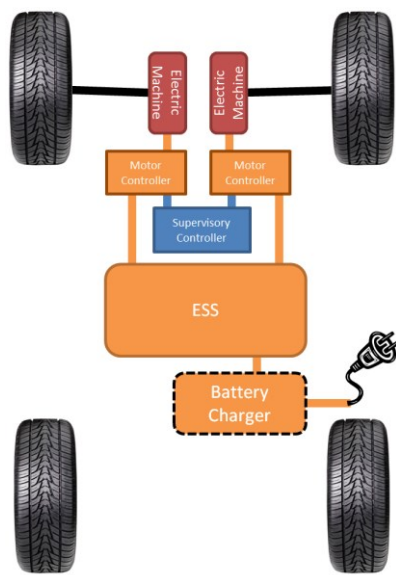
### **B.2.5.1 - Introduction**

With the resurgence of electric drive vehicles in the transportation industry in the last decade, automobiles are seeing the most radical drivetrain changes in history. Electric motors are simple and can be scaled to a wide variety of design power requirements with minimal detriment to operating efficiency, while their gasoline counterparts require extremely complex control systems just to sustain efficient operation. Rather than satisfy a driver's tractive power demand with a single power source, multiple electric motors allow a vehicle to split the demand over several components.

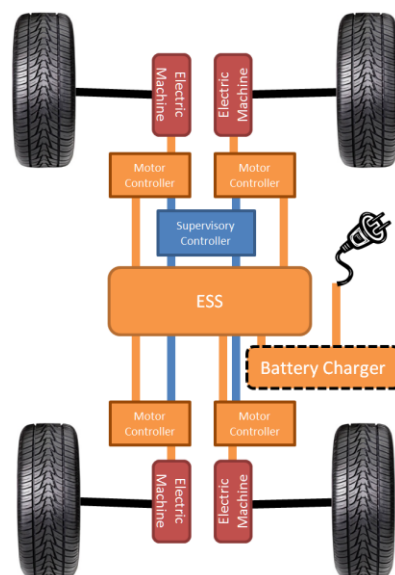
Improving the efficiency of electric drivetrains is an important engineering problem that faces full electric vehicles. Current battery technology cannot compete with a conventional gasoline vehicle in terms of useable energy storage and "refill" time, so even small improvements in the "fuel economy" of an electric vehicle are important.

The VEV1 developed by the student team Voltaic Drive Systems in 2011 demonstrated a prototype drivetrain which used axle-mounted BLDC motors that independently drive each wheel. This type of drivetrain eliminates the mechanical differential necessary to split the power from a single motor to both sides of a vehicle, and it allows explicit control over the power sent to each wheel of the vehicle. This type of drivetrain also offers benefits such as traction control, 0-pt turning, improved safety from faster steering response, and more. These features may be a deciding factor for consumers to purchase an EV instead of an ICE vehicle as their next automobile.

When combined with high-torque motors, a vehicle design can even avoid using a single-speed gearbox for each motor saving on weight, efficiency, and complexity. Two-wheel and Four-wheel versions of this drivetrain are shown in Figure 27 and Figure 28 below.



**Figure 27: 2WD Axle-mounted motor drivetrains**



**Figure 28: 4WD Axle-Mounted Motor Drivetrain**

Unique drivetrains such as 2WD and 4WD axle-mounted drivetrains require control strategies that can take advantage of embedded control of electric motors in strategic ways to improve performance in a variety of categories. This paper will use basic calculations from an energy standpoint to verify the possibility of

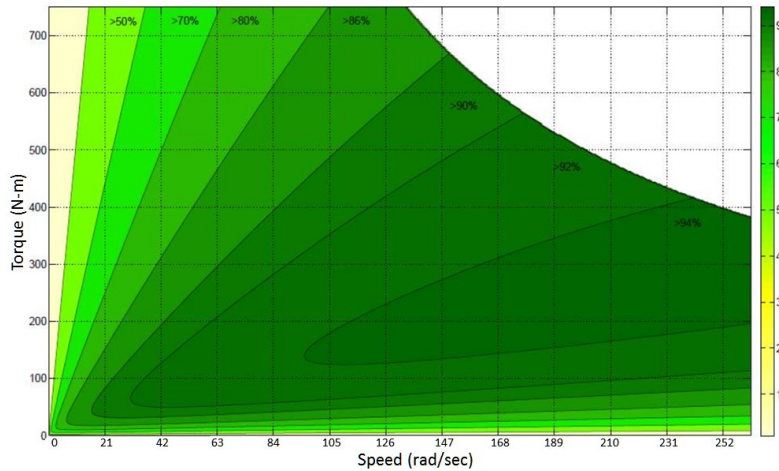
improved efficiency, show possible traction control methods, and discuss a variety of other benefits of axle-mounted drivetrains.

### **B.2.5.2 - Methods, Assumptions, Test Model**

By starting with hand calculations to explore the possibility of efficiency gains of an axle-mounted motor system, a theoretical estimate of the efficiency gain limit has been determined. To evaluate the effectiveness of the control strategy alone, efficiency gain is the difference between the overall drivetrain efficiency before and after control scheme alteration.

This report assumes that electric motor scaling is possible without significant changes to efficiency characteristics. The motor parameters remain similar enough for comparison as identical motors with only the power characteristics scaled. Individual wheel speeds are assumed to be a function of turning radius, vehicle width, and vehicle speed. Wider vehicles and vehicles with a tighter turning radius demonstrate a more significant difference in the individual wheel speeds between the left and right sides of the vehicle at a given turning radius. The motor explored similar to the YASA-750 high torque axial flux motor developed at Yasa Motors from Oxford, England. The motor's characteristics and example efficiency map are in Table 6 and Figure 29 below.

<b>Table 6: Test Platform Motor</b>	
Motor Type	YASA-750
Peak Power Rating	100kW
Peak Torque	750 N-m
Peak Current	360 Amps
Voltage	380 V



**Figure 29: Efficiency Map for YASA-750 (YASA-750, n.d.)**

The 2WD axle-mounted test platform will consist of two of the motors described above. The 4WD test platform will have four.

For each motor there is a separate inverter of matching power. A suitable inverter would be a Sevcon Gen4 Size 8 at 380V per motor. There is a supervisory controller that monitors wheel speeds, throttle or braking request, steering angle and other variables. The supervisory controller uses these values to calculate and delegate power requests to individual motors. A prototype supervisory controller with adequate computing power and connectivity would be a dSPACE MicroAutoBoxII controller.

#### **B.2.5.2.1 Vehicle Platform**

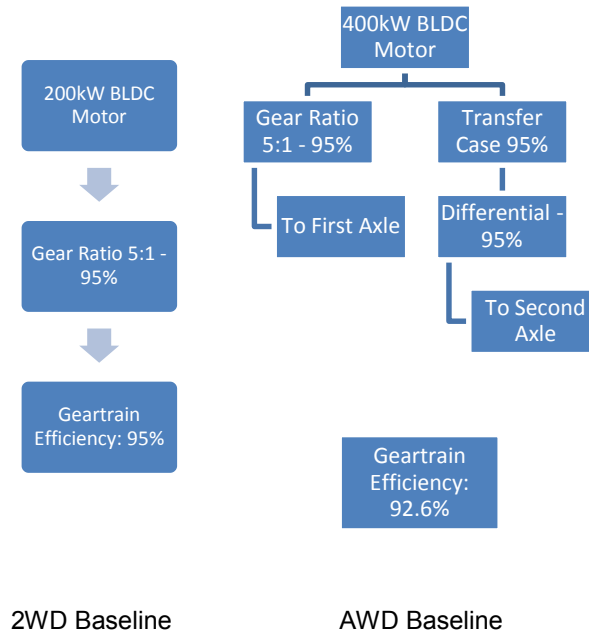
The test platform modelled in this report is described by Table 7 below.

Width	73 in
Wheelbase	107.8 in
Turning Circle	37.4 ft.
Wheel diameter	16"

The test platform is indicative of a generic full size sedan. The wheel diameter used is smaller than an average consumer vehicle to justify eliminating the gearbox between motor and wheel for the test platform.

### B.2.5.2.2 High-Level Power Flow

The baseline vehicle is powered by a single electric motor of equal design power to the sum of all axle-mounted motors. It is assumed that the baseline vehicle has a transaxle for each axle with an average efficiency of 95%, and a transfer case for 4WD vehicles with an average efficiency of 95%.



### High-Level Power Flow Charts

Axle-mounted motors provide freedom from geartrain efficiency losses by entirely avoiding them. Contingent on maintaining an identical operating efficiency of the motor in each drivetrain, axle-mounted motor drivetrains offer a baseline efficiency increase of up to a 7.4% before implementing the control strategies introduced in the next section.

### B.2.5.2.3 Efficiency

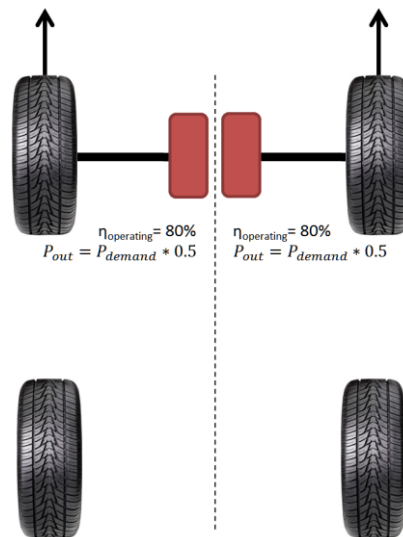
There are two main strategies which are explored in this paper to increase efficiency with axle-mounted motor drivetrains. The first deals with varying the tractive power distribution between the left and right side of the vehicle. This strategy can be applied for axle-mounted drivetrains with two or four wheel drive. The second works on the principle of varying the power distribution between the front and rear axles in a four-motor drivetrain to stay in more efficient operating regions. Both strategies can be used together on 4WD axle mounted drivetrains for the maximum efficiency increase.

## Left-Right Control Variation

Certification cycles for current production automobiles give a measure of the fuel consumption during a standard drive cycle in a straight line, but they do not account for cornering. When considering a system with multiple axle-mounted motors, cornering must be included to examine the operating point differences between each side of the vehicle and analyze consumption.

After examining the difference in operating points between the left and right sides of the vehicle, it may be valuable to develop a control scheme that can calculate which motor should be satisfying most of the tractive power demand based on the difference in operating points. Rather than attempting to develop a certification cycle representative of a typical driver which includes steering, the results of this paper will be presented as an inventory of the range of efficiency gains in different scenarios. The main variables which will be examined are steering angle, speed, and tractive power.

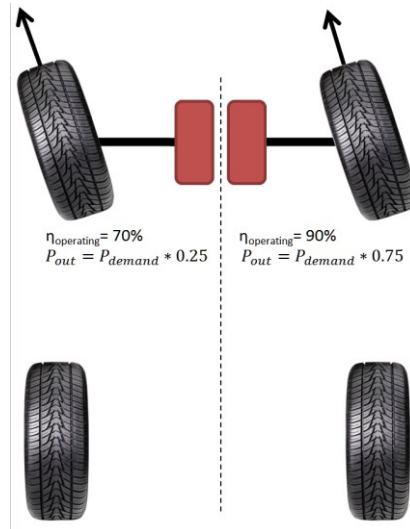
Take for example a vehicle equipped with two axle-mounted motors. At a given speed in a straight line each motor satisfies half of the tractive power demand and may be operating at an efficiency of 80%, shown in Figure 30 below.



**Figure 30: Traveling in a straight line**

If a steering angle is introduced, one motor may be operating around 70% while the other is now able to provide power at ~90% efficiency. Rather than continuing to satisfy the total tractive power request with a

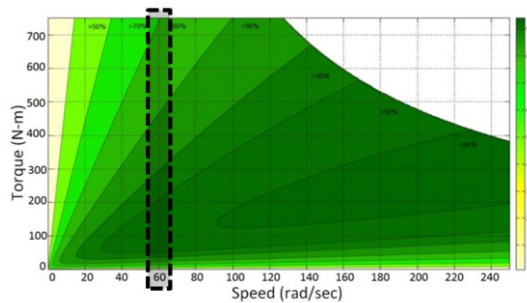
50/50 split between both motors, it is valuable to satisfy a higher portion of the power demand with the motor at a higher efficiency state, while satisfying the remainder of the power request with the motor at a lower efficiency state to prevent significant course alteration. This case is shown in Figure 31 below.



**Figure 31: Traveling with a turning angle**

### ***L-R Control Variation Example***

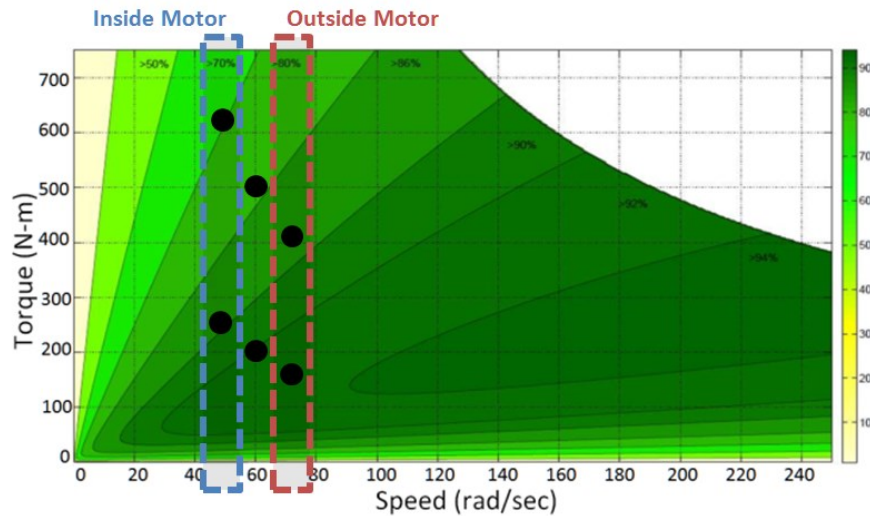
Consider a vehicle moving at a constant 27 mph in a straight line, resulting in a motor speed of 60 rad/sec. The black rectangle shows the operating column for this speed in Figure 32 below. In this state, both electric motors produce the same amount of power at the same efficiency.



**Figure 32: Constant speed straight line**

The vehicle traveling at the same speed but with the steering wheel locked to one side will cause a difference in the operating RPM between each motor. This difference is calculated using the turning circle

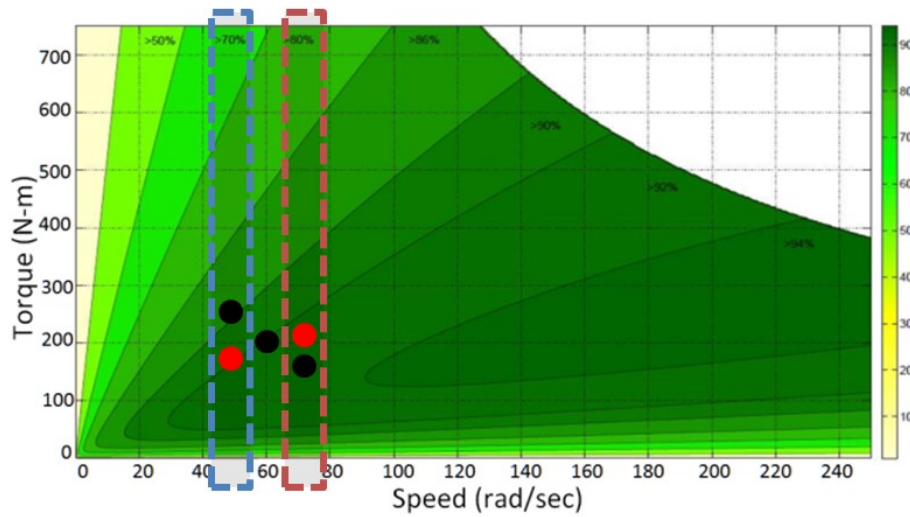
traced by the rear axle of the test platform. The inside motor is now operating at  $\sim 48$  rad/sec and the outside motor is operating at  $\sim 72$  rad/sec. Two scenarios in which the tractive power demand is split equally to the L and R motors for this speed are shown for the straight-line and the steering locked case in Figure 33 below.



**Figure 33: Efficiency map with overlaid example operating columns**

By examining the operating columns now available to each motor, it can be determined whether or not it is valuable to unequally load the driving motors to satisfy the tractive power demand. There are two mechanics that improve efficiency by shifting power. First, the motor operating at a higher efficiency can be favored for satisfying the power demand. Second, changing the loading to each motor can potentially change the operating efficiency favorably.

For a tractive power request of 24kW, a power balance of 65% to the outside motor and 35% to the inside motor is chosen. This choice improves operating efficiency of the inside motor while maintaining the efficiency of the outside motor at the same time as shifting more demand to the more efficient motor.



**Figure 34: Operating Shift Example**

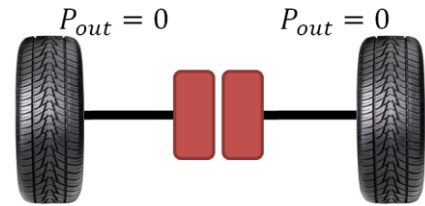
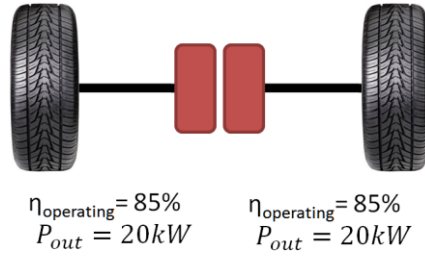
In this case, the outside motor is operating around 6% more efficient than the inside motor, and shifting power demand off of the inside motor improves its operating efficiency by almost 4%. Before the L-R power variation is applied, the weighted average motor efficiency is ~89.5%. Using the power shift of 65/35, the overall powertrain efficiency is improved to 91.5% for a gain of 2% efficiency.

### ***Front-to-Back Control Variation***

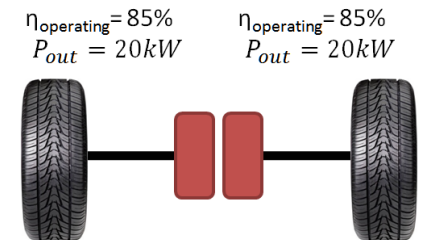
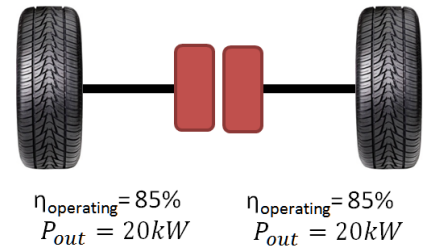
On quad axle-mounted motor drivetrains, as with other drivetrains which include separate power sources on separate axles, the vehicle controller is able to operate a single axle at high efficiency rather than both axles at lower efficiencies.

#### *Axle Power Split Strategy*

In some quad axle-mounted motor drivetrains the power specification of each motor will be identical. For low power demands, it may be most efficient to only power one axle. Increasing that power demand at the same speed could require operation of both axles for maximum efficiency. This effect is demonstrated in Figure 35 and Figure 36 below.



**Figure 35: 40kW power request  $\eta=85\%$**



**Figure 36: 80kW power request  $\eta=85\%$**

### *Design Variation between axles*

Quad axle-mounted motor vehicles can take advantage of the axle power balancing in their design. Rather than designing a vehicle with identical powertrains on both axles, the power specifications of a single axle's motors can be changed to introduce additional efficient power zones.

For example, a given two-axle electric drivetrain has axle design powers of 150kW (75kW + 75kW) and 250kW (125kW+125kW). There are now three distinct efficiency regions which should be taken advantage of, described below.

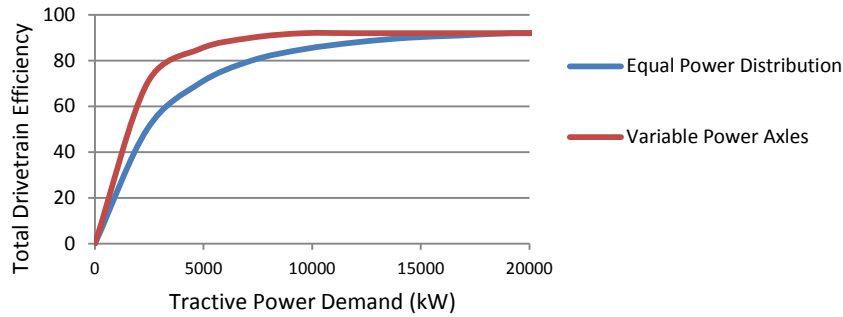
1. For power demands below the power at peak efficiency of the low power axle, that axle should be controlled to satisfy the power demand alone.
2. For power demands between this value and the power near peak efficiency of the high power axle, use the high power axle alone.
3. For power demands above this value, split the power to each axle by the ratio of their design powers.

There is also some blending between these regions to avoid jolting the driver. These design powers should be chosen to satisfy the highest density of power requests during certification cycles.

### ***F-B Control Variation Example***

First, we compare a 4WD test platform where the power demand is split equally between both axles to the 4WD test platform with the power delivered to each axle controlled separately. Each axle's design power is 200kW.

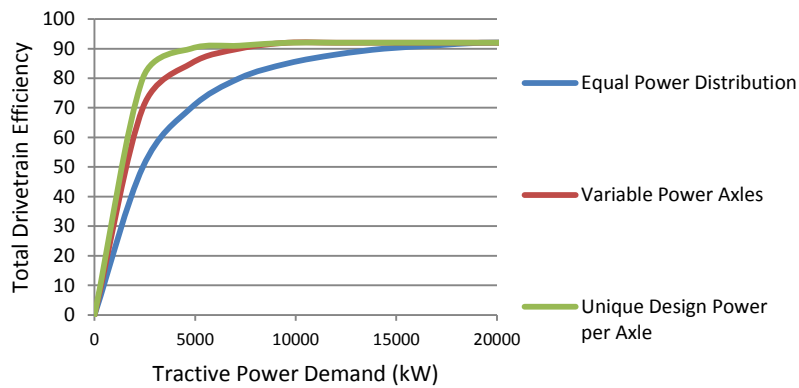
As an example, a vehicle is traveling at 27 mph, causing a motor speed of 60rad/sec. The resulting efficiency for low power requests is shown in Figure 37 below.



**Figure 37: Efficiency versus motor power request at 60 rad/sec motor speed**

At power requests below the power output at peak efficiency of a single axle, the variable power control vehicle will only use a single axle to satisfy the demand, while the equal power distribution vehicle will be operating all four motors at lower efficiency.

Taking advantage of the ability to control power between each axle, the design power of each axle can be altered to provide a greater boost while under a single axle's power demand at peak efficiency. This is demonstrated by Figure 38 below using axle powers altered to 150kW and 250kW.



**Figure 38: Efficiency versus motor power of equal powered axes, variable power, and variable power with different design powers**

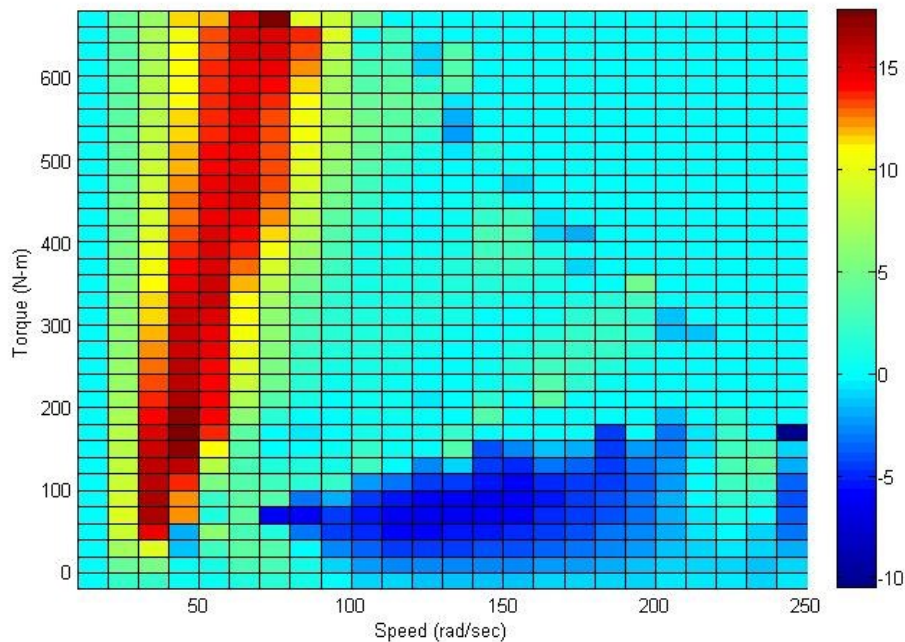
For lower power demands, efficiency is based on the low design power axle. For medium demands, efficiency is based on the high design power axle. For larger demands, the power is split between both axles based on the ratio of their design powers.

### B.2.5.3 - Results

Inspecting the efficiency charts shows distinct regions where L-R and F-B control variation is valuable for the test platform.

#### ***L-R Control Variation Results***

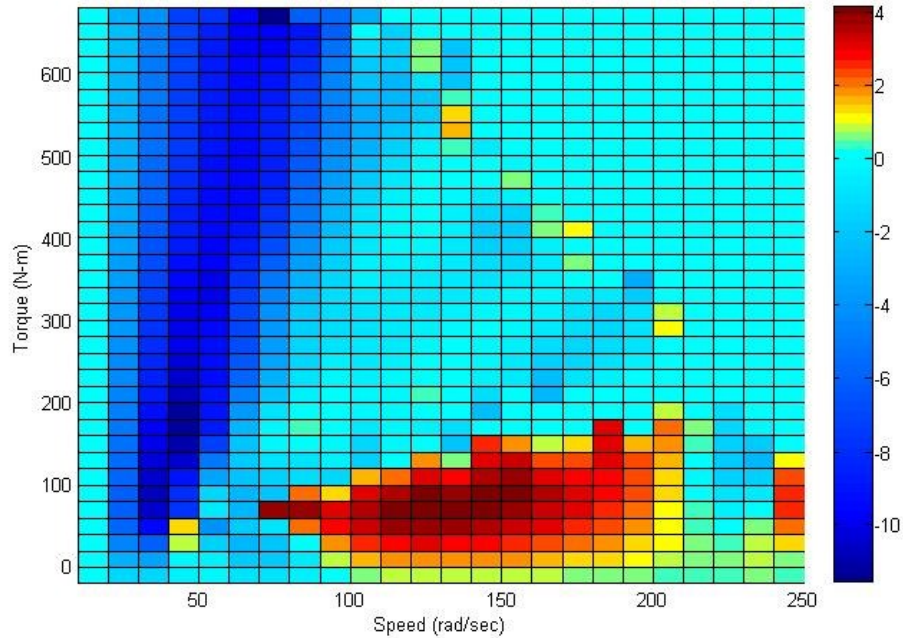
To demonstrate the maximum improvement in drivetrain efficiency, a full inventory of locked-steering efficiency improvements with a power distribution ratio of 1:0 (100% power to outside wheel) is shown below in Figure 39.



**Figure 39: Weighted Average Motor Efficiency at locked steering with full power to outside wheel**

There is a distinct zone at low speed and high torque in which L-R torque variation is beneficial to drivetrain efficiency with a maximum improvement of 18%, or a maximum of 9kW power savings at 750N-m and 70 rad/sec. However, at high speeds and low torque requests shifting power to the outside wheel is undesirable, resulting in an overall loss in efficiency. Inspecting the efficiency map for the test platform motor reveals the cause; the outside wheel is initially operating at a lower efficiency than the inside. By

changing strategy to shift power to the inside wheel, efficiency improvements are seen in the high-speed low torque zone of Figure 40 below.

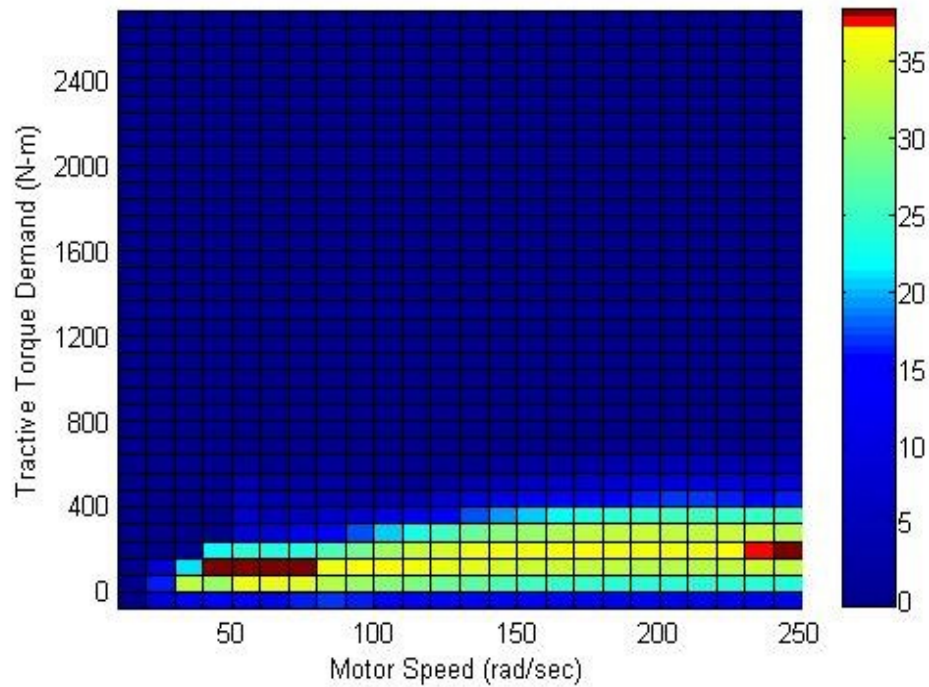


**Figure 40: Weighted Average Motor Efficiency at locked steering with full power to inside wheel**

Shifting power to the inside wheel at high-speed low torque operation provides a maximum efficiency boost of 4%, or a maximum of 1kW at 150 rad/sec. It should also be noted that the combination high speed with a locked steering wheel is rarely encountered. In such a case the efficiency of the vehicle drivetrain may be less important than the stability and control of the vehicle, which would likely change if power was shifted to the inside wheel.

### ***F-B Control Variation Results***

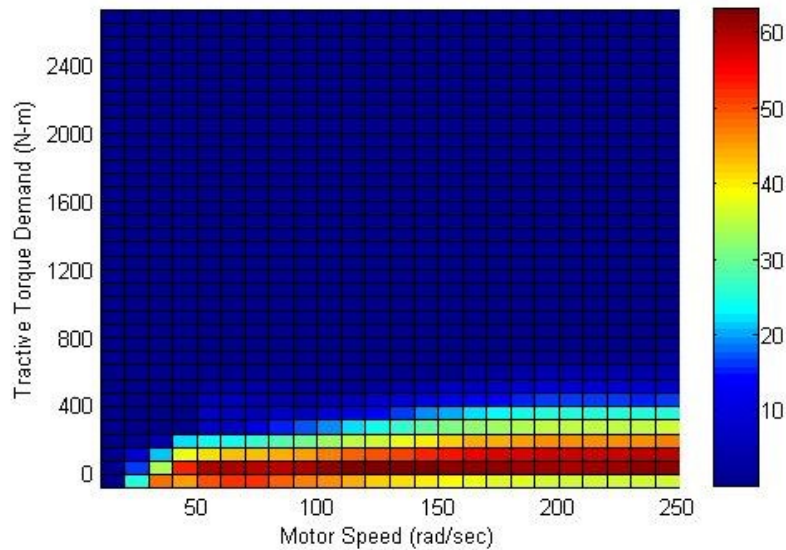
For a test platform with equal-power axles at 200kW each (100kW+100kW), the efficiency improvement of using F-B control variation is inventoried by Figure 41 below.



**Figure 41: F-B, equal axle power, total tractive power demand vs motor speed**

As discussed, there are significant gains in efficiency during low-torque requests. There is a maximum of 38% efficiency gain, or a maximum power savings of 19kW at 250 rad/sec (112mph) and 200N-m torque.

The efficiency gains resulting from F-B control variation on a test vehicle with different axle design powers of 100kW (50kW+50kW) and 300kW (150kW+150kW) are shown in Figure 42 below.



**Figure 42: F-B, design powers of 100kW and 300kW, total tractive power demand vs motor speed**

The efficiency improvements of using F-B power variation on the test platform of different axle design powers is significantly more than the improvement due to power variation alone. There is a maximum of 63% efficiency gain, or a maximum power savings of 31.5kW at 250 rad/sec (112mph) and 200N-m torque.

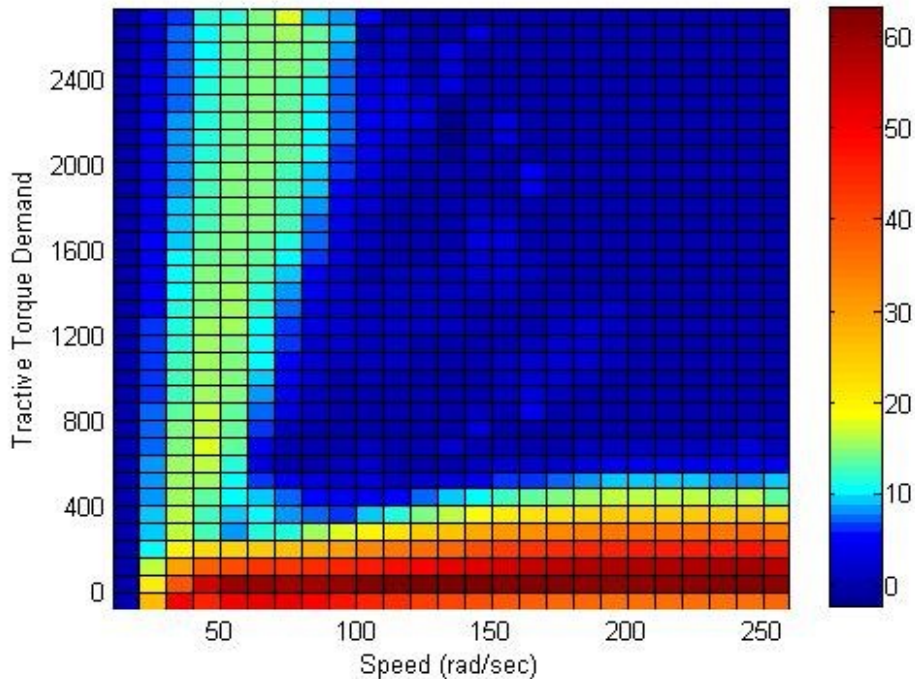
Due to the different design powers of each axle, there are three separate peak efficiency operating torques at any given speed, increased from two. For a tractive torque request, the efficiency peaks in equal power axle vehicles are at ~200 N-m and ~300N-m. For different design-power axles, the peaks are at ~100 N-m and 325 N-m, giving a wider spread of high efficiency points when a single axle is powered.

### ***Combined L-R and F-B***

More exploration must be done to manage corner-to-corner power blending in 4WD axle-mounted vehicles, but a general blending based on the two presented power splitting strategies can be applied for a reasonable improvement.

To combine the effects of L-R variation with F-B variation, the improvement efficiency plots are added together to create a new overall drivetrain efficiency plot. In a locked-steering scenario, the resulting

improvement in overall drivetrain efficiency, including L-R variation and F-B variation, is shown in Figure 43 below.



**Figure 43: Combined Strategies Efficiency Improvement over single motor**

The largest efficiency gain is a result of F-B axle variation for low torque requests at high speeds. In this figure, L-R power variation is not implemented for high-speeds to avoid altering vehicle dynamics.

#### **B.2.5.3.2 Other Considerations**

The benefits of axle-mounted motor drivetrains are only highlighted by the possibility of improved drivetrain efficiency. To consumers, it will be the sum of all features that dictates the final decision about what new vehicle to buy. Offering a range of unique features, vehicles with axle-mounted motors may be able to fare well in the current automotive market.

Safety features are an extremely valuable selling point. Vehicles with an axle-mounted motor drivetrain have abilities that improve safety over conventional vehicles.

### ***0-pt turning***

Axle-mounted motors enable explicit control not only of the power supplied to each wheel explicitly, but they also over the rotation of each wheel. More precisely, the driver can be given control over the direction of rotation of the wheels on each side of the vehicle, enabling the possibility of zero-point turning on everyday automobiles, making parallel parking possible in tighter spots than on a conventional vehicle.

### ***Torque vectoring and Traction Control***

By increasing the amount of power to the outside wheel, vehicles equipped with axle mounted motors can show improved steering response because of the additional forces acting to cause rotation of the vehicle. In terms of safety, this can decrease lane change maneuver time, potentially reducing the chance of an accident.

Traction control is the act of monitoring and automatically adjusting power output to the road, and in rare cases to individual wheels. With axle-mounted motors, the performance of such a system can be improved by allowing the supervisory controller explicit control over the power to each wheel individually.

### ***Backup System***

Should one of the electric motors fail, axle-mounted motor drivetrains naturally have a backup system which can allow the driver to continue vehicle operation in a “limping” state to get off of the road to a safe place before stopping.

## **B.2.5.4 - Conclusions**

The range of an affordable electric vehicle is arguably the largest deterrent to potential customers deciding between gas and electric. By improving drivetrain efficiency, axle-mounted motor drivetrains can help mitigate this roadblock by more effectively using the limited battery capacity available in an electric vehicle. The additional features of axle mounted motors (zero-point turning, explicit advanced traction control) can be used to provide an additional draw for potential customers.

Axle mounted motor drivetrains offer a baseline 5%-7% increase in operating efficiency due to the lack of geartrain losses. Additionally, left-right power variation and front-back power variation offer a theoretical

maximum efficiency gain of 18% and 63% respectively. The main mechanic of efficiency gain is effectively a widening of a drivetrain's high-efficiency operating region due to intelligent satisfaction of power demand by multiple motors. More exploration must be done to optimize power shift ratio in scenarios where the steering wheel is only partially turned.

Vehicle stability must be addressed further for implementation of axle-mounted motor drivetrains. With an aggressive power shifting strategy for efficiency, vehicle dynamics may become unpredictable to a driver who is used to a standard drivetrain. More effort must be placed on ensuring that the vehicle travels on the driver's intended path due to unintended power variance across the vehicle.

## **B.2.6 - Proposed Architecture Matrix**

### **B.2.6.1 - Selection Criteria**

Listed in Appendix D.1 - Proposed Architecture Selection Matrix Assumptions are technical assumptions made during development of the Proposed Architecture Matrix. These technical assumptions allowed the University of Washington to appropriately weight each architecture in the different categories. Additionally, these technical assumptions give team members a reference able document should questions arise about selection criteria or why a previous decision was made. The three architectures referenced in these tech assumptions are Series, TTR, and TTR+BAS.

The TTR architecture received the highest weighted rating. It is important to note the high cost of the Series architecture, and that the TTR+BAS charge sustaining efficiency was the highest of the three proposed architectures. See Appendix D.1 - Proposed Architecture Selection Matrix Assumptions for assumptions associated with scoring.

### **B.2.6.2 - Proposed Architecture**

The University of Washington EcoCAR2 team has used a variety of tools and methods to select a final architecture. The availability and specifications of major powertrain components (engine, motor,

gearboxes), drove the original selecting of the three different architectures (Series, TTR, TTR+BAS). These different architectures were eventually narrowed down to a specific component set based upon the availability of and support for the components.

These main components consist of a 100kW 1.7L diesel engine from GM, a 150kW traction motor/generator from AMR, a gearbox from GKN driveline and a motor inverter from Rinehart Motion Systems. These components were used to model the three different architectures inside Autonomie. The results for these architectures were placed inside the Architecture Trade Matrix seen in Table 8. It is observable from the matrix that the TTR architecture is the highest graded option. This means ultimately that the car will be powered by a 1.7L diesel engine with transmission in the front of the vehicle, and by a 150kW electric motor with a single speed gearbox in the rear of the vehicle.

Based on the complexity of the design, availability of components which satisfy the requirements of each architecture and the overall performance and efficiency results, the University of Washington EcoCAR2 team requests approval to move forward with a Through-The-Road hybrid architecture described in the previous sections of this report. See Table 8 below for the resulting scores of each architecture.

<b>Category</b>	<b>Weight</b>	<b>Series</b>	<b>TTR</b>	<b>TTR + BAS</b>
<b>UF-Weighted Total Energy Consumption</b>	30%	4	4	5
<b>Space Claim</b>	10%	5	4	3
<b>Controls Complexity</b>	10%	5	4	3
<b>Electrical Complexity</b>	10%	4	5	4
<b>Mechanical Complexity</b>	10%	3	4	3.5

<b>Overall Weight</b>	10%	5	4.5	4
<b>Performance</b>	10%	3	5	5
<b>Cost</b>	10%	3	5	4
<b>Total Score</b>	100%	4.00	4.35	4.15

## B.2.7 - Component Analysis

This section outlines the size and characteristics of the components and subsystems selected for the proposed vehicle architecture. The list includes the Non-Donated Components with specifications, cost, and lead time, as well as the components donated free of charge (Table 9).

**Table 9. Component Outline**

<b>Non-Donated Components</b>				
<b>Component</b>	<b>Specifications</b>	<b>Vendor</b>	<b>Cost</b>	<b>Lead Time</b>
Traction Motor	150kW 300 N-m Peak Torque 10,000 Peak RPM	Remy	\$6,930	3 Weeks
Controller	150kW Peak	Rinehart	\$7,500	12 Weeks
DC-DC Converter	2.2kW Peak 400 to 12 Volts	GM		
<b>Donated Components</b>				
Battery Pack	177kW, 340V 15s3p 6 Module 16.2 kWh	A123	\$0	
Engine	1.7L LUD Diesel 100kW Peak	GM	\$0	

Gearbox	8:1 200N-m Cont. Input Single Speed	GKN	\$0	10-12 Weeks
Transmission	Automatic, matching the 1.7L LUD	GM	\$0	

The performance limits of the proposed vehicle limit:

- Rear Axle
  - 250Nm Peak Torque Limit – Rinehart Controller
  - 170Nm Continuous Torque Limit – AMR Motor
  - 150kW Peak Power Limit – AMR Motor
  - 60kW Continuous Power Limit – A123 ESS
- Front Axle
  - 100kW Peak Power Output – LUD Engine
  - 310Nm Peak Torque – LUD Engine

The battery pack's capacity was maximized to increase the charge depleting range and increase the vehicle's reliance on grid electricity energy.

The efficiency maps of the diesel engine and the electric motor are shown in Figure 44 and Figure 45 below. With the plan to use our RTM for load-leveling on the ICE during CS mode, care must be taken to ensure that non-efficient zones of the RTM operating map are not used. Below 25 N-m or below 2000RPM the efficiency of the Remy motor falls off significantly and should therefore be avoided. The diesel engine, however, is a much more difficult to satisfy component, with low maximum efficiency and a very steep efficiency drop-off as it operates only slightly out of its ideal range.

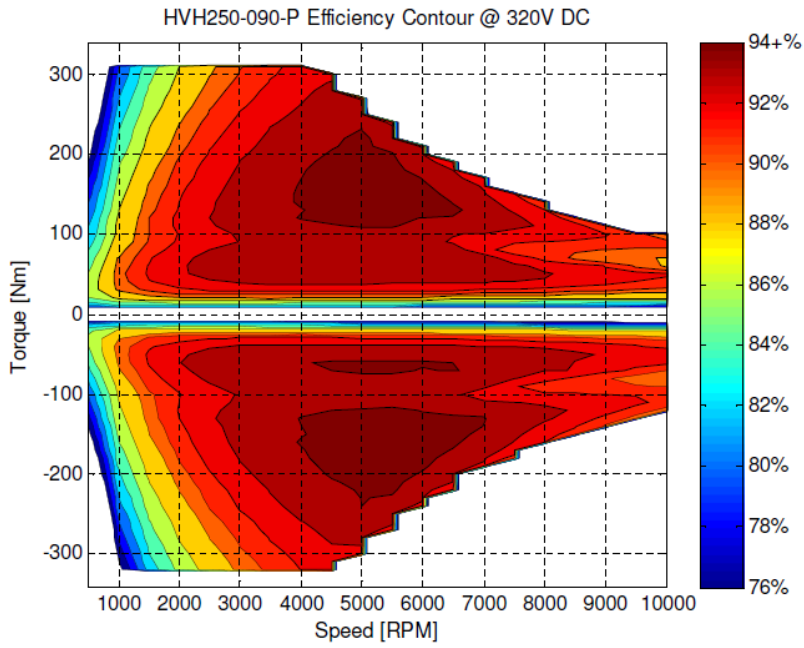


Figure 44. Remy HVH250 Efficiency Contour Plot

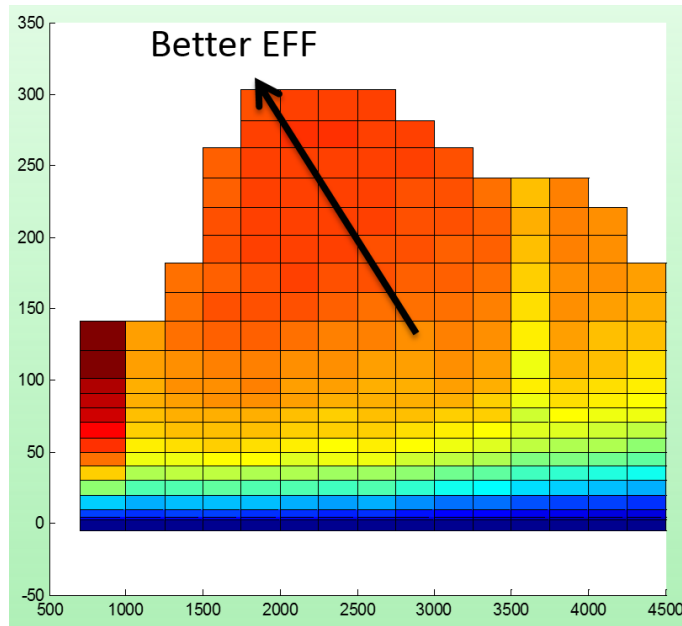


Figure 45: GM 1.7L LUD Efficiency Map

## B.2.8 - Vehicle Technical Specifications (VTS)

The VTS or Vehicle Technical specifications are given to indicate some level of vehicle performance on different categories within the vehicle. The event organizers have presented to the team a table of VTS for the stock vehicle with separate categories for competition goals, and competition requirements. The stock vehicle VTS relates the performance abilities of the stock 2013 Chevrolet Malibu. The competition goal VTS relates what level of performance the organizers would like the team(s) to meet and the competition requirements relate what the minimum level of performance that the teams must meet in order to receive scores during competition.

The Stock Vehicle Technical Specifications were considered during the development of University of Washington's target VTS specification decision. The teams VTS does not exactly match the stock vehicle requirements, or meet all of the design targets because of our chosen architecture. We have chosen to sacrifice in some areas to gain performance or economy in other areas.

Specification	Production 2013 Malibu	Competition Target	Competition Requirement	UW EcoCAR2 Target VTS
Acceleration 0-60 mph	8.2 s	9.5 s	11.5 s	7.2 s
Acceleration 50-70 mph	8.0 s	8.0 s	10.0 s	3.0 s
Braking 60-0 mph	143.4 ft.	143.4 ft. (43.7 m)	180.0 ft. ( 54.8 m)	N/M
Highway Gradeability @ 20	10+% @ 60 mph	3.5% @ 60 mph	3.5% @ 60 mph	>7%
Cargo Capacity	16.3 ft <sup>3</sup>	16.3 ft <sup>3</sup>	7 ft <sup>3</sup>	7ft <sup>3</sup>
Passenger Capacity	5	>=4	2	5
Mass	2250 kg	<2250 kg	<2250 kg	1997 kg
Starting Time	<2 s	<2 s	<15 s	<4s
Ground Clearance	155 mm	155mm	>127 mm	155 mm
Vehicle Range	736 km	322 km [200 mi]	322 km [200 mi]	676 km
Charge-Depleting Range	N/A	N/A	N/A	70.6 km
Charge-Depleting Fuel	N/A	N/A	N/A	0 Wh/km
Charge-Sustaining Fuel	N/A	N/A	N/A	619 Wh/km
UF-Weighted Fuel Energy Consumption	787 Wh/km	7.12 (lge/100km) [634 Wh/km]	N/A	215 Wh/km
UF-Weighted AC Electric	N/A	N/A	N/A	138 Wh/km
UF-Weighted Total Energy	787 Wh/km	634 (Wh/km)	N/A	353 Wh/km

UF-Weighted WTW PEU	774 Wh PE/km	624 (Wh Pe/km)	N/A	189.4 Wh PE/km
UF-Weighted WTW GHG	253 g GHG/km	204 (g GHG/km)	N/A	151.6 g GHG/km
Estimated Energy Cost	\$8.40/100km	N/A	N/A	\$3.40/100km

All three vehicle architectures were modeled to see if they met minimum EcoCar2 requirements, and those that did participated in the architecture selection process. Once the preferred architecture (TTR) was selected, hand calculations were done on some of the modeled results, specifically the gradeability and 60-0 stopping distance, to verify the integrity of the data. Once the Autonomie results and the hand-calculated results were verified as having similar magnitudes, the VTS requirements were produced.

Also observable from the table is the added data point of estimated energy cost. The University of Washington team believes that when designing a vehicle for consumer acceptability, operating cost should be an important selling point. This shows that the design team is striving to improve not only performance metrics and emissions, but to make the car cheaper to drive over its lifespan. Our estimated energy cost is less than 50% of the stock cost.

# C - Vehicle Control Strategy Documentation

The vehicle level control strategy is responsible for deciding how to control the various torque producing components in order to meet the demands of the driver. If the algorithms that dictate torque control are not designed well, they could be the cause of poor drivability, inefficient operation, and potentially unsafe scenarios. These criteria can be seen as the high-level requirements that the vehicle-level control strategy is responsible for, which are detailed in the following section.

## C.1 - Vehicle-Level Control Strategy Requirements

Defining the requirements of the control strategy in all modes as:

1. Keep the driver safe
2. Minimize energy consumption (total and Petroleum)
3. Minimize emissions (GHG and Criteria)
4. Provide good “driveability”

The only strict requirement is that the driver is kept safe. Upon inspection of energy consumption, emissions, and drivability it is easy to conclude that there is no way to absolutely maximize all of these requirements at the same time. Therefore it becomes an optimization problem in which the point where the combined equivalent maximum of these three criteria is continually calculated and gravitated towards within the controller.

This optimization problem turns out to be have a lot of “special case” scenarios where the general rules must be ignored. Sometimes the strategy must be ignored to keep the driver safe, while other times the strategy must be ignored due to the limitations of our vehicle drivetrain. For example, with a PTTR

architecture the electric motor speed is geared directly to the road, meaning that you can't regenerate electrical energy from the internal combustion engine while stopped.

Detail of each optimization parameter is given in the following sections.

## **C.1.1 - Emissions and Energy Consumption Optimization**

### **Parameters (E&EC)**

EcoCAR2 divides the score used to evaluate the emissions and energy consumption of a test vehicle into four equal categories. These categories and general strategies for optimizing for each are provided below.

- Total Energy Consumption
  - Total energy consumption can be reduced by maximizing grid electricity energy, because the electric powertrain is much more efficient than the diesel powertrain
  - Can also be reduced by improving overall drivetrain efficiency – fuel to electric conversion may be more efficient in certain driving conditions
- Petroleum Energy Consumption
  - Petroleum energy consumption is offset by maximizing grid electricity usage, and reduced by keeping the engine in high efficiency regions of operation.
- Criteria Emissions
  - Criteria emissions are defined as CO, Total unburned Hydrocarbons (THC), and NO<sub>x</sub> (NO and NO<sub>2</sub>)
  - Can be reduced by avoiding operating the diesel engine in regions which produce extra emissions per fuel used. Typically these points are at high torque
  - During cold-start warm-up periods criteria emissions are especially bad, necessitating a special warm-up strategy to be implemented when the engine is first turned on.
  - NO<sub>x</sub> can be mostly eliminated via the urea injection aftertreatment system, but only once the exhaust system is warm enough.

- GHG Emissions
  - GHG Emissions can be reduced by maximizing grid electricity energy usage and locating engine operation zones which minimize GHG per fuel usage.

## **C.1.2 - Other Optimization Parameters**

### **C.1.2.1 - Performance**

It is desirable for the vehicle to automatically determine when the driver wants extra power available at the wheels, so that both diesel and electric powertrains can be used in parallel for maximum acceleration. For this requirement a special performance mode has been added to the controller, with special entry conditions that have yet to be designed.

### **C.1.2.2 - Driveability**

CS mode should be designed to feel identical to the CD mode in terms of wheel torque per accelerator pedal depression percentage

### **C.1.2.3 - Noise, Vibration, and Harshness**

The PTTR architecture prevents the vehicle from regenerating electrical energy to the pack while stopped. Once at speed, the vehicle must regenerate more vigorously to anticipate the vehicle being unable to be charged while stopped. This poses an NVH issue while at speeds between 10-30mph where the driver is not used to an engine running at 60% throttle without pushing the accelerator pedal.

Torque holes during gear shifts while under power from the engine should theoretically be “filled in” with the electric powertrain, however due to CAN transmission delays this effect is not 100% effective.

### **C.1.3 - General Rules**

There are a few general rules that should be emphasized by the control algorithms in all drive modes. These rules should be followed to improve upon all of the control strategy optimization

#### **C.1.3.1 - NEVER use hydraulic brakes to slow the vehicle**

Whenever the driver is forced to rely on the hydraulic brakes, the decrease in kinetic energy of the vehicle is transformed directly into useless thermal energy. The control strategy should attempt to utilize the electric drivetrain to regenerate as much of the kinetic energy as possible from deceleration events. This rule will improve upon all E&EC optimization parameters, but care must be taken to avoid unsafe braking situations.

#### **C.1.3.2 - Maximize reliance on grid electricity energy for the strategy**

Maximizing the usage of the high-voltage pack will improve upon all of the E&EC optimization parameters.

#### **C.1.3.3 - Avoid startling the driver**

There are many “ramps” that are based on vehicle speed or based on time which smoothly transition between two separate torque commands. This avoids startling the driver and improves drivability.

## **C.2 - Control Algorithm Top Level Modes**

The highest level of the torque controlling algorithm can be seen in Figure 46 below. There are two main modes of operation to satisfy the requirements of the torque control strategy. These modes are Charge Depleting (CD) and Charge Sustaining (CS). To transition from CD to CS mode, the state of charge on the ESS must be equal to a Target SOC. The CS state will attempt to maintain the ESS SOC somewhere near this target, with some bounds.

There is an IceOnly state which is used as a fault mode if the electric powertrain ever goes offline. There is also a performance mode state that currently has no natural transitions, but will be used to provide maximum tractive power to the road when desired.

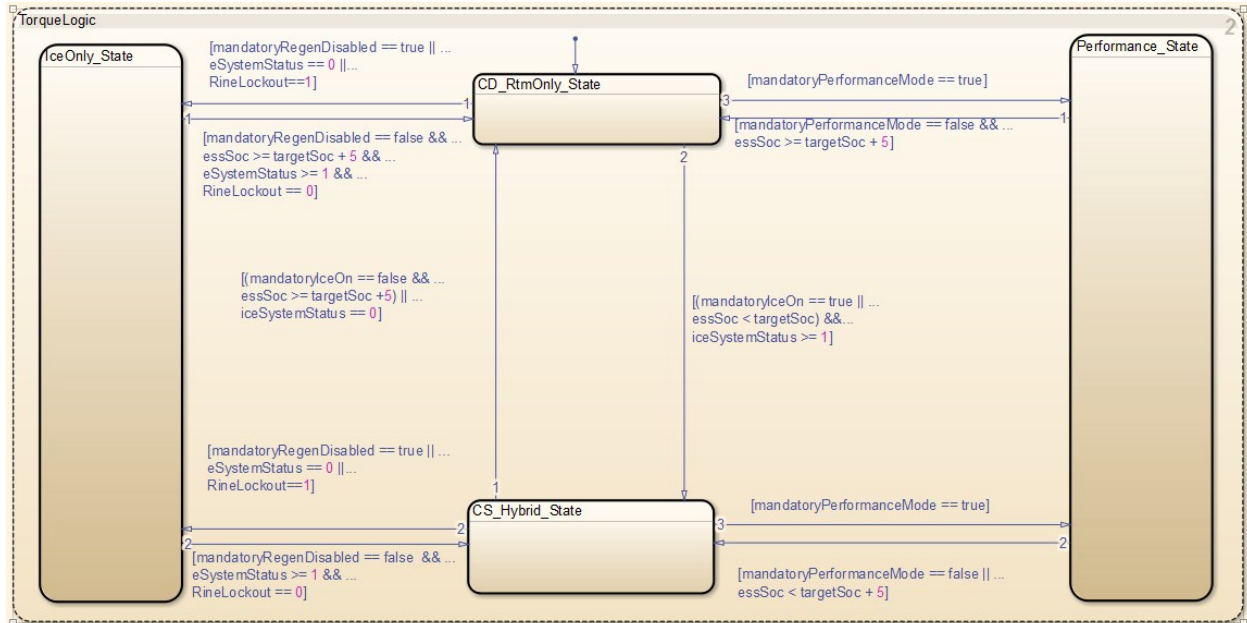


Figure 46: Torque Logic Chart

## C.2.1 - Charge Depleting State

In CD mode the vehicle will operate as a pure EV in order to maximize grid electricity usage. During short trips, petroleum usage will be nearly completely displaced with this strategy. Statistically using SAE J2841 (J2841, 2005), the all-electric range of ~50 miles will reduce the number of miles driven on petroleum energy by 70%. Because the torque out of the engine is effectively 0 at all times while the transmission is in neutral, 100% of the driver intended wheel torque is passed to the electric powertrain.

## C.2.2 - Warmup State (Within CS State)

Upon transition to CS mode, the vehicle will enter a Warmup Strategy. This strategy is meant to minimize the excessive criteria emissions typically associated with cold-starting an internal combustion engine.

Currently, the strategy will idle while the vehicle is stopped, and will provide 30% throttle to propel the vehicle once at speed. As always, the electric motor will provide positive or negative torque to force the effective wheel torque to match the driver's demand.

Figure 47 below shows that the Warmup State within the CS state chart is currently a manually enabled state. For final builds, this state should be automatically utilized when naturally transitioning to charge sustaining mode. When using the charge sustaining switches, it may be necessary to skip the warm-up state.

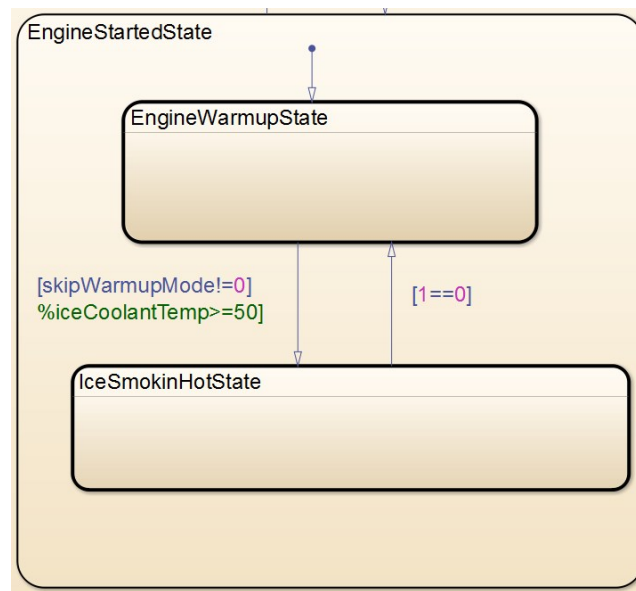


Figure 47: Warmup State is currently a manually enabled state

### C.2.3 - Charge Sustaining State

The charge sustaining strategy is by far the most complicated part of the torque control logic. It is responsible for determining the most effective torque split between the different powertrains that balances all of the emissions and energy consumption requirements. This mode will adjust the torque request that is given to the diesel engine and allow the electric motor to either take up the “slack” or regenerate the excess power. This is accomplished with the engine torque feedback and the transmission gear ratio signals via the following equation:

$$RTM_{Torque\ Command} = WheelTorqueRequested_{Driver} - WheelTorqueAchieved_{Engine}$$

With this difference equation, no matter what the diesel engine is commanded to do the electric powertrain will force the wheel torque to match that which would otherwise be seen in CD mode. Because the electric drivetrain has an almost instant torque response at all times, this is a very effective way of matching calibration between CS and CD modes. The only issue with this strategy is that the torque feedback signal from the diesel engine is only an estimated value, and may be different from the actual torque achieved.

There are several general rules that are followed in the design of this mode.

- Keep the SOC window as small as possible. This will ensure maximum grid electricity usage by allowing for a smaller Target SOC to be chosen by the controller.
- Avoid providing power through the engine while the torque converter is not locked
- Keep  $\frac{\partial Throttle}{\partial t}$  low to avoid very off-center torque/speed operating regions.
  - Very high torque and very low speed will be encountered if engine tip in is too fast
  - Very low torque and high speed will be encountered if engine tip out is too fast
- Only request throttles at or below a “target throttle” requests to the engine
  - Because the total tractive power available to this vehicle is much larger than it needs to be for the EcoCAR2 drive cycles, during non-performance-mode operation we want to limit the diesel engine so that it does not operate at excessively high throttle requests
  - The “target throttle” shall be determined by an overlay of the efficiency and emissions maps on a torque/speed basis
- Once at the target SOC, the vehicle should not convert energy from fuel to stored electric energy unless the losses associated with doing so are offset by the efficiency gain of the engine’s new operating point. Note – this scenario is encountered very rarely, but can be simply calculated with efficiency maps for each energy conversion.

## **C.2.3.1 - Charge Sustaining Propulsion Modes**

While within the Charge Sustaining state, the overall vehicle powertrain can operate in a variety of modes:

1. Accelerating
2. Cruising
3. Coasting
4. Decelerating
5. Stopped
6. Minimum SOC

The total tractive force request from the driver is compared to the total road load forces to determine which state the vehicle is in.

### **C.2.3.1.1 Accelerating – Tractive Force Request is greater than Road Load**

Provide 100% of the torque request with the electric powertrain at 0mph to avoid torque converter losses. As soon as the transmission's torque converter is no longer slipping, begin ramping in engine throttle. At this point the ESS should be losing SOC. Do not allow the engine to throttle beyond the target throttle, as the vehicle will have the opportunity to regenerate during cruising, coasting, and braking.

### **C.2.3.1.2 Cruising – Tractive Force Request equals Road Load**

#### ***Below Target SOC***

At steady state speed, the engine command will slightly out-weigh the driver intended wheel torque. The offset in the command is linearly related to  $SOC_{Target} - SOC_{ESS}$ . This will cause the electric powertrain to regenerate the difference back to the high-voltage pack in preparation for the next acceleration event. Do not throttle the engine beyond the target throttle.

## ***At Target SOC***

Once at the target SOC, the engine wheel torque should exactly match the driver intended wheel torque request. No regeneration should be performed unless the losses associated with the conversion from fuel to stored electrical energy are more than 100% offset by the efficiency increase of the engine's operating region. Do not throttle the engine beyond the target throttle.

### **C.2.3.1.3 Coasting – Tractive Force Request is close to zero**

This mode is not implemented yet.

With no pedal depressed, this mode should allow the engine to cut fuel, and should ramp in some arbitrary amount of electric regen to provide some coasting deceleration. Note – the more pronounced this effect is, the less the driver will want to press the hydraulic brakes! Care may need to be taken on how this affects drivability.

### **C.2.3.1.4 Decelerating – Tractive Force Request is less than zero**

When the brake pedal is depressed, the engine should quickly cut throttle to zero. The electric powertrain shall still satisfy the difference equation of wheel torque demand, so that the brake pedal requests negative torque.

### **C.2.3.1.5 Stopped – Vehicle is stopped, brake is depressed**

Engine continues to idle to keep the exhaust hot, RTM gives no torque. May consider implementing an auto-stop feature?

### **C.2.3.1.6 Minimum SOC – ESS is at a pre-determined minimum**

Do not allow positive propulsion through the RTM, only allow regen.

## **C.2.4 - Other Modes**

### **C.2.4.1 - Performance State**

No natural transition into this state. Torque request is sent to both powertrains, resulting in double the “pedal feel” as in all other modes.

### **C.2.4.2 - Ice Only State**

This is a fault mode in case the electric powertrain goes offline and we are unable to provide or regenerate power through the RTM.

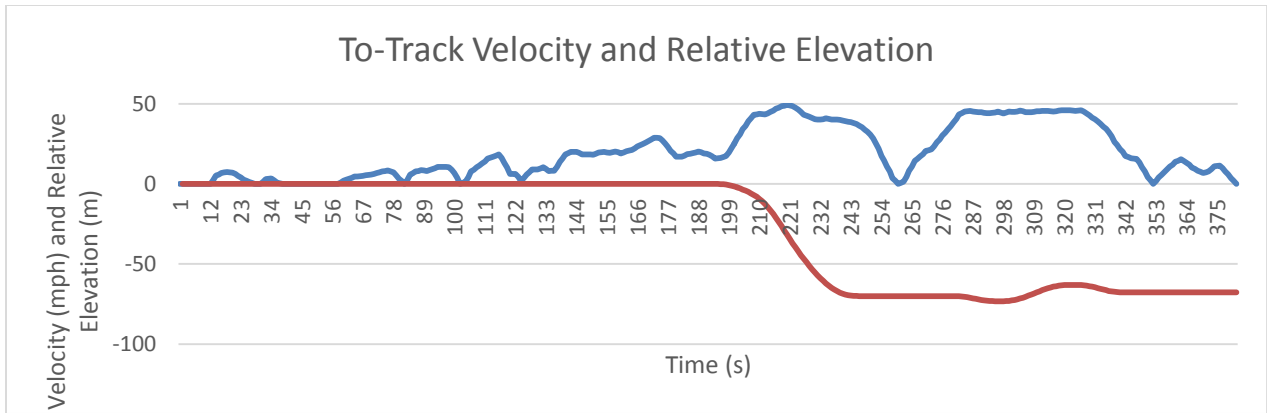
## **C.3 - Results from Emissions Testing Event 2014**

The following analyses are based on the results from the Emissions Testing Event at Argonne National Laboratory. At this event the UWEC2 team was able to test a variety of operating conditions:

1. Warmup Cycles for emissions
2. Steady-State engine operation for emissions
3. Charge-sustaining mode for debugging, energy consumption, and emissions
  - a. To-Track EV, EEC in EV and in CS
4. 0-60 and 50-70 performance tests

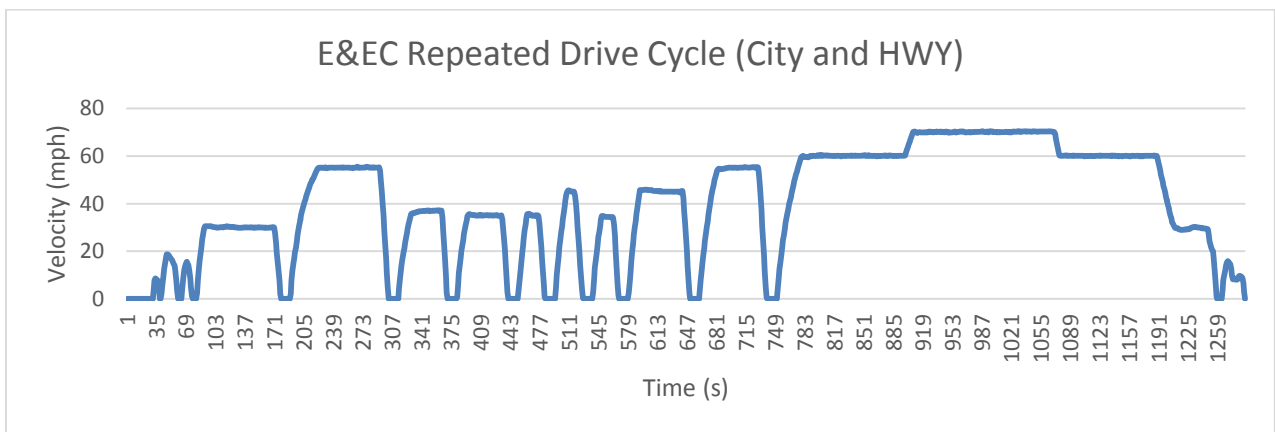
### **C.3.1 - Drive Cycles Used at ETE**

Year three competition will not use the EcoCAR2 4-cycle velocity trace blend, instead it will use a custom drive cycle that will approximate similar driving conditions. The custom trace consists of three sections: ToTrack, EEC (repeated 7 times) and FromTrack. These drive cycles are Figure 48, Figure 49, and Figure 50 below.



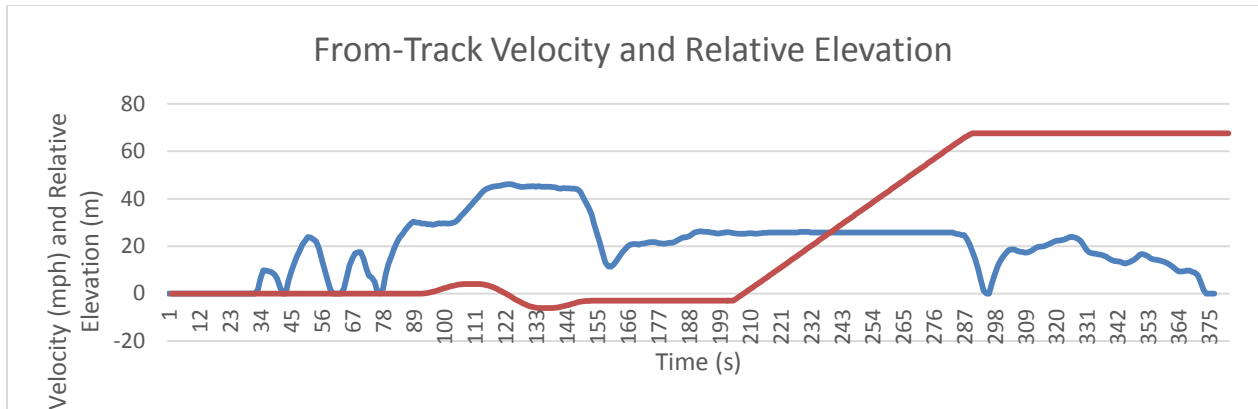
**Figure 48: To Track Drive Cycle with Elevation**

The ToTrack cycle consists of relatively slow driving on Milford Proving Grounds public roads. The drive consists of one significant downhill coasting halfway through, which can be used to regenerate energy from.



**Figure 49: EEC "CityHighway" Cycle**

The EEC "CityHighway" cycle is the cycle that is repeated seven times. This cycle makes up the bulk of the energy consumption of the EEC event.



**Figure 50: From Track Drive Cycle with Elevation**

The FromTrack cycle is the drive from the circle track to the charging station, driven on public roads. The significant elevation change must now be driven upwards.

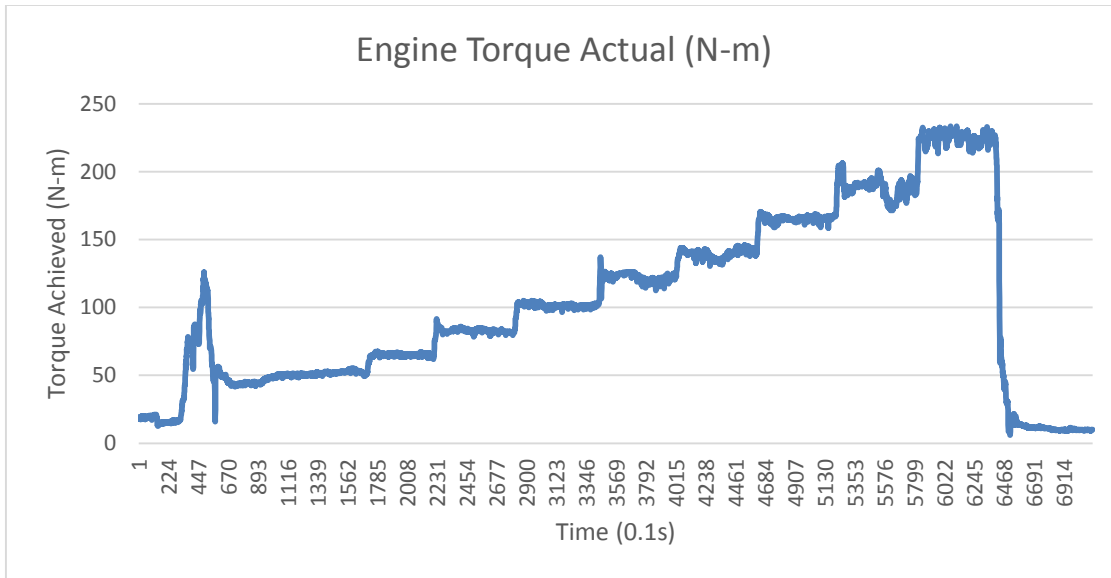
### C.3.2 - Cold Start Tests

Refer to MSME thesis document created by Trevor Crain, June 2014 for analysis of cold-start strategy emissions comparisons.

### C.3.3 - Engine Steady State Raw Data

**WARNING: THIS DATA IS ONLY APPROXIMATELY RELEVANT FROM 1400 TO 2300rpm, AND FROM 50 TO 225NM TORQUE.** Outside of these bounds the maps are extrapolated.

Engine steady-state emissions results were obtained by setting the dynamometer into speed mode at a constant velocity, then requesting steady-state torque outputs from the engine for 60 seconds or until criteria emissions measurements settled. At 1400 RPM, an example torque request profile is shown in Figure 51 below in 60 second increments.



**Figure 51: Steady state tests, one minute each**

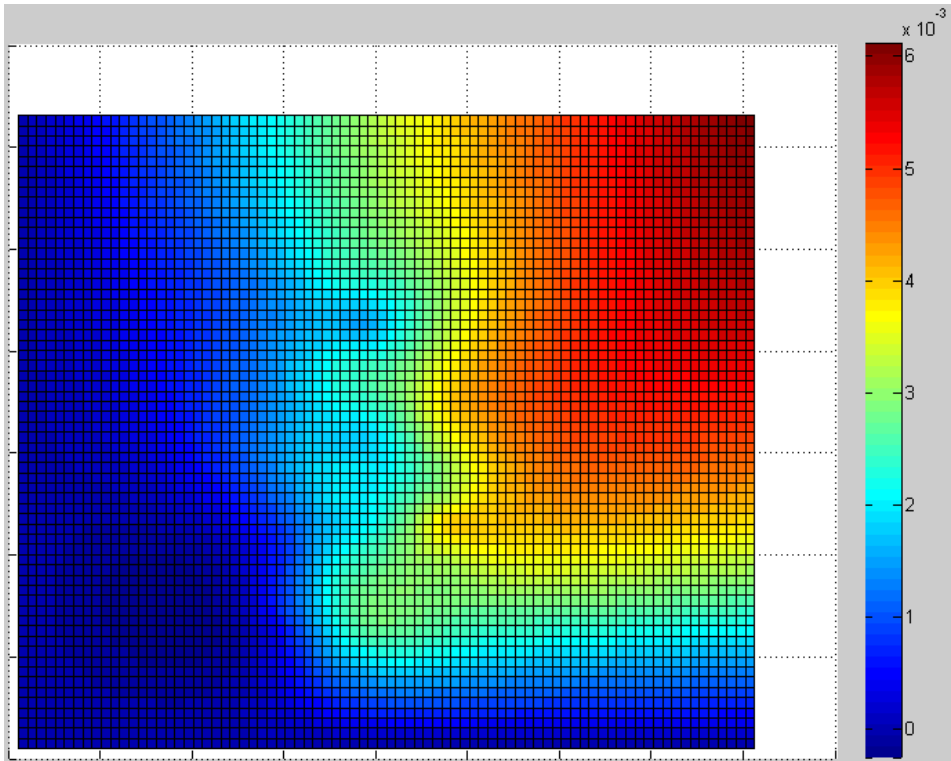
At the end of each 60 second segment, criteria emissions measurements are read from the SEMTECH sensors (in ppm). Density and flow rate from the SEMTECH are used to convert the ppm measurements to grams per second. Sensors for CO<sub>2</sub>, CO, NO, NO<sub>2</sub>, THC, and O<sub>2</sub> are recorded for the following map locations:

1400 RPM	1850 RPM	1730 RPM	2310 RPM
Torques (N-m)	Torques (N-m)	Torques (N-m)	Torques (N-m)
53.5	60	70	108
65	74	83	88
83	90	100	118
102	108	118	139
124	127	137	165
141	150	160	
165	175	190	
188	206	224	

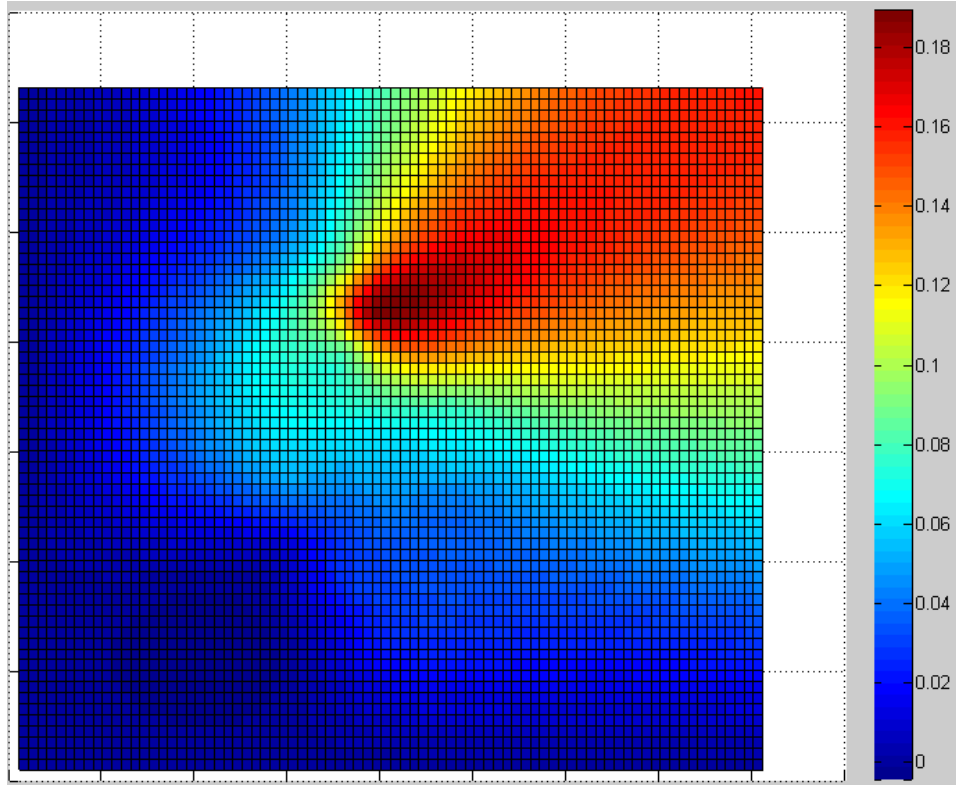
225			
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These points are interpolated/extrapolated to create two dimensional steady state operating maps of engine criteria emissions.

The extrapolated maps range from [0,0] to [310, 4000] (Torque N-m, RPM). The emissions value associated with the third dimension of the map is in units of grams per second. All source data for these maps can be found on the UWEC2 File Server.



**Figure 52: Torque vs Speed CO Emissions Map**



**Figure 53: Torque vs Speed NOx Emissions Map**

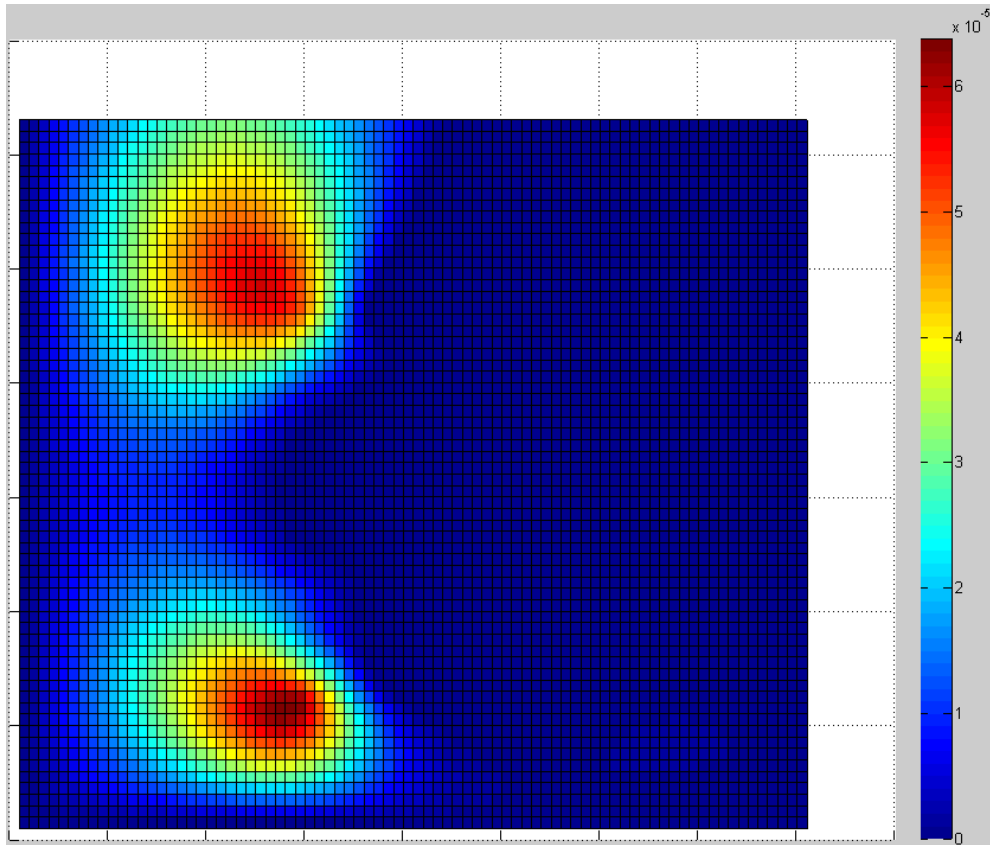


Figure 54: Torque vs Speed THC Emissions Map

### C.3.4 - Criteria Emissions Maps

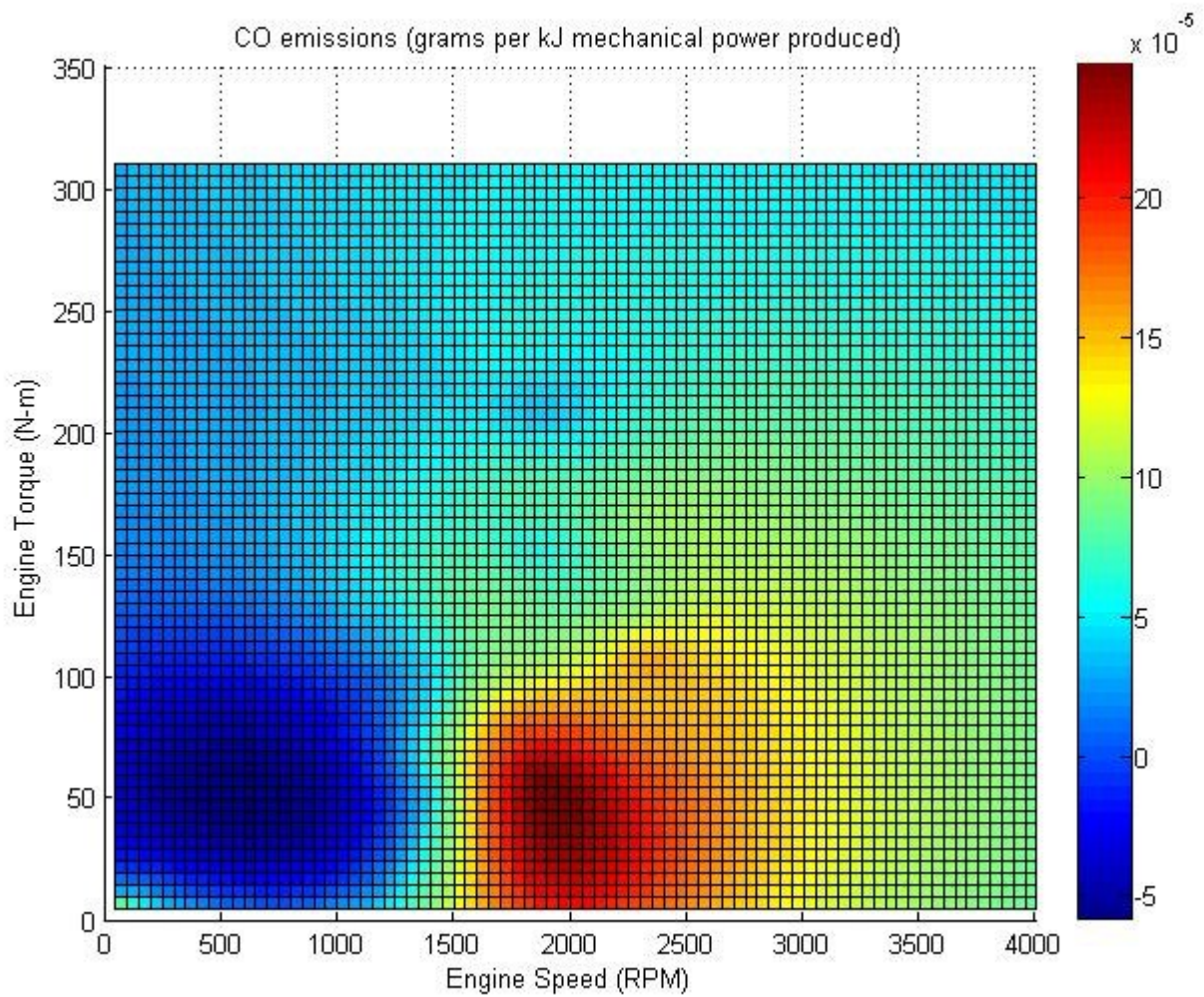
**WARNING: THIS DATA IS ONLY APPROXIMATELY RELEVANT FROM 1400 TO 2300rpm, AND FROM 50 TO 225NM TORQUE.** Outside of these bounds the maps are extrapolated. See ETE results for exact data points.

Emissions will be scored at Year 3 Competition by the following equation, with each emission variable in grams/km.

$$Total\ Criteria\ Emissions\ Score = \frac{1}{\sqrt{\frac{CO^2}{10} + THC^2 + NOx^2}}$$

Because tractive power generated by the ICE can be partially regenerated by the high-voltage energy storage system, it is more useful to put criteria emissions in terms of grams per kJ of power output from the engine. Using these units will be helpful in determining a steady state loading target to minimize emissions.

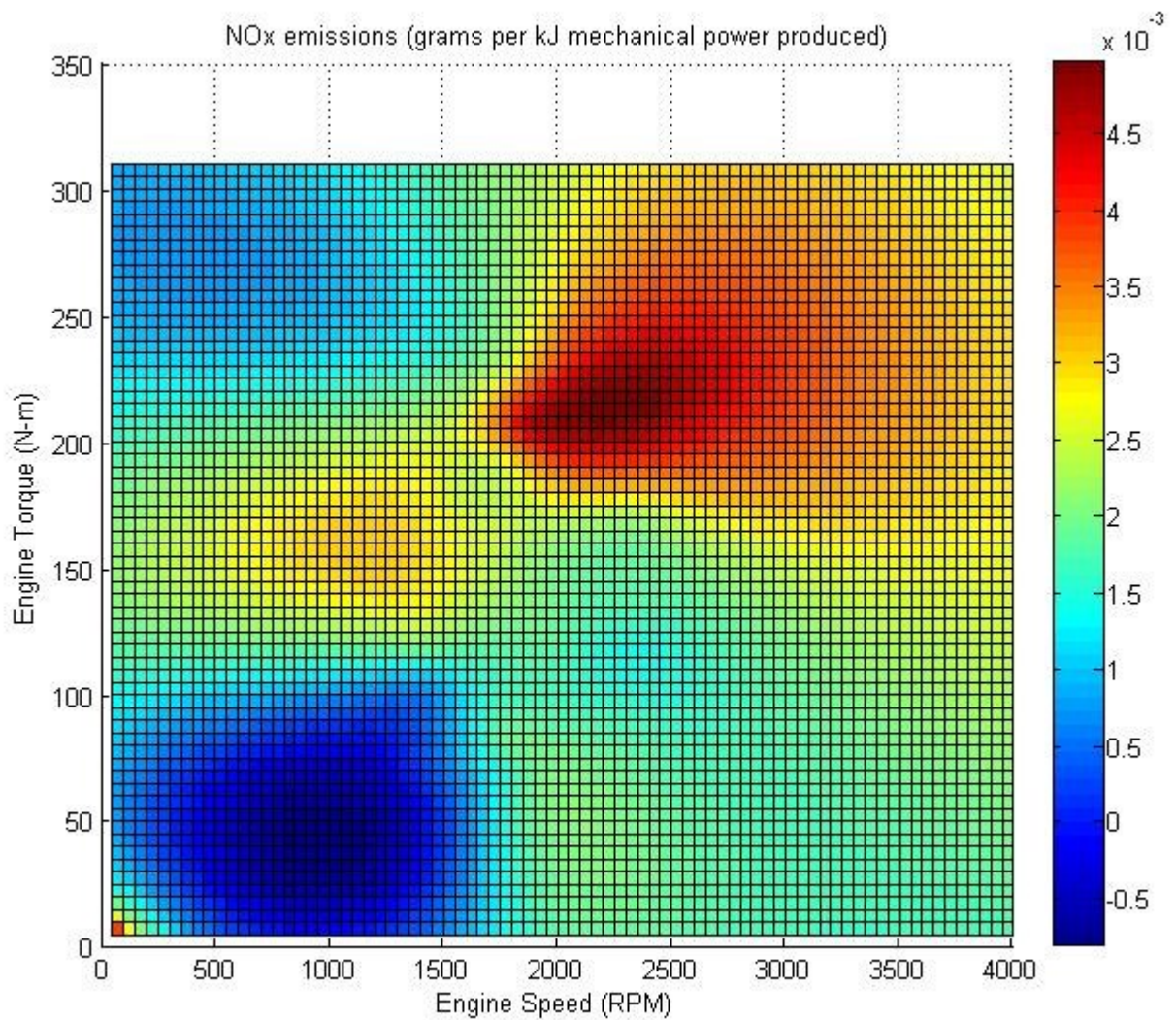
Converting the above maps to a per kJ of mechanical power basis:



**Figure 55: CO Emissions per kJ of Engine Power Output**

These results suggest that high engine speeds and low torque requests release a lot of carbon monoxide emissions per kWh of power supplied. It is desirable to operate in high-torque regions to minimize CO during steady-state operation.

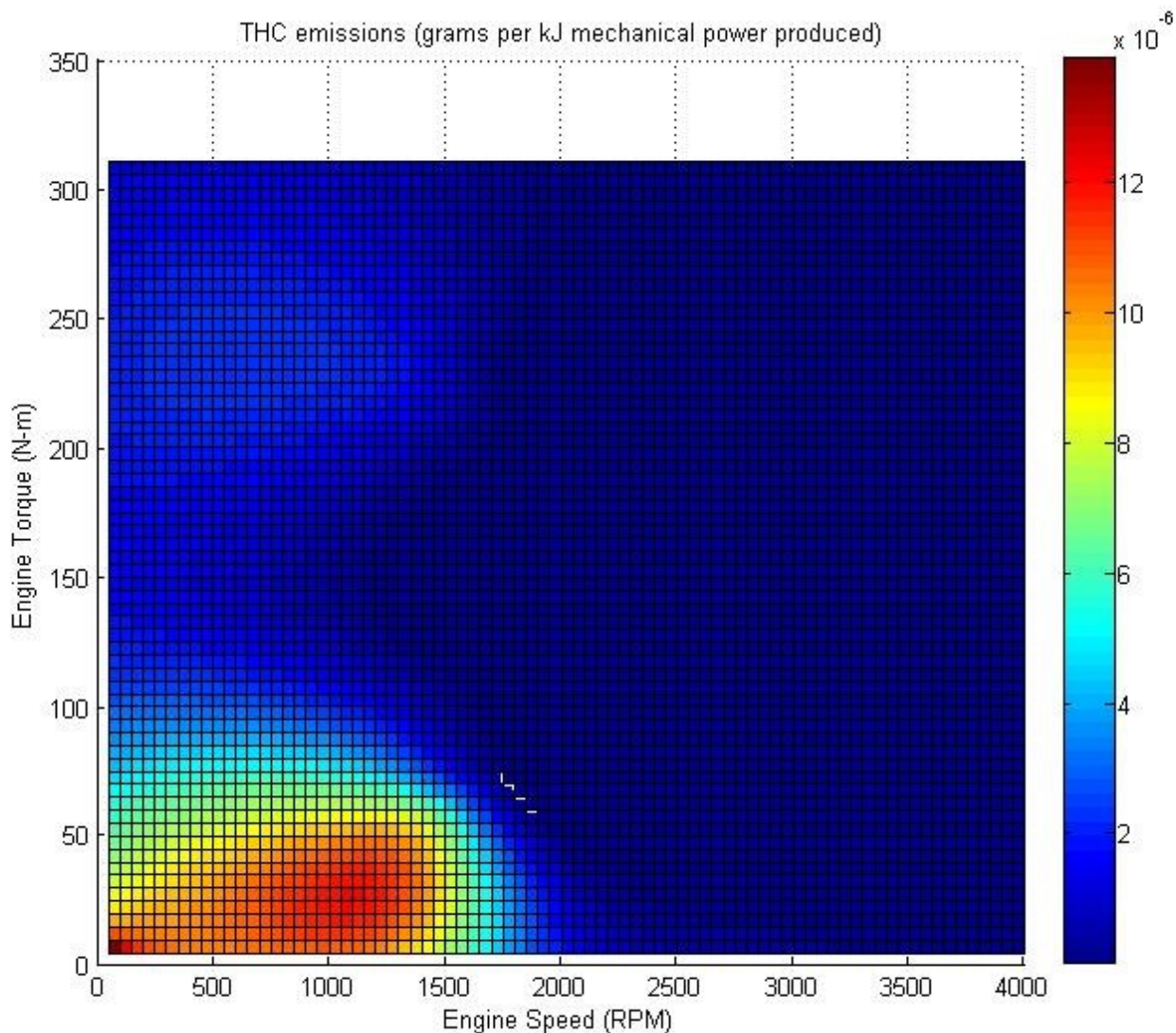
The heavy CO-emitting region may be seen under quick tip-out scenarios, which would drop torque output before the engine speed and transmission have time to respond.



**Figure 56: NOx Emissions per kJ of Engine Power Output**

The NO<sub>x</sub> emissions map suggests that generally high-torque results in more NO<sub>x</sub> emissions. The magnitude of NO<sub>x</sub> emissions are 2 orders of magnitude higher than the peak CO emissions, and 3 orders of magnitude higher than the peak THC emissions while at steady state

Given the way that the EcoCAR2 rules are designed around Urea Injection Aftertreatment systems, it may be possible to rely on the aftertreatment alone to handle NO<sub>x</sub> emissions. From general results quoted from Bosch and EcoCAR2, a NO<sub>x</sub> reduction of >90% may be possible. If 90% is expected, NO<sub>x</sub> are still an order of magnitude larger than CO and 2 orders of magnitude larger than THC. It is extremely important, therefore, that this system be functioning as well as possible for competition. It may be desirable to avoid the NO<sub>x</sub> saturated zones from this graph in addition to performing the urea injection aftertreatment.

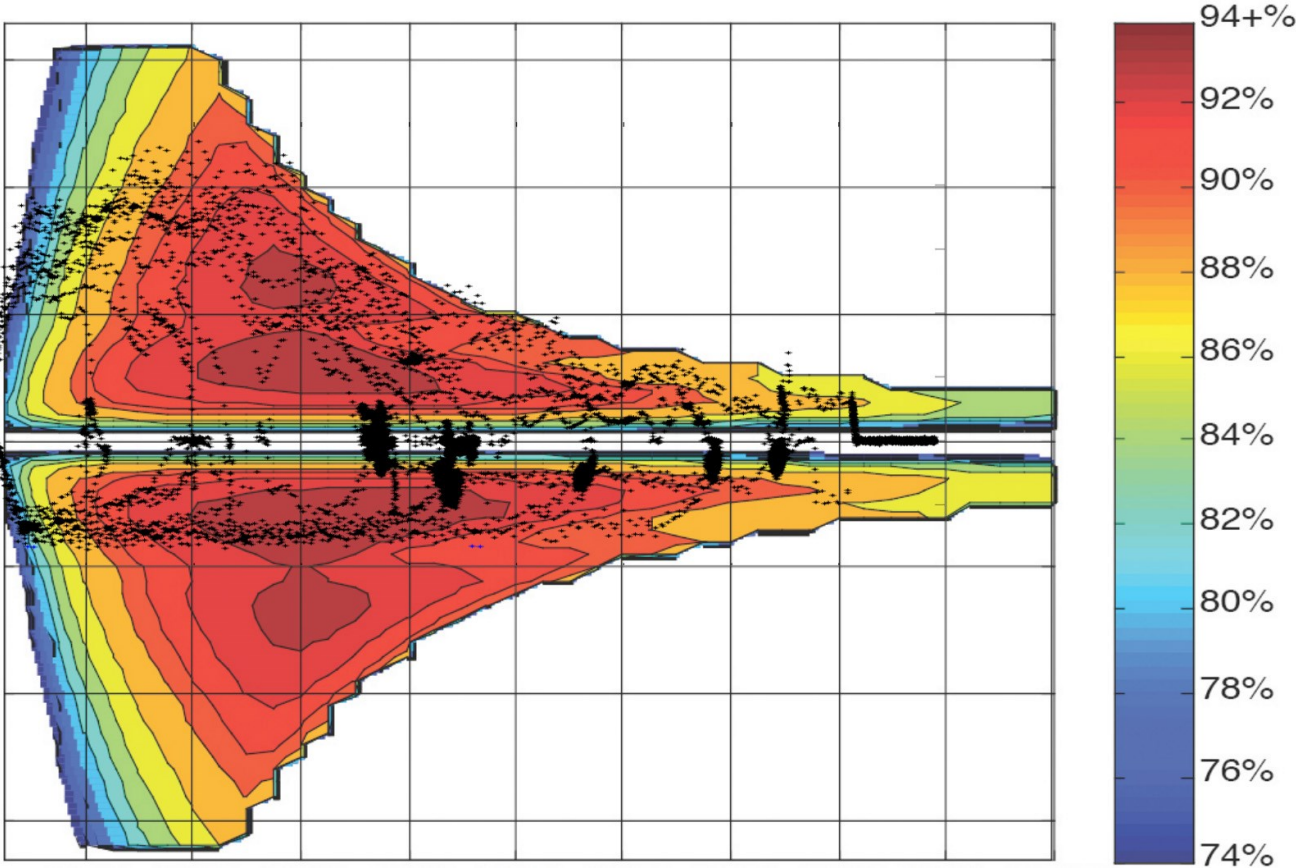


**Figure 57: Total Hydrocarbon Emissions per kJ of Engine Power Output**

Total unburned hydrocarbons is largely seen at very low RPM, especially under very low torque requests. These regions are seen sometimes when tip-in is very fast, when torque rises quickly but engine speed has not yet responded.

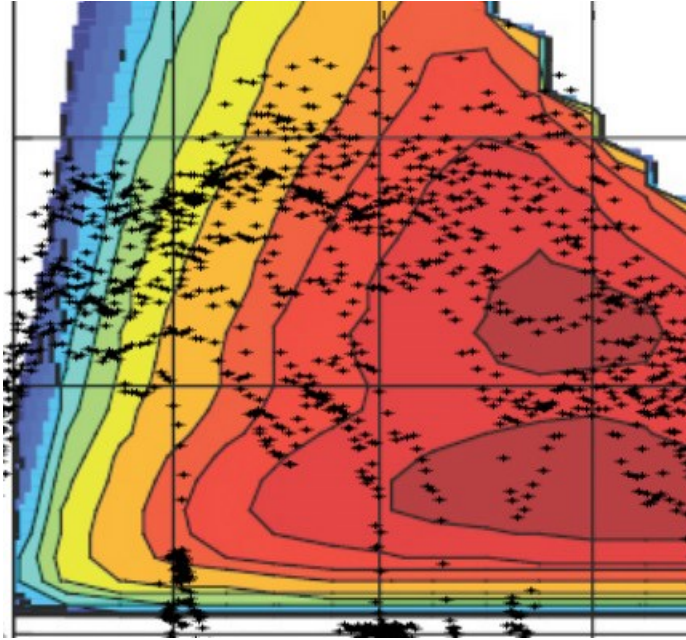
### C.3.5 - Charge Sustaining Operation Points

Figure 58 below shows the operating points of the electric motor during a single EEC “City Highway” cycle in charge sustaining mode. This figure shows the propulsion, braking, regeneration, and erroneous zones of operation during the test.



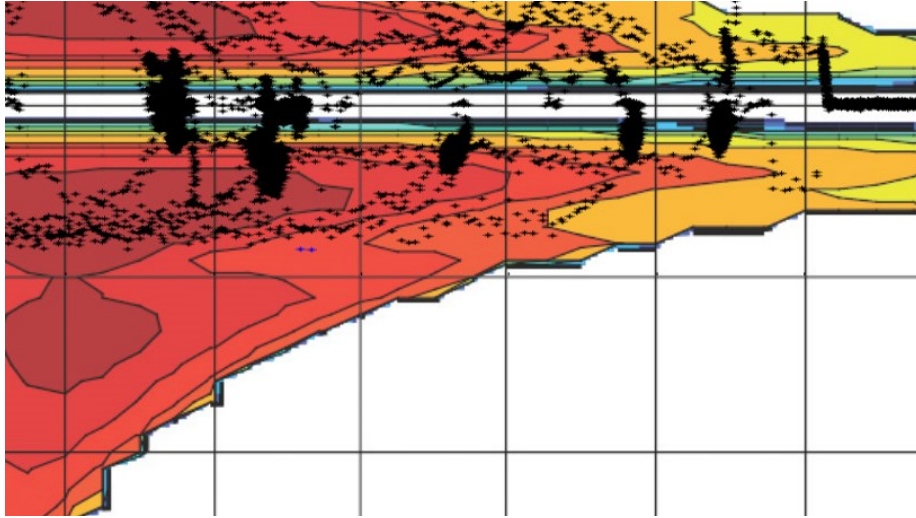
**Figure 58: Electric Motor Operating Points during Charge-Sustaining EEC Cycle on Dyno**

Looking closely at the low-speed positive propulsion requests on the motor, it is obvious that from a standstill, the electric motor is being forced to operate in very inefficient regions due to high torque demand. If desired, an artificial limit could force the operating regions at very low speeds to more efficient allowable requests.



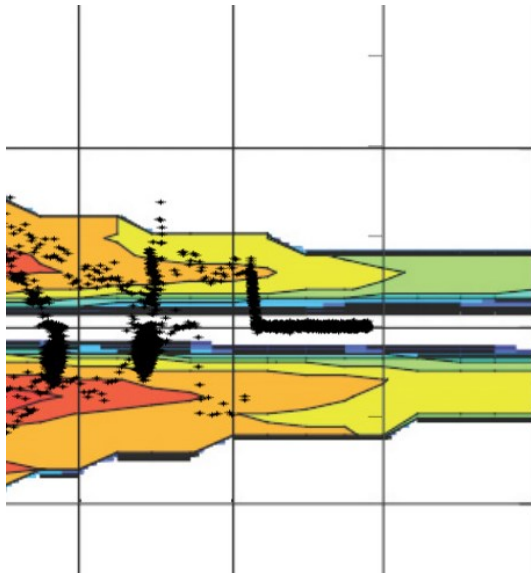
**Figure 59: Acceleration Operating Points**

The dense zones of operating points seen below the X axis in Figure 60 below are due to the “steady state” nature of parts of the EEC “City Highway” drive cycle. The regeneration efficiency could be improved on the electric motor if the engine is loaded slightly more, increasing the negative torque applied to the electric drivetrain. Care must be taken to not increase losses on the engine for this efficiency increase, however.



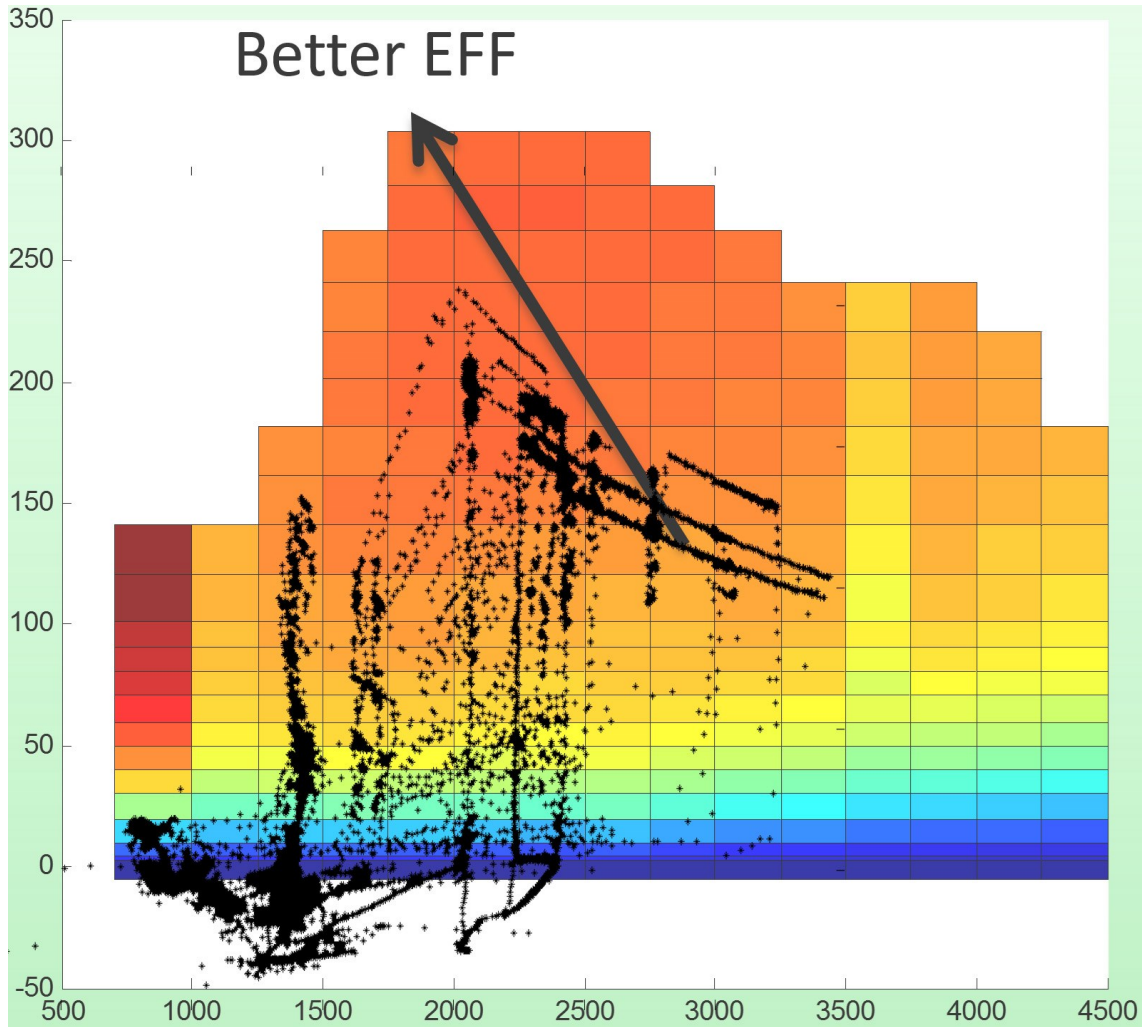
**Figure 60: Resulting Regeneration Zones**

At speeds over 65mph the electric motor is demonstrating an erroneous inability to provide any torque to the road, causing a thick line at 0 N-m at those speeds. Shown in Figure 61 below. This needs to be fixed.



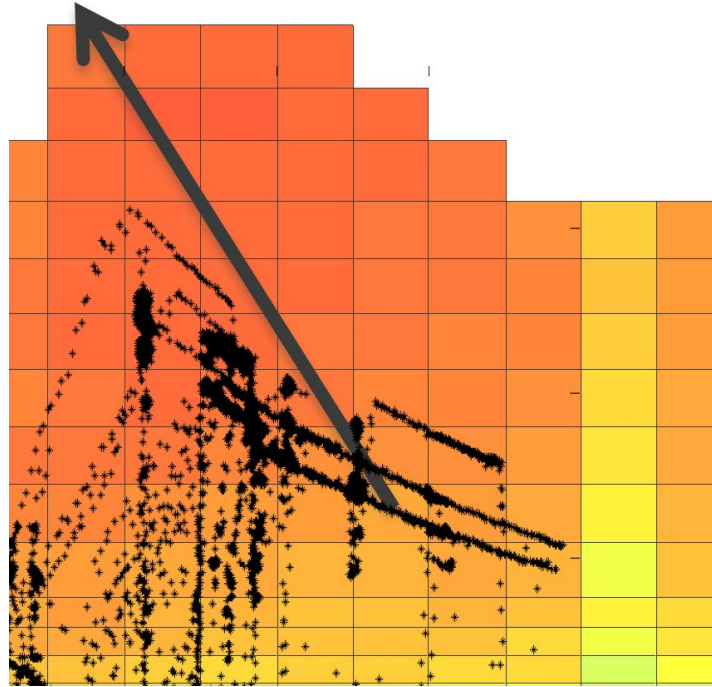
**Figure 61: High speed zero torque**

Figure 62 below shows the operating points of the biodiesel engine overlaid on its efficiency map for observation. This overlay demonstrates the idling, propelling, and engine braking regions of engine operation.



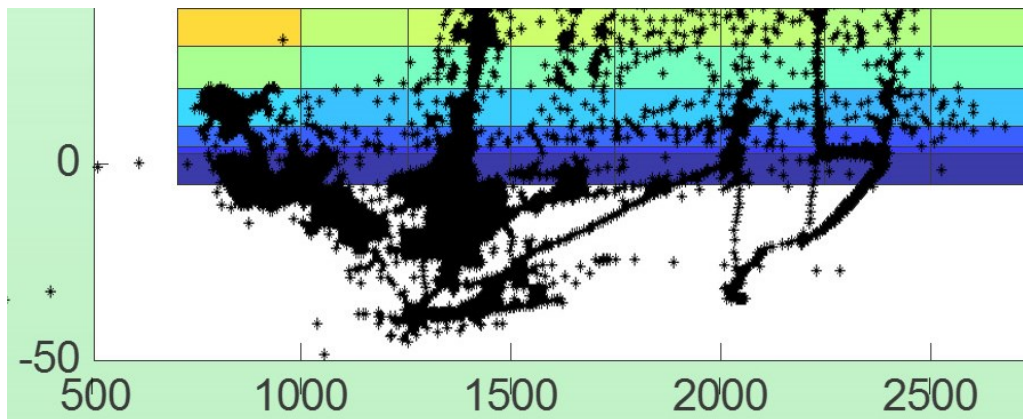
**Figure 62: Engine Operating Points during Charge-Sustaining EEC Cycle on Dyno**

Figure 63 below shows distinct propulsion regions as a result of the engine constant's throttle command during portions of the acceleration events. Slightly emphasized dots are regions of steady-state engine operation at steady speeds.



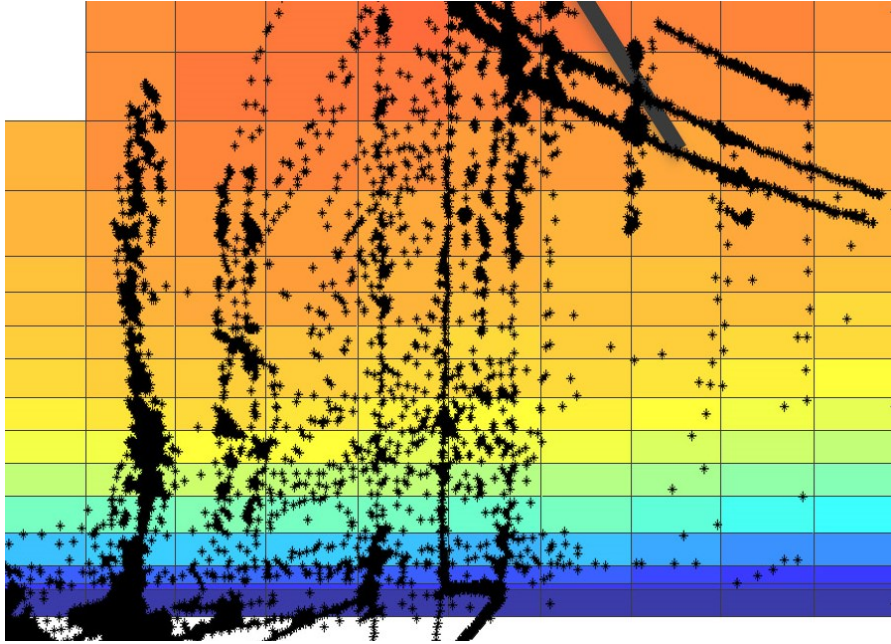
**Figure 63: In Gear propulsion regions**

Figure 64 below shows the idle region (~500-700rpm, positive torque) and the engine braking regions, which extend down to -40 N-m.



**Figure 64: Idle and Engine Braking Regions**

Figure 65 below shows the operating points that are passed transiently during the throttling up of the engine. Also seen in this figure are some vertical columns (1400RPM) that are unexplained at this point.



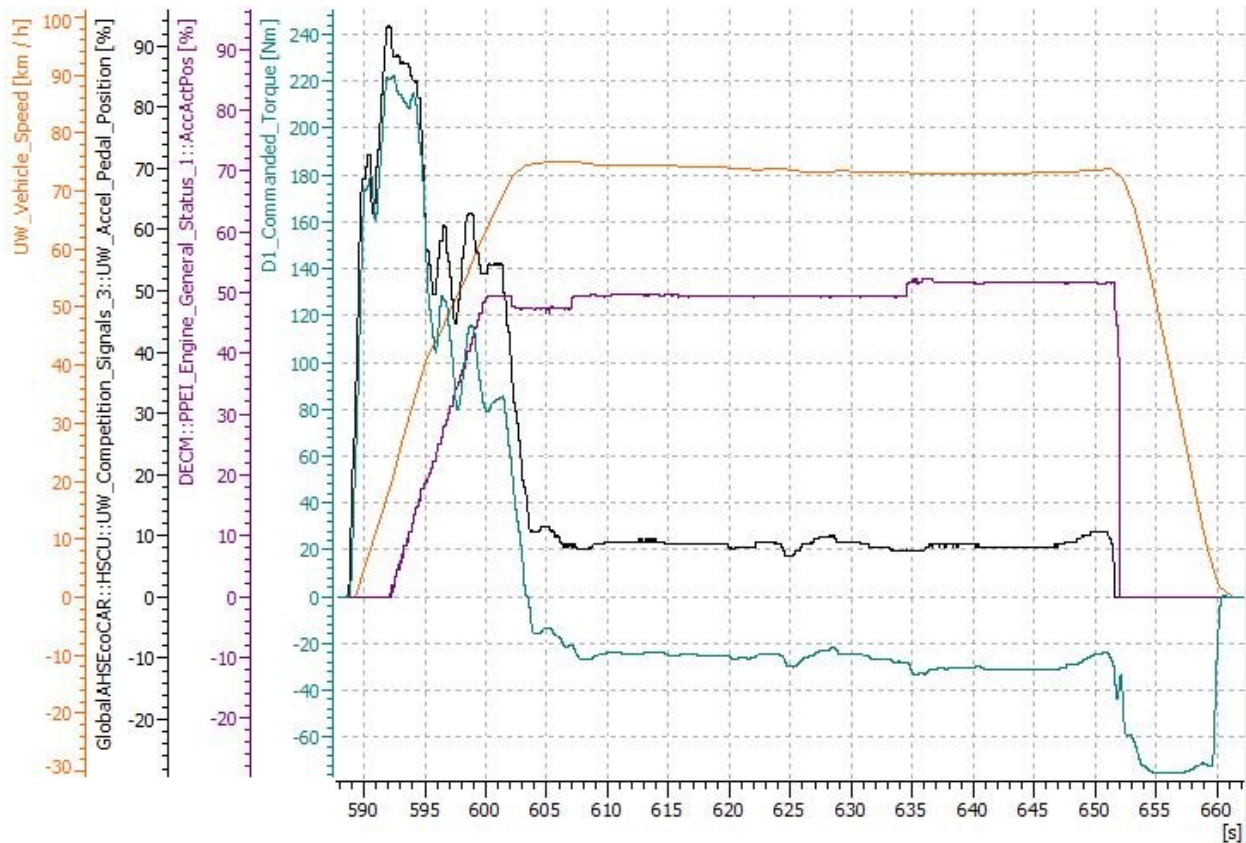
**Figure 65: "Tip in/Out" regions**

It would be extremely useful to develop a way to watch the engine operation during a drive log to see in which situations the engine enters these regions to better understand how to control them.

### **C.3.5.1 - CS Examples of Operation**

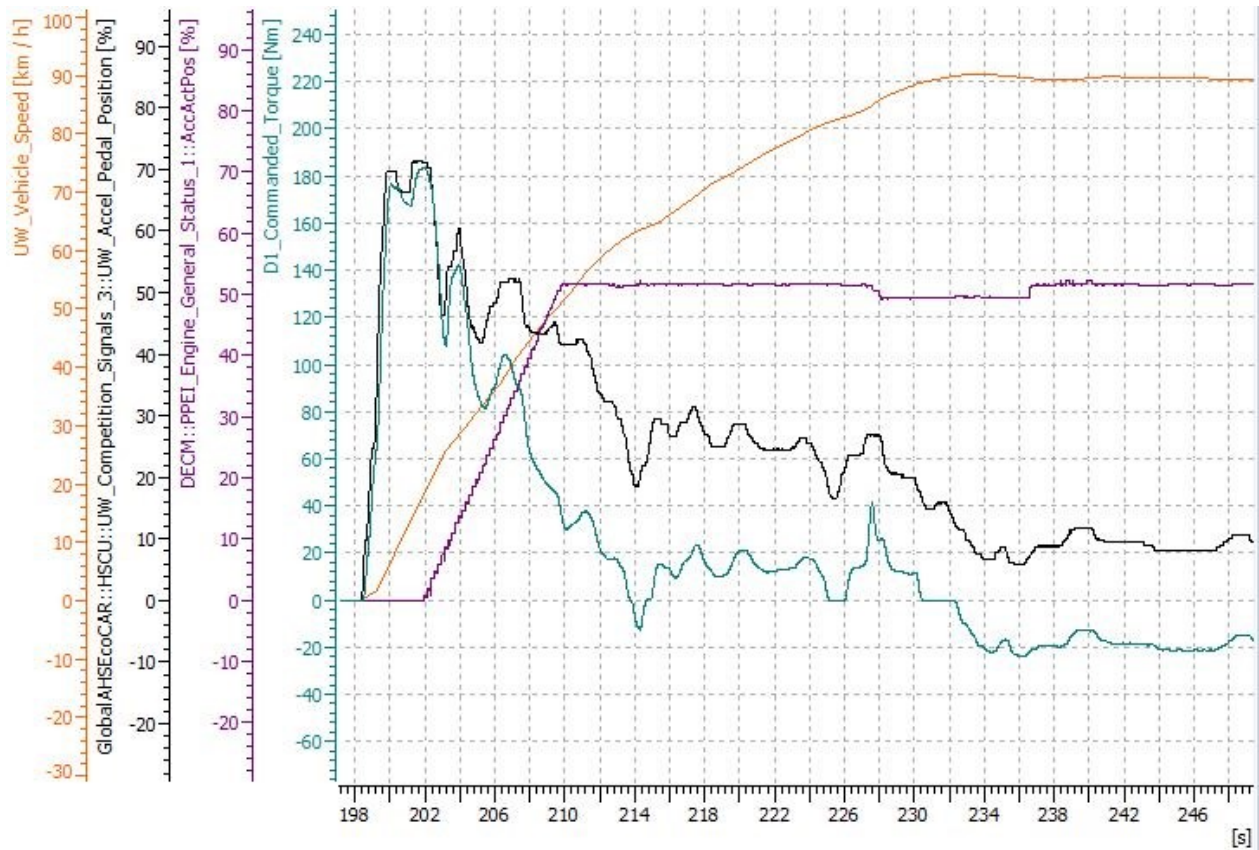
The next few graphs show the Driver Request (black, %), ICE command (Purple, %), and RTM command (Teal, Nm out of 250 max) all normalized with each other. Also included is the vehicle speed (kph, orange). A single acceleration and deceleration's effect on the vehicle powertrains can be seen in Figure 66 below. Aspects of this test to take note of are:

- This test consumed ~1% state of charge on the ESS, then regenerated 1.5% to above the starting value
- The engine begins ramping up at approximately 20kph
- The engine ramps up to a steady state value of ~50%



**Figure 66: Velocity and Powertrain Responses of a single drive**

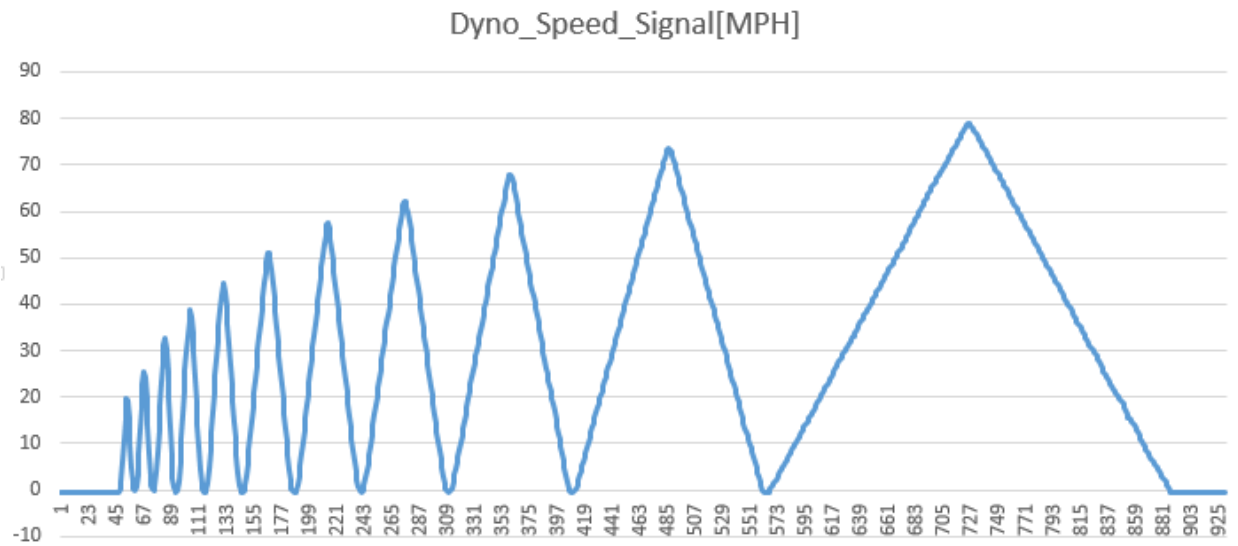
Figure 67 below shows that regeneration to the battery pack is not allowed until the engine has extra power to spare while running at the target throttle. By tuning this target, we can rely on the battery pack to absorb high power demands and only run the engine at or below the target throttle. From this figure you can also see the functioning “wheel torque desired” difference equation controlling the Rinehart, while allowing the engine to remain at a steady target throttle.



**Figure 67: Regen does not begin until there is excess energy to regenerate from the engine**

### C.3.6 - Duoba Cycle Tests

The Duoba cycle is a useful cycle to understand the criteria emissions performance of an engine under dynamic loading. The drive cycle is shown in Figure 68 below.

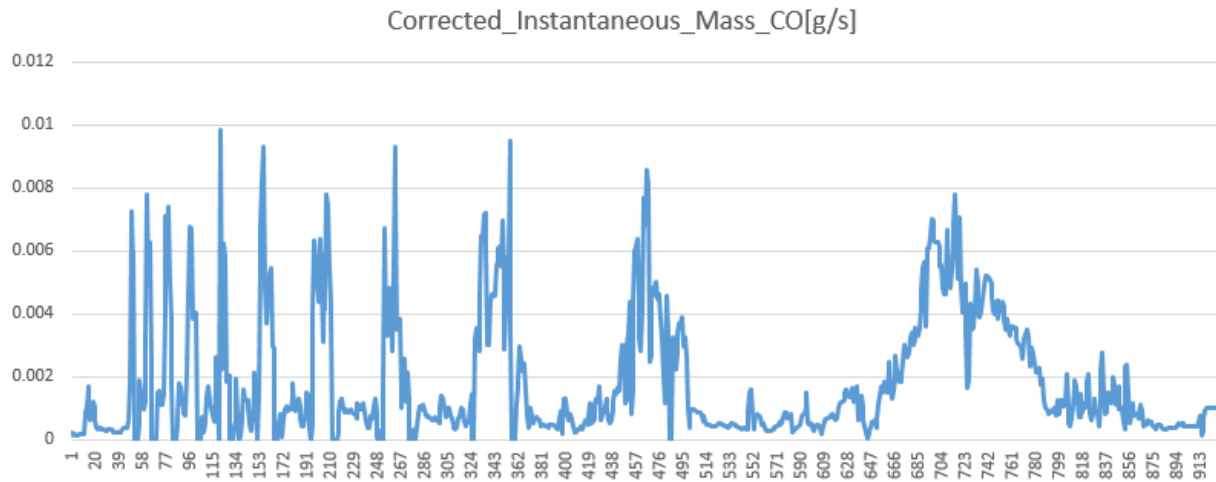
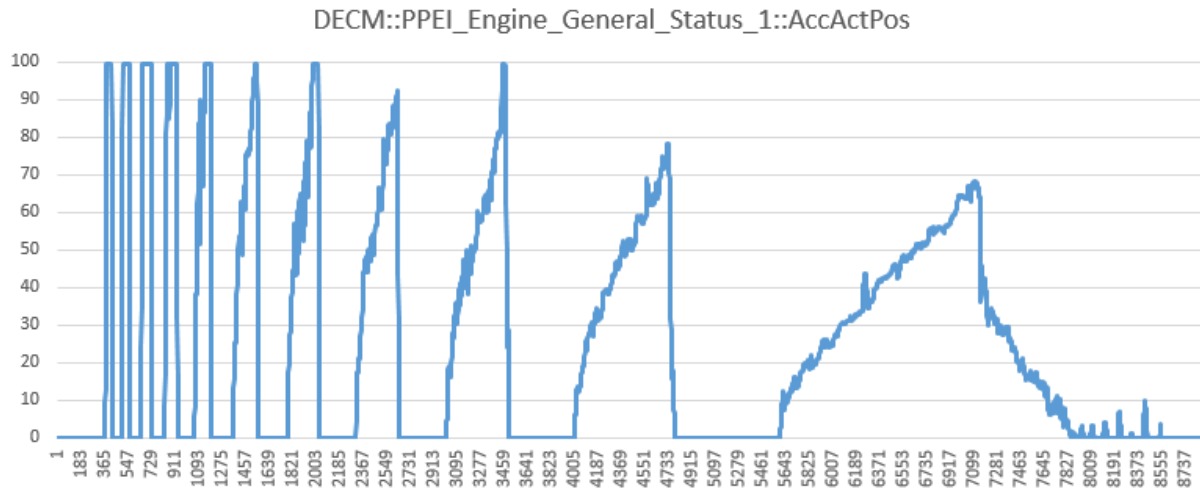


**Figure 68: Duoba Cycle Velocity Trace**

From this data, tentative statements can be made about the “target throttle” that should be chosen for the engine. (DATA TO BE RETRIEVED FROM PATRICK/KEVIN)

It appears that above 40% throttle CO emissions start to ramp up significantly (grams/second). This has to be weighed based on the energy obtained from the fuel to make any recommendations, but CO rate seems to come to a maximum at ~50% throttle.

Because this is a dynamic loading it is difficult to draw concrete conclusions about the justification of the results that are observable, but a significant amount more work should be done to understand the effects of this drive cycle. With more insight, further control strategy optimizations can be made with regard to how the engine is commanded during CS mode.



## C.3.7 - Discrete Issues with Current Controller

### C.3.7.1 - Engine ramp begins too late

Currently the engine throttle starts ramping up at a vehicle speed that is a little bit too high. It is apparent from the gear ratio signal that the torque converter is locked in first gear at about 5kph, but the controller does not begin ramping engine throttle up until 20kph. Because the engine command is 0%, at 10kph the fuel cutoff mode kicks in and starts providing negative torque through the transmission. The result is a very jerky shift into 2<sup>nd</sup> gear as soon as throttle is applied.

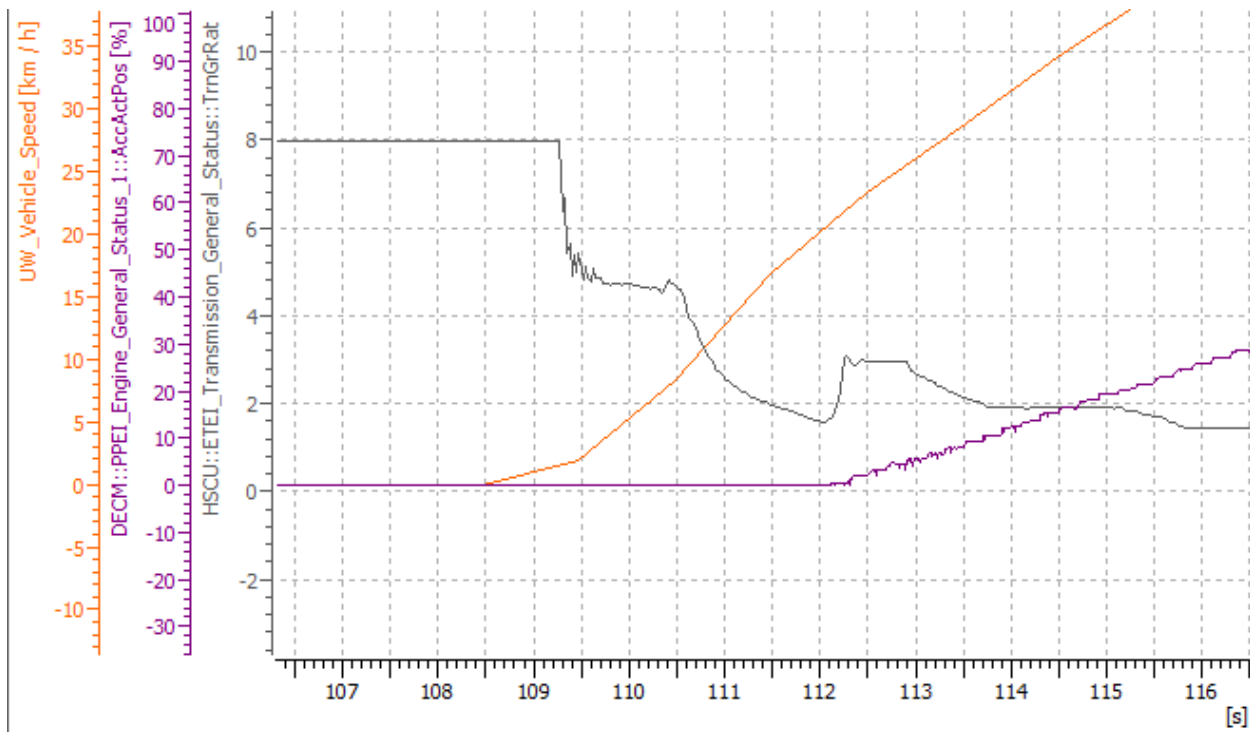


Figure 69: Engine throttle starts ramping too late

### C.3.7.2 - RTM control – Braking torque

Driver requested brake torque needs to be included in the difference equation that commands the RTM, otherwise as soon as the brake pedal is depressed the previously commanded regen will be removed from the RTM and the driver feels an initial forward lurch. Figure 70 below demonstrates this effect. With RTM commanded regen on its way downward, the brake pedal signal causes the state to shift and no longer be watching the Ice torque output.

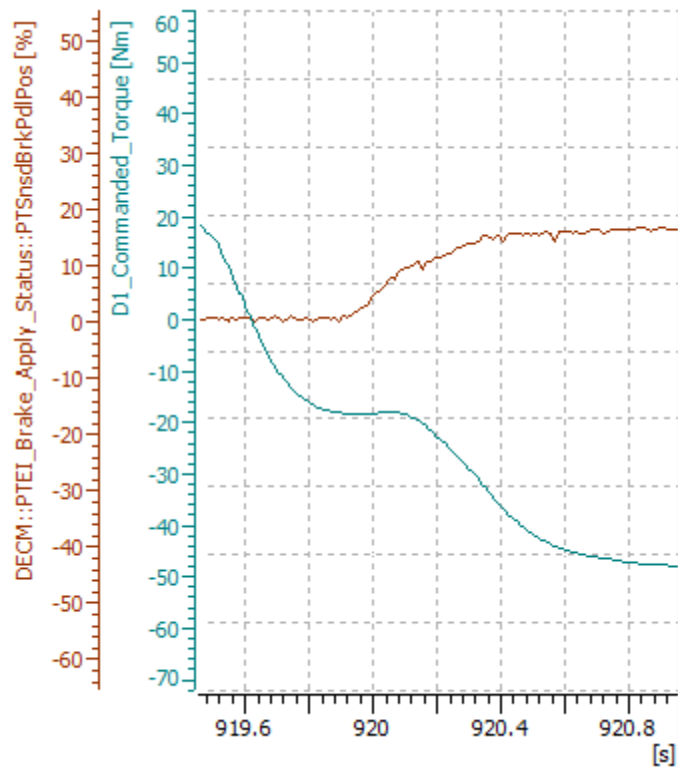


Figure 70: Commanded "lurch" on the RTM from pressing the brake pedal

# D - Conclusion

Rather than reduce the transportation sector's activity to cut back on emissions and energy consumption, engineering solutions can be explored for automobiles to improve overall energy efficiency, reduce criteria emissions, and reduce reliance on fossil fuels. Some of these solutions allow the economic activity that is reliant on transportation of goods and people to continue to grow, and they prepare us for a future when fossil fuels eventually begin to diminish further.

It has been demonstrated that powertrain electrification can reduce the environmental impact of a modern passenger vehicle, without sacrificing the vehicle's performance. Because hybrid vehicles consist of two or more torque producing components but only one driver input (at a time), there is a need for a supervisory control strategy that controls the torque output of each component. In a vehicle with significant levels of powertrain electrification the impact of this torque controlling algorithm on the vehicle's emissions, energy consumption, and performance is huge. Because of the strong impact, it becomes necessary to develop a systematic approach to the optimization of these parameters in order to take full advantage of what the physical architecture is capable of.

The UWEC2 team came up with a Parallel Through the Road (PTTR) PHEV that can operate as an EV for the first 50 miles after being charged off of the grid. This very heavy reliance on grid electricity for propulsion is the main mechanism relied on to reduce the environmental impact of the vehicle's operating lifetime. Once the battery pack is depleted, the vehicle turns on a 1.7L turbo diesel engine operating on B20 to drive the vehicle as a HEV for the following 350 miles in a charge-sustaining fashion. Biodiesel reduces the criteria emissions and petroleum energy consumption of the charge-sustaining mode. The baseline hybrid strategy developed are a very good starting point to take advantage of the physical architecture's abilities and a small amount of optimization has been performed to improve performance, however it has become apparent that a lot more time and resources need to be allocated to optimization for full refinement in future competitions.

It was discovered at the Emissions Test Event that diesel engines exhibit similar sensitivities to criteria emissions during off-center engine loading, IE very low or very high torque or RPM. This conclusion was important to provide a basis for the torque control strategy because very little/no documentation exists in publications that describes the effect of artificial loading via electric motors of diesel engine operation. The results can also be used to create a baseline urea injection strategy. Also important from the Emissions Test Event are the cold-start criteria emissions results, which are discussed in the thesis by Trevor Crain, MSME University of Washington June 2014.

# Appendix

## D.1 - Proposed Architecture Selection Matrix

### Assumptions

#### *UF-Weighted Total Energy Consumption*

All three architectures give varying levels of efficiency. The modeling results from Autonomie are used to rank the three architectures to provide a final ranking. This number represents the total energy consumption for Charge-Depleting and Charge-Sustaining ranges. The main difference in total energy consumption will come from how efficient each architecture is during charge-sustaining mode.

Series hybrid operate in charge sustaining mode by using a petroleum based motor to power a generator, which then charges the battery pack. This means series hybrids have multiple energy conversions happening, which may affect efficiency. TTR hybrids operating in charge sustaining mode generate electrical power in two ways. If the TTR hybrid has a BAS assist, that can be used to generate energy to maintain SOC, the second way to generate electricity is by regenerative braking through the RTM. Autonomie will allow the University of Washington to obtain results to compare these three different efficiencies. **Highest scores are given for better efficiency; highest score is normalized to 5 in each category.**

#### *Space Claim*

Packaging space is at a premium in the mid-sized Chevrolet Malibu. Fitting all of the drive-train components into the car will present some technical challenges. There must be enough space to fit all of the motors, engines, batteries and various electronics components into the car. Series allows for movement of the internal combustion engine so it receives a higher rating than TTR. TTR+BAS requires high voltage routing through the entire vehicle. **Higher scores are given to architectures with simpler space claim needs.**

## ***Controls Complexity***

Controls complexity addresses the issue of safety and performance control system complexity. All three architectures present significantly different controls strategy. The series architecture requires control of the generator and electric motor interdependently to balance the efficiency. The TTR hybrid requires the control system to blend torque in the front and rear to prevent excess wear/tear on the chassis and other driver-train components. All three architectures present safety concerns that are currently being investigated; they should not vary significantly from each other. **Higher scores are given to simpler controls difficulty.**

## ***Electrical Complexity***

Electrical complexity refers to the overall, low voltage and high voltage electrical sub systems. Series architectures would require two electric motors, one to act as a generator, one to act as a traction motor. Both motors would require some sort of motor controller/inverter and associated switching circuitry raising electrical complexity. The series architecture would also require high voltage cabling to be run to both ends of the car. TTR and TTR+BAS would allow high voltage systems to be placed at one end of the car, preferably at the rear of the car. The rear traction motor of the TTR option would provide the regenerative capability needed. TTR+BAS would add a front electrical motor and possibly secondary high voltage battery pack. **Higher scores are given to architectures with lower electrical complexity.**

## ***Weight Distribution***

Weight distribution between the front and rear axles *must* comply with the requirements provided in the rules. Within these limits, the more balanced the distribution, the better. **Higher scores are given for better weight distribution.**

## ***Overall Weight***

Weight will impact overall performance of the car. Lighter cars will have lower energy requirements for acceleration, and are likely to handle better. **Higher scores are given for lower weight.**

## ***Acceleration***

Acceleration is measured by the architecture's 0-60 times. The best 0-60 time is normalized to 5, and the other architectures are given a percentage of that score based on their specific time. **Higher scores are given for faster acceleration times.**

## ***Mechanical Complexity***

Mechanical complexity refers to the ease to which the specific architectures can actually be mechanically assembled. This means that it addresses both component sourcing (i.e., if a component is available) or the complexity of building a needed component. The series hybrid and through the road hybrid present roughly the same mechanical complexity because they can be built with mostly off the shelf components. TTR requires two transmissions and two sets of axles, raising the mechanical complexity. **Higher scores are given to less mechanically complex designs.**

## ***Cost***

Overall cost of each architecture varies with the component count. The series hybrid requires two electric motors, a fuel based engine, and a differential/transmission to provide power to the ground. The Pre-Parallel hybrid needs only one electric motor, one fuel based engine and a single transmission/differential unit. The TTR hybrid will require, one electric motor, one fuel based engine, and two differential/transmission units. **Higher scores are given to architectures with lower cost.**

## ***Support***

Support is a dual category. Support comes in two forms, monetary/component donation and technical support. Some companies may be willing to donate components, but unwilling to provide technical support in the form of service manuals, CAN database and so forth. **Higher scores are given to architectures with higher levels of support.**

## ***Experience***

Overall team experience influences the architecture selection from the standpoint of mechanical complexity, or required software programming needed for an ECU re-configuration. If one architecture has an

experience level below 2, it would disqualify that architecture from possible selection. **Higher scores are given to architectures that corresponded with higher levels of previous team experience.**

## **D.2 - Fuel Selection Matrix Assumptions**

### ***Engine Efficiency***

For each of the fuel selection categories, engine efficiency was taken into account for each score. E10/E85 has lower total engine efficiency than B20 engines. The higher efficiency of the B20 engines (about 2%) is due to high compression ratio which gives engine a better thermal efficiency than E10/E85 engines. **Higher scores are given to engines with better efficiency; highest score is normalized to 5 in each category.**

### ***Range***

Range is an important consideration; however, all three fuel types will provide enough range for competition requirements. E85 and E10 represent a blend between ethanol and petroleum. The B20 is a blend of diesel derived from soy and petroleum stocks. The diesel engine offers better range on a fixed volume of fuel because of the slightly higher energy density of fuel, along with higher efficiency. **Higher scores are given to engines with better range (fixed fuel tank volume).**

### ***CO<sub>2</sub> Emissions***

CO<sub>2</sub> emissions numbers are obtained from the Autonomie simulation results. Results are organized by examining the CO<sub>2</sub> emissions per mile. E10 has the highest CO<sub>2</sub> emissions, because it has the lowest efficiency engine and highest blend of petroleum usage. B20 has second highest CO<sub>2</sub> emissions; because of its higher efficiency it emits less CO<sub>2</sub> per mile than E10. E85 has the lowest CO<sub>2</sub> emissions, because it has the lowest amount of petroleum in its blend. Because the difference between E85 and B20 emissions is negligible, both were given a normalized score of 5, with E10 receiving a lower score of 4. **Higher scores are given to engines with lower CO<sub>2</sub> emissions.**

## ***Petroleum Usage***

E85 has the lowest petroleum usage, because 85% of its mixture comes from corn based ethanol. B20 has the second lowest usage of petroleum, with the 20% of its mixture coming from algae or soy oils. E10 has the highest petroleum usage with only 10% of its mixture coming from corn based ethanol. **Higher scores are given to engines with lower petroleum usage.**

## ***Engine Weight***

E10/E85 engines tend to be weigh less than B20 engines. This weight difference is most likely because of the higher compression ratios required by the diesel cycle in the B20 engines. The weight difference is mainly accounted for by extra engine block thickness. For vehicle performance and dynamics it is desirable to have the lowest weight engine possible. Thus the E10/E85 engines have an advantage over the diesel in this category. **Higher scores are given for lower total engine weight.**

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