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Supervisory Controls Strategy to Reduce Utility Factor Weighted Criteria Emissions for a Plug-In Hybrid Electric Vehicle

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SUPERVISORY CONTROLLER TO REDUCE UTILITY FACTOR WEIGHTED CRITERIA EMISSIONS FOR A PLUG-IN HYBRID ELECTRIC VEHICLE

by

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A Thesis Submitted to the College of Engineering Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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"It's not about how hard you hit, but how hard you get hit and keep moving forward. How much you can take and keep moving forward. That's how winning is done" - Sylvester Stallone

Abstract

Researcher: Thomas Francis Gorgia III

Title: Supervisory Controls Strategy to Reduce Utility Factor Weighted Emissions for a PHEV

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Criteria emission reduction techniques are being more sought out in the automotive industry due to current government regulation for light duty vehicles. Parallel-series plug-in hybrid electric vehicles can have multiple strategies to balance emissions and fuel consumption. Common controls strategies in industry target fuel economy by using a large electric vehicle range, known as charge depletion, followed by maintaining a state of charge after a specific vehicle threshold, or charge sustaining. A charge preserve strategy works by running an engine at an optimal loading condition, the engine will burn the fuel more complete reducing criteria emissions. Charge preserve will charge the vehicle more rapidly by loading the engine to achieve optimal loading conditions and yield a quicker recharge. The charge preserve strategy had the best results when compared to the corporate average fuel economy 2025 standards that regulate solely criteria emissions. The nitrogen oxides emissions of a Max Depletion strategy were higher than the standard by 200%. The Charge preserve strategy decreased Nitrogen oxides by 41%.Greenhouse gas emissions from a Charge Preserve strategy, however can see an increase up to 15% and a 2% decrease in fuel economy was observed.

Table of Contents

Table of Tables

Table of Figures

List of Acronyms

APP	Accelerator Pedal Position
ANL	Argonne National Laboratory
BEV	Battery Electric Vehicle
CAFE 2025	Corporate Average Fuel Economy
CARB	California Air Research Board
CD	Charge Depleting
CP	Charge Preserve
CS	Charge Sustain
CO	Carbon Monoxide
CO_2	Carbon Dioxide
E85	85% Ethanol
EPA	Environmental Protection Agency
ESS	Energy Storage System
FTP	Federal Test Procedure (Cold Start Drive Cycle)
ICE	Internal Combustion Engine
FUF	Fleet Utility Factor
Gen MTR	Generator Motor
GHG	Greenhouse Gas Emissions
GREET	GREENHOUSE gasses, Regulation Emissions, and Energy use in Transportation
MPGGE	Miles Per Gallon of Gasoline Equivalence.
NO_x	Nitrogen Oxides

IMG	Bosch Integrated Motor Generator
PEU	Petroleum Energy Usage
PHEV	Plugin Hybrid Electric Vehicle
PM	Particulate Matter
PTW	Pump to Wheel
SCU	Supervisory Control Unit
SIL	Software in the Loop
SOC	State of Charge
THC	Hydrocarbon
Trac MTR	Traction Motor
TRC	Transportation Research Center
UDDS	Urban Dynamometer Driving Schedule (Drive Cycle)
UF	Utility Factor
UFW	Utility Factor Weighted
US06	United States 06 (Drive Cycle)
VMT	Vehicle Miles Traveled
WTP	Well to Pump
WTW	Well To Wheel
ZEV	Zero Emissions Vehicle

Chapter I Introduction

Significance of the Study

In recent years automotive technology has rapidly grown into a hybrid vehicle platform. A cultural trend has begun to take place in which consumers want vehicles that are fast and performance based but desire the technological advances in fuel economy and emissions reductions.

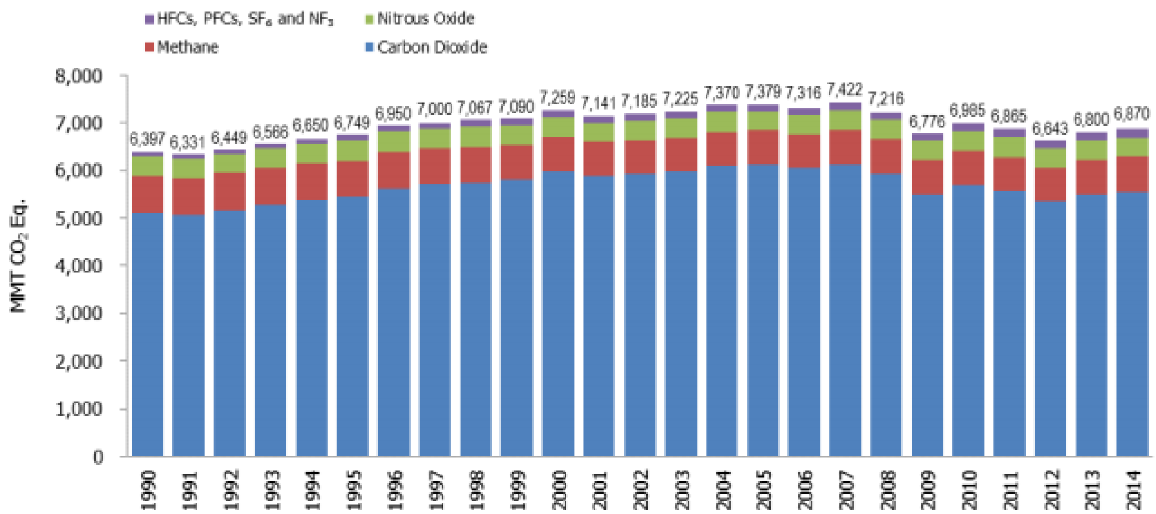

Figure 1 - United States Emissions from 1990-2014 reported by the EPA [1]

Figure 1 is a trend of the greenhouse gas emissions in metric tons versus the year in which measurement occurred. From the years of 1990 until 2006 a trend can be seen where emissions increased. From 2009-2012 GHG emissions decreased however in 2013 due to the increase in clean energy technologies.

A hybrid powertrain can be used to not only improve the fuel economy of a vehicle but also be used to reduce emissions. The “sweet spot” of efficient engine operation can be achieved by changing the load on the engine.

Statement of the Problem

Greenhouse gas and criteria emissions are an issue to the environment and need to be reduced. Climate change is a very big topic in the scientific commercial and transportation is responsible for 26% of total emissions **[1]**. Vehicle design comes down to three critical factors for an overall system including efficiency, emissions, and performance. Commonly only one of the three factors can be achieved. A parallel-series hybrid architecture can better balance the three critical factors.

The most common emissions reduction technique on conventional vehicles is a passive catalytic converter. A catalytic converter achieves the highest possible efficiency when light off temperature is achieved. During a cold start the catalytic converter has poor efficiency that increases as exhaust temperature increases. Once light off temperature is achieved the catalyst is operating at its highest possible efficiency.

Purpose Statement

The purpose of this study is to analyze a parallel-series hybrid architecture with the intent of reducing the emission. The most common strategy is a Max Depletion case that uses the full electric vehicle range and sustains charge in the ESS. This strategy is good for fuel economy and meets emissions standards could be improved upon.

Using the hybrid powertrain to load or assist the engine based on the optimal efficiency can improve operation of the catalyst. Maintaining temperature of the catalyst above the light off temperature threshold will maintain peak efficiency in an exhaust after treatment system. Running the engine more efficiently will result in a more complete combustion and fewer criteria emissions pre catalyst. A minimal impact on fuel economy with reduced emissions will help tackle two of the three factors driving vehicle design.

Test Vehicle

The vehicle being used as the test bench for this study is the Embry-Riddle Aeronautical University EcoCAR 3 vehicle. EcoCAR 3 is a four year competition program in which select universities are given a 2016 Chevrolet Camaro to convert into a hybrid performance car. The competition is sponsored by the United State Department of Energy, General Motors, Argonne National Laboratory, and more. This vehicle serves as a great test bench for this development due to the emissions and efficiency testing that is conducted at a professional level on the vehicle.

The Embry-Riddle Camaro is a parallel-series hybrid in a rear wheel drive format. The parallel-series architecture consists of a 2.4L ICE coupled to two Bosch IMG electric motors. The IMGs house internal hydraulic clutches that can engage and disengage various torque producing components. The transmission is an 8 speed automatic. The ESS consists of an A123 18.9kWh Lithium Ion chemistry set up. Figure 2 is a diagram of the components laid out in the ERAU EcoCAR 3 vehicle.

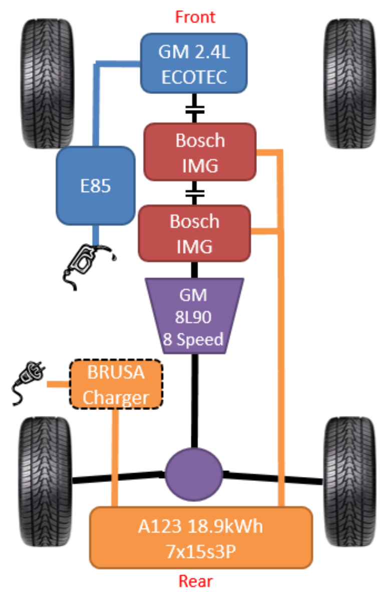

Figure 2 - ERAU EcoCAR 3 2016 Camaro Eco Super Sport

The clutch allow the Camaro to have several modes of operation. Each component is assigned a name for ease of description. The electric motor bolted directly to the engine is referred to as the generator (Gen). The clutch that bolts the shafts of the engine and motor is the Gen clutch. The traction motor (Trac) is motor that is bolted to the transmission. The traction motor clutch connects the output shaft of the Gen to the input of the Trac. The modes of operation are defined in Table 1.

Table 1 - Eco Super Sport Camaro Modes of Operation

Mode	GM 2.4L Ecotec	Gen Clutch	Bosch IMG Gen	Trac Clutch	Bosch IMG Trac
ICE Only	Torque Producing	Engaged	Minimal Power	Engaged	Free Spinning
Parallel CS	Torque Producing	Engaged	Minimal Power	Engaged	Generating
Dual CD	ECM off	Disengaged	Torque Producing	Engaged	Torque Producing
CP Mode	Torque Producing	Engaged	Torque Producing	Engaged	Torque Producing

In dual Charge Depletion mode the gen clutch is disengaged and can spin freely. The engine is decoupled from the road and cannot drive the vehicle. Both electric motors will produce torque to the rear wheels. Figure 3 is an image of the power flow in CD mode from source to the rear wheels.

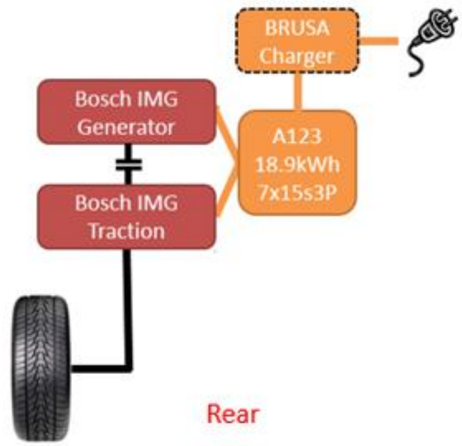

Figure 3 - CD Mode Power Flow

Parallel Charge Sustain mode is the mode in which the state of charge of the vehicle is maintained. The motors will assist the engine to perform optimally for fuel economy and charge the energy storage system. The SOC is maintained by using one of the IMGs as a generator to charge the battery. Figure 4 is the power flow schematic in CS mode. In CS mode all power is generated using the engine and its fuel E85. The vehicle has some series functionality and fault case modes, but those modes are irrelevant to this study.

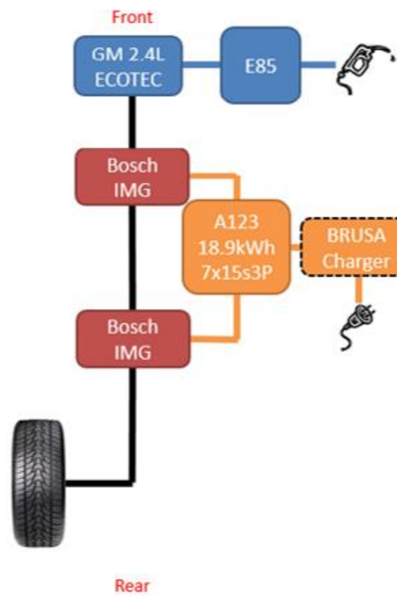

Figure 4 - CS Mode Power Flow

CP mode is the mode discussed in the study. This mode is a combination of CS and CD mode. In this mode the vehicle will go between CS and CD mode based on measured parameters such as state of charge and exhaust temperatures. The charge is preserved in given states by going from CD to CS mode when the controller determines the SOC or exhaust temperature is sufficient therefore resulting in the optimal usage of fuel and reduced emissions.

Limitations and Assumptions

Due to the limited availability for emissions testing on the Camaro this study will primarily use pre measured data in a model. The team also is only given one emissions testing event prior to the construction of this paper. Using the data from the testing event a catalytic converter model can be developed and tested against prior data. The ERAU EcoCAR 3 vehicle is the only available test vehicle for the paper in which a control strategy can be implemented.

This paper assumes that the trends found in the different controls strategies modeled will yield similar trends when measured. By using this particular platform the same equations could be used with other components and configurations.

Thesis Statement

Through the use of the hybrid powertrain, a supervisory controller can be developed to reduce utility factor weighted criteria emissions below CAFE 2025 standards by maintaining catalyst light off temperatures within the exhaust.

Chapter II: Review of Relevant Literature

Utility Factor SAE Standards

SAE Standard J2841 was issued in 2009 and revised in 2010. This standard discusses the accepted and known curves used to calculate the UF. The UF is used to combine the CD and CS modes for a PHEV. This is done by measuring the impact of the electrical energy and fuel usage separately. The electrical energy is then converted to a gasoline equivalence. The UF can be implemented onto the electrical gasoline equivalence and fuel usage to get a total energy consumption. Emissions are measured over the duration of the entire UF weighted cycle.

Assumptions for the UF include that the operation begins after a full charge and the CD mode is the default starting mode [2]. Further assumptions includes that immediately after driving for the day the vehicle is charged fully off of grid electricity. Unknown behavior includes how often throughout the day a PHEV driver would wall charge based on charging opportunities or forgetfulness of the driver to charge [2].

The UF is the limited utility of a particular operating mode, for PHEVs that is commonly the CD mode. VMT is the total distance traveled by a vehicle in a particular day or cycle [2]. The FUF is based on the number of miles a fleet of vehicles will travel. The FUF is calculated by dividing the depleting miles by total miles traveled and is useful for calculating both fuel and electrical energy consumed for a fleet of vehicles.

$$FUF = \frac{Depleting\ Miles}{Total\ Miles}$$

Equation 1 - Fleet Utility Factor Calculation [2]

The utility factor for an individual vehicle should be used to estimate a single vehicles fuel economy. *N* is the number of vehicles that are being individually tested.

$$UF = \frac{1}{N}(1 + 1 + 0.8 + 0.67 + 0.5)$$

Equation 2 - Utility Factor Calculation Based on Number of vehicles tested [2]

The curves for the FUF and UF are shown in Figure 5. These curves are used to apply the UF and FUF weighting to both fuel economy and emissions. GHG and criteria emissions have the same factor applied based on the distance traveled in the measured test. Multiple trips can be combined to measure data and apply a given UF. [2]

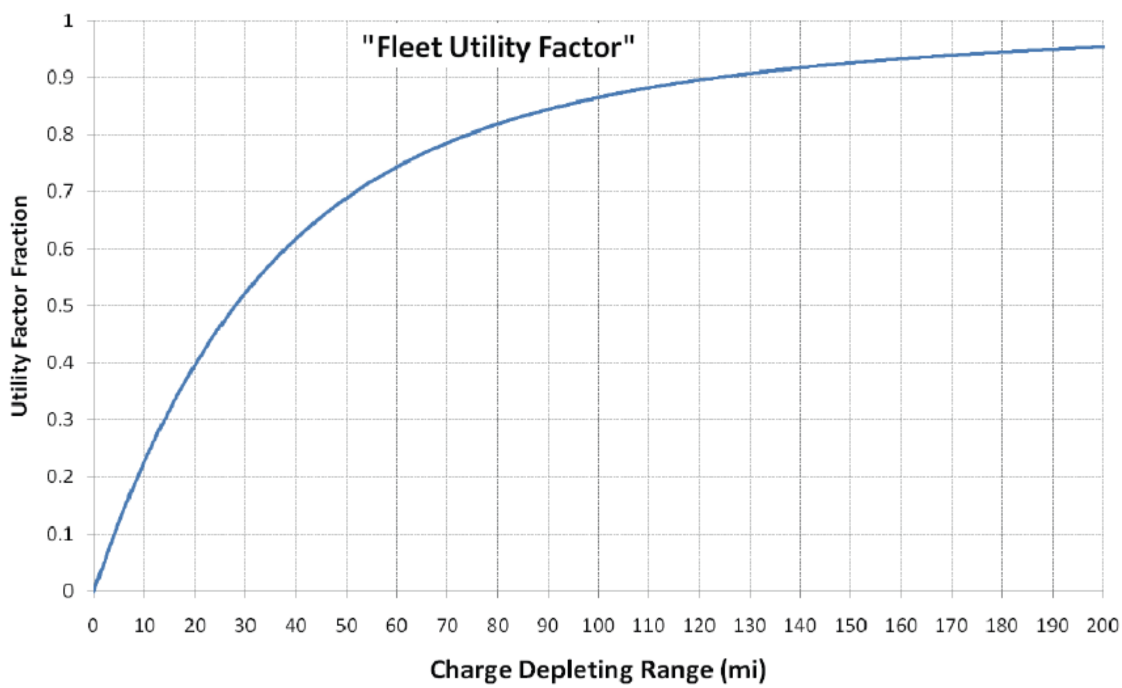

Figure 5 - FUF and UF curves [2]

SAE standard 1711 was reevaluated and reissued in June of 2010. A standardized dynamometer procedure for HEVs and PHEVs that calculates and measures fuel economy and emissions is discussed. The standard includes the UDDS, HFEDS, US06, and SC00 drive cycles. Other drive cycles can be used to test. Emissions are measured and weighted equally whether it is criteria emissions or GHG emissions [2].

Cold start emissions and CD mode range weightings for PHEVs are weighted similarly to conventional vehicles and are not the main focus of this test. Cycles of measurement are weighted within the overall drive schedule of the test using Equation 2. The cycle's measure distance traveled and each cycle is given a weighted UF [3]. The average emissions and energy consumption over the cycle within the schedule is then measured.

For a PHEV the electrical energy consumption is measured during the CD mode operations [3]. The AC electrical energy usage is measured for each CD mode cycle and applied a UF but fuel consumption is not calculated. The CS mode fuel consumption values are calculated separately and UF weighted for each cycle of operation. Electrical energy is not calculated in CS mode cycles [3]. Fuel and electrical energy consumption for each cycle is then summed among the measured cycles to find the total energy consumption.

Total energy is then converted from an energy per distance value to Miles per Gallon of Gasoline Equivalence with the energy density of the specified fuel. The total energy per distance is in the unit of kWh/mile. Energy density of fuel is in units of kWh/gallon of the specific fuel. Multiplying the two numbers yields the miles per gallon of gasoline equivalence. MPGGE is a unit to estimate how much fuel would be used by the vehicle over a total test and set a fuel economy value.

Emissions are applied the same UF factor over several cycles within the drive cycle. The average value of emissions are measured and then UF weighted to see the GHG and criteria emissions effect. [3]

The SAE standards discussed are relevant due to the fact that these standards apply to emissions. Emissions are utility factor weighted to determine the impact of a fleet of vehicles on the environment. The test vehicle is an industry level simulation so the car needs to adhere to the SAE standards of emissions measurements. Development in simulation space allows for a better test case development.

CAFE 2025 Regulations

The Corporate average fuel economy standards that need to be met by 2025 for a light duty vehicle are set by the United States Environmental Protection Agency. A light duty vehicle is defined as a vehicle with a gross vehicle mass below 10,000lbs and is used to transport personal property [4]. The ERAU EcoCAR 3 Camaro qualifies as a Ultra-Low Emissions Vehicle and must meet the standards in Table 2.

Table 2 - CAFE 2025 Emissions Standards ERAU EcoCAR 3 Camaro [4]

Emissions Category	Useful Life Standard	NO_x (g/mi)	CO (g/mi)	PM (g/mi)
ULEV	Intermediate	0.2	1.7	N/A

E85 Emissions

The emissions benefit of bioethanol fuel blends E5, E10, E25, E50, and E85 are rather impactful due to the carbon cycle. The carbon cycle is the life cycle in which ethanol is created from feed stock. The Improving the emissions of a flex fuel vehicle will reduce the overall impact if it's strictly ethanol. Due to current market requirements the test vehicle only operates on E85. The temperature effects the performance of biofuels due to a low energy content [5]. Bioethanol is produced from sugar rich crop and has the following characteristics [5]:

- High octane rating compared to gasoline

- Higher oxygen content allows for a better combustion
- Liquid fuel and easy infrastructure compliance
- Poor lubricity
- High volumetric fuel consumption due to a low energy content

Testing of light duty vehicles yielded GHG emissions such as CO_2 had seen a 13% decrease in emissions production [5]. NO_x had seen approximately a 13% to 43% decrease on emissions compared to a non-blended gasoline [5]. CO and HC had seen a drastic decrease in emission of approximately 50% each [5]. E85 the fuel of choice for the test vehicle reduces the environmental impact before an after-treatment method and powertrain controller is introduced. The higher the ethanol content the lower the emissions with little to no change in performance.

Three fuels compared head to head yielded results that show a benefit in E85 over conventional fuels throughout a generation change. The three fuels explored were blends of E85, average fuel composition of 1988 pump gasoline, and average fuel composition of the 1996 fuel composition standard for California [6]. The average value of exhaust emissions was collected and no utility factor was applied.

NO_X emissions of E85 were 49% lower than the 1988 blend and 37% lower than the 1996 blend. The overall toxins of E85 emissions such as GHG and other criteria emissions were 108% lower than the 1993 blend and 255% lower than the 1988 fuel composition [6]. The fuel economy of the fuels was compared and the 1988 blend had a 29% higher fuel economy then E85. The 1996 composition had 26% better fuel economy than the E85 [6]. E85 has a lower fuel energy density and yields a lower fuel economy but benefits emissions reduction techniques.

The higher the blend of ethanol in the fuel mixture the more emissions were reduced. This also leads to a small trade off in efficiency due to the low energy content. As temperature increase the higher blend ethanol fuels blend also due to the low energy content number. To get the engine to a better operating temperature more fuel is needed. Performance has a slight increase due to the higher octane rating of ethanol fuels [5].

E85 by nature has a lower energy density and is less efficient than standard gasoline but results in reduced CO_2 and HC. NO_X however is slightly increased due to a higher air to fuel ration needed [7]. Ethanol's chemical makeup of (CH_3-CH_2-OH) is highly oxygenated and has 35% more oxygen by weight then standard gasoline [7].

The increased oxygen has a more complete combustions and reduces HC but due to less combustion more fuel is consumed. The test vehicle adapted to the fuel by increasing the rate at which fuel entered the cylinder [7]. The ECU maintained the stoichiometric air-fuel ratio.

E85 had 70% less CO then gasoline [7]. The particle mass had decreased and the duration at which particulates were produced decreased 30%. The only concern generated from the form the testing was that the NO_x emissions had increased 50%. [7]

Ethanol is normally used in a blended context in the automotive industry. The blends are E5, E10, E25, E50, and E85. Two vehicles were studied by Michael Duoba at ANL with E85 used as the fuel. One of which was a standard direct injection engine with a stock engine calibration from the factory [8]. The other vehicle was an engine tuned for the stoichiometric combustion of ethanol based fuels [8].

Vehicles with an E5, E10 and E25 blend had similar results in emissions [8]. The E50 blend had a good performance in reducing emissions and comfortability to the driver. The E85 blend was a rougher ride and had higher HC results [8].

Both HC and CO emissions were low however the blend with the largest change was when E5 went to E10. Higher blends had a more significant drop in emissions on startup but the benefit was lost during higher loading operations. [8]

Energy Consumption Management

The utility factor is calculated using Equation 3 is based on distance traveled rather than the number of vehicles.

$$UF(R)_{CD} = \frac{\sum_{d_k \epsilon S} \min(d_k, R_{CD})}{\sum_{d_k \epsilon S} d_k}$$

Equation 3 - Utility Factor weighting based on distance [9]

The variables are as followed:

- $UF(R_{CD})$ is the utility factor at a given CD range
- R_{CD} Charge Depletion Range
- d_k is the distance driven in a day of record k in driving set S

The utility factor can be applied using two different methods. One is measured with which the total range of a trip is averaged [9]. This will essential have one full utility factor applied. The other method was a three cycle road trip in which multiple stages of UF are tabulated [9].

A test comparing the two methods yielded results with less than 1L/100Km difference in fuel economy [9]. This means that the trip can be fractionalized based on the resulting drive cycle and order in which data is collected [10].

A PHEV blended strategy compared to a BEV all electric strategy leads different results in infrastructure and design for a UF weighted system. The two strategies compare the use of electricity and fuel to improve the efficiency of the vehicle. The all-electric range method is a BEV that meets CARB's ZEV standards. This vehicle is more complicated due to the larger and more costly electrical components [10]. A PHEV with a CD range is more cost effective

The BEV is sensitive to aggressive cycle changes due to the power needed to overcome the cycle operations requirements [10]. In the blended strategy of a PHEV has sensitivity towards the driving distance due to the fact that the CD range must be depleted to achieve maximum benefit of efficiency [10]. A shorter distance will effect a blended strategy if the engine turns on due to the use of the ICE.

The PHEV blended strategy may have the most beneficial energy usage if the vehicle can intelligently predict the driving habits of the current cycle. Based on duration, length, and power demands the vehicle could go between CD and CS mode to have the optimal CD mode range without wasting energy at high power demands [11].

This paper explores the first generation Toyota Hybrid System on the first generation Toyota Prius. The primary usage of the Prius was to have an electric motor in retransmission configuration to assist the engine.

To benefit the efficiency of an engine, powertrains more commonly today have start/stop functionality. To improve the emissions during engine start under load the electric motor can be used at start up to load the engine and achieve catalyst light-off quicker [12].

The engine is run richer but at a more efficient operating point as too produce a more efficient vehicle [12]. The catalyst under engine restarts has serious issues with NO_X reduction due to the O_2 saturation of the catalyst. The air fuel ratio is also richer to maintain the O_2 storage properly. This strategy helps to mitigate the increased NO_X emissions [13].

Previous ERAU Thesis Work

Abdulla Karmustaji studied a controls strategy monitoring the torque and power through the powertrain of the ERAU EcoCAR 3, the same test vehicle for this thesis, in modeling. The Real-Time energy and Emissions Minimization Controller finds the optimal split of torque among the powertrain components [14].

The controller looks at the current operating range of the powertrain and calculates the current energy consumption of each component. The overall efficiency is found and then compared to determine which mode of operation is the most efficient. A user defined weighting is applied to determine which component is more desirable for current operations.

The vehicle had taken emissions into account but was not used to decide modes of operation. The main target of this thesis was to improve efficiency of the powertrain. The strategy has a 10.2% reduction in city fuel economy and 5.3% in highway driving [14].

A controls strategy that uses both torque monitoring system for fuel economy and ICE engagement to reduce emissions could complement one another well. A PHEV can use both strategies and run clean and optimally.

Powertrain Modeling Strategies

An engine emissions map is necessary to develop an emissions model for regulatory reasons. When developing a map the following needs to be considered [15]:

- Engine information should be accurate
- The engine should be tested based on its operation
- A powertrain representation should be modeled

An engine only model approach has a cycle specific map and a steady state map. The cycle specific map was more accurate yielding a 1.7% more accurate response then steady state. The procedures for developing an emissions map include [15]:

- Generate engine torque and speed cycle from the vehicle certification cycles using GEM(greenhouse gas emissions model) and generic vehicle configuration
- Run Engine test and tabulate cycle average CO2, N/V and cycle work for use in certification

The cycle average map technique is better for mapping fuel consumption and emissions for vehicle regulations [15].

The vehicle used as the test bed for this paper is a power split hybrid with a generator and traction motor contained within a transmission. The engine can drive the vehicle and charge the generator. To reduce the usage of the ESS the engine will turn on for high power demands in a blended CD mode.

Several strategies were explored including a blended CD mode strategy and an EV/CS mode strategy. Each mode of operation would have the vehicle enter CS mode at 30% SOC [16]. The EV/CS mode strategy is one in which the EV range is depleted and the vehicle enters a CS mode to maintain charge or if the road load exceeded the power capabilities of the electrical system. The blended CD modes explored include an engine differential power, engine full power, and engine optimal power.

The differential power is identical to the EV/CS mode however the power threshold to enter CS mode was lowered. The engine full power has the ICE drive the vehicle alone with no input from the electric drive train when CS mode was entered. Engine optimal is similar to the engine full power strategy but would have the engine operate at a higher power but would maintain the peak performance of the engine [16].

The blended CD mode out performs the EV/CS strategy when the vehicle can predict the operations of the drive cycle [16]. Of the blended CD modes the engine differential power was less efficient than the other strategies [16].

WTW Emissions Measurements and Reduction Techniques

Previous works had tested applications of the SAE J1711 Utility Factor fleet estimation for vehicles from the EcoCAR 2 competition. In the EcoCAR 3 competition criteria emissions and greenhouse gas emissions are utility factor weighted alongside energy consumption.

The comparison of the full vehicle average and the UF weighted emissions shows a reduction in all of the test cases in CO_2 emissions. The OSU vehicle saw a 35% reduction in the CO_2 emissions when the UF was applied [17]. Every set of emissions saw a similar trend in reduction in which the UF reduced the overall impact.

Vehicles with a larger CD mode rage saw a more significant decrease due to the UF impact due to drive schedule resulting in more CD mode miles driven then in CS mode.

The full test average is dependent on the cycles being measured. Due to the nature of the EcoCAR E&EC test the vehicles weighted cycles would alter the overall impact of the UF on emissions [17].

A control group of 1405 privately owned Chevrolet Volts from 18 metropolitan model years 2011-2013 were used to evaluate the Fleet Utility Factor fuel economy standard [18]. The Fleet Utility Factor weighting comes from SAE standard J2841. The FUF is calculated using Equation 4.

$$FUF(R_{CD}) = \frac{\Sigma_{k=1}^{N} \min(d(k), R_{CD})}{\Sigma_{k=1}^{N} d(k)}$$

Equation 4 - UF Weighting Regarding Vehicles Traveled and Number of Vehicles [18]

- *K* represents a single vehicle driving a day
- *d(k)* is the distance that vehicle has traveled
- *N* is the total number of vehicles

This study determined that FUF was 14-15% higher than the projected curves from the J2841 standard [18]. The observed volts had fewer long distance travel days then what was surveyed from NHTS in 2001.

The My2011/2012 Volt group has an FUF weighting of 65% in the standard and the My2013 group 68% [18]. The measured FUF values were 72% and 74% respectively [18]. UF variations were so different due to the frequency at which consumers would charger there vehicles with an average of 1.4 charges per day. Consumers had such a wide variation of used EV mode rage of approximately 50-80% of their total EV range [18].

The WTW and WTP emissions of generating electricity is relevant to BEVs and PHEVs when understanding the environmental impacts. A BEV has higher WTP effects due to the high cost of emissions to generate grid electricity. Coal, natural gas, and other infrastructure fossil fuels are used to generate electricity at a grid level but create high forms of pollutants both GHG and criteria.

Infrastructure needing to operate at a more efficient point to generate electricity. This leads to a BEV and PHEV having a reduced GHG footprint [19]. The more control over the generation of the power to the road the more reduced the implications are. A vehicle will see more variation in load which can produce more GHG. The correlation that emissions such as CO_2 are produced proportionally to load demand at the road [19].

Vehicles such as the Toyota Prius have an HEV emissions strategy focusing on loading the engine. A standard production Prius was compared to one with an aftermarket ESS [9]. The Prius has a maximum depletion CD strategy and a CS mode. The Renault Kangoo is a series hybrid and has a CD mode with a range extender CS mode.

The Toyota Prius was tested with a UDDS cycle and tested energy consumption, GHG emissions, and criteria emissions. The vehicle started with a cold start UDDS cycle. The Prius in the CS mode emissions testing had high levels of HC and NO_x compared to the aftermarket battery pack ESS. The California Variant of the Prius had 50% fewer NO_x and HC emissions compared to the standard model [9]. In both cases the production Prius had fewer emissions then the aftermarket ESS. A larger ESS leads to fewer emissions due to a larger CD mode range. Less fuel consumed is better, but if the ICE runs at a more optimal point then neither emissions nor energy consumption need to be compromised.

Criteria emissions however are more common in the methods to produce grid electricity and actually increase with a larger CD range [19]. PTW emissions are more commonly found in criteria emissions due to the large volume of coal used to generate grid electricity [19]. Criteria emissions vary greatly with road load and production unlike GHG emissions which follow their respected stoichiometric properties.

Estimating a PHEVs' WTW and GHG emissions are needed to weight the UF emissions. Not only is the effects of the vehicle identified but the process of creating petroleum takes a toll on a vehicle in reducing its footprint. CD and CS mode WTW impacts are scored separately and combined with UF to get a representation of the CD VMT.

Grid electricity for the PHEV tests varied from 6% to 24 % of the total energy used by the vehicle [20]. The WTW petroleum energy use of a PHEV is lower than an HEV. The large the CD mode range the less petroleum energy use the vehicle used [20]. This is to be expected based on the different techniques used to generate electricity.

The emissions of GHG from a PHEV were reduced from an HEV due to the generation of electricity being more consistent and controlled. CO_2 emissions are approximately proportional to the load at which an ICE runs [20]. An HEV has no CD range and results in higher GHG emissions. The larger the CD mode range the more reduced GHG emissions are impacted. If the CD mode range could be stretched then emissions would be reduced.

A direct injection spark ignited, reciprocating engine operations with a spray guided legislated emissions level has higher NOx emissions due to ethanol based fuel. Injection-timing can lower NO_X emissions for gasoline and E85 engines [21].

Gasoline injection-timing is limited for gas to achieve a complete combustion that is stable. E85 has a larger range of stability including top dead center of the cylinder [21]. Retarding the engine to top dead center with E85 reduced NO_x and PM emissions drastically [21]. A higher combustion efficiency lead to reduced NO_x emissions. To achieve a higher efficiency reducing the flame speed is the key factor. This is done by changing the timing and exhaust gas recirculation.

Changing the timing reduces the delay between the end of injection and combustion causing more turbulence in the cylinder. More air reduces temperature of the combustion and reduces the thermal NO_X production [21]. A cooler burn is the cause of higher NOx emissions at which the catalyst cannot efficiently compensate for.

The CAFÉ 2025 regulations means to reduce all vehicles for the new government regulations. The regulations of light duty vehicles have a high demand not only to improve fuel economy on vehicles being produce but a desire to reduce GHG and criteria emissions impact as well.

Light duty gasoline engine technology is trending to reduce CO_2 emissions by 40% in the next few years [22]. The technologies driving this trend include direct injection, turbo charging, and variable valve actuation. NO_X emissions in light duty diesel engines is important towards the new regulations. A 1% decrease in efficiency of deNO_X technology results in a 33% increase in NO_X average emissions for a vehicle [22].

The three-way catalyst is changing rapidly by eliminating the usage of precious metals to reduce emissions needed to extract the precious metals [22]. The three way catalyst effects emissions greatly by treating the exhaust. The reactions cause the emissions of a vehicle to be reduced.

Three Way Catalyst Performance

A catalytic converter is a steel container of precious metals such as platinum or palladium, and rhodium [23]. The platinum or palladium handle HC and CO emissions by accelerating oxidation [23]. Rhodium primarily eliminates the NO_x emissions [23].

$$2\,NO + 2\,CO \rightarrow N_2 + 2\,CO_2$$

$$2\,NO_2 + 2\,CO \rightarrow N_2 + 2\,CO_2 + O_2$$

Equation 5 - Three Way Catalyst Stoichiometric Equations

A catalyst will achieve light-off temperatures and the efficiency will remain constant at a manufacturer specified level [23]. Figure 23 is a diagram of pre and post treated emissions described from the Bosch Automotive Handbook. Criteria and GHG emissions are emitted but based on the efficiency of the catalyst N_2, O_2, H_2O, and CO_2 are produced.

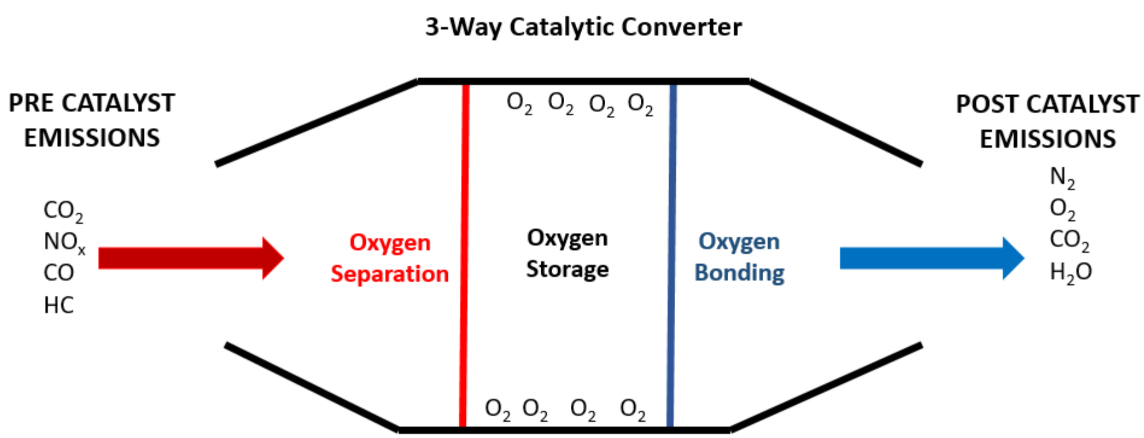

Figure 6 - Three Way Catalyst Diagram [23]

Commonly the three way catalytic converter is looked at as a passive component in a conventional HEV control strategy. An HEV with start/stop capabilities will get the exhaust warm and then have the exhaust cool. The light off temperature of the exhaust is achieved the chemical reactions to improve HC and NO_x emissions is at its most efficient. For most vehicles light off is approximately 400°C.

Once the engine is initially started the engine attempts to heat the exhaust up rapidly by having a rich air fuel ratio so light off temperatures can be achieved [24]. Once the engine goes through start/stop procedures after the initial cold start the exhaust cools due to the movement of the car but not much.

The vehicle is moving and the exhaust is warm but the engine enters the cold start procedures and runs a rich air fuel ratio [24]. The efficiency of the catalyst is down even if the exhaust is warm at approximately 150°C and can contribute to higher emissions [24]. As the catalyst tem approaches the light off temperature the efficiency of the catalyst increase to over 50% from the engine start in the start/stop scenarios [24].

To achieve better performance in the catalyst for a HEV after start/stop the engine starts should have a leaner air fuel ration. The engine does not need to use as much fuel to achieve light off quicker [24]. The catalyst should maintain 350°C when the engine is not in operation to achieve better light off.

Virginia Tech EcoCAR Emissions Reduction

The Virginia Tech EcoCAR team had explored a split-parallel hybrid architecture and used the SCU operations to reduce criteria emissions. The team used their hybrid strategy to reduce emissions with the intent of achieving loading points in the engine to have the catalytic converter achieve light off temperatures quicker [25].

The change in the control strategy to achieve a more steady state and desired loading point had resulted in a decrease in emissions. From the first set of testing to the second set of testing the NOX and THC emissions were reduced less than 1% and 18% respectively [25].

The strategy of loading the engine to achieve light off had also not effected the fuel consumption. The fuel consumption was reduced approximately 60% overall from stock proving that emissions reduction techniques do not have an adverse effect on efficiency [25]. The fuel consumption is UF weighted but GHG and criteria emissions were measured and averaged over the drive cycle.

The team analyzed various fuels and architecture possibilities through modeling to determine the best vehicle for the competition. The selected vehicle was a Parallel-Through the Road hybrid with a belt alternating starter on the engine. The selected fuel for the vehicle was E85 with a CD range running off of grid electricity. The team modeled the selected architecture using GREET and ran the vehicle at the final competition.

The team modeled the PEU of the architecture and had modeled the accuracy of their actual measured value had a 110% error [26]. The low accuracy is due to the nature of the competition in the fact that the year the data was collected is strictly a mule vehicle year. Further optimization may have led the measured values to be closer for the fuel economy strategy. Emissions data had a 25% error as well. Initial data from EcoCAR competitions tends to have a large error compared to measure due to the understanding of component functionality, competition goals of achieving a very basic level of functionality, and skewed assumptions [26]. The EcoCAR competition is a great proxy for development of emissions and fuel economy strategies.

The vehicle in the final years of testing and refinement had a focus on improving the cold start emissions. Three different strategies were explored with the intensions of heating up the catalyst.

The first strategy was based on a lower fuel consumption and had two phases to the start [27]. The engine would ramp torque into the power split hybrid slowly. The second strategy is target to reduce emissions compared towards the other [27]. The engine ramps torque faster and has a higher torque limit then the first strategy. The third strategy the engine was operational and generating torque but not driving the vehicle [27]. The engine served as a generator.

The results showed that the ideal strategy was the third. The emissions of HC were reduced due to the engine being operated at its most ideal operational point. Heat was generated for the catalyst to achieve light off quicker [27]. Reducing emissions by warming the exhaust catalyst through engine loading seems to have a high effect on criteria emissions and reduction on GHG emissions.

Blended Mode Strategies Emissions Reductions

Development of the SCU to develop a controls strategy that would reduce emissions on a pre-transmission hybrid has been explored previously. This method has two phases in which Phase I is modeling and Phase II is platform testing. Previous studies ran 6 UDDS cycles one after the other for data collection.

Maximum deplete CD mode in which the vehicle will discharge its maximum EV range immediately and a blended mode known as CP [28]. When the vehicle enters CP mode rather than depleting the battery to its maximum range the vehicle would enter CS mode prior to a full depletion of the batter [28]. The CS mode load following in which the power demand at the road is matched by the engine to maintain charge was used as well as Engine Optimal load points in which the engine was loaded to optimal performance based on operating conditions.

The four cases explored included:

- Maximum Depletion and Load Following
- Maximum Depletion and Engine Optimal
- Blended Operation and Load Following
- Blended Operation and Engine Optimal

Based on the current loading to the rear wheels and need for an engine cold start the vehicle would cold start the engine in blended modes throughout operation. The maximum depletion methods had one cold start but yielded a smaller CD mode range then a blended strategy. The impacts on fuel economy of a maximum depletion vs blended mode yielded a less than 3% positive impact [28].

THC emissions of a blended mode decreased approximately 50% from the maximum depletion [28]. CO emissions were reduced significantly but followed the linear curve of power matched to the road based on engine operation. NO_x emissions were decreased in a blended strategy due to the fewer number of cold start the engine experience. While the engine starts more the engine maintains a higher temperature then ambient and is warm prior to start up [28]. More energy in th engine leads to a more complete combustion. Fuel is used more towards its entirety and results in fewre emissions. The engine needs less fuel to over compensate for cooldown in the cylinder if the engine is warm.

A full charge test is commonly used to test PHEV's for government standards such as the CAFE and CARB regulations with repeatability in mind full charge test is one where the depleting aspect of a PHEV is really tested [12]. A. A drive cycle is run continuously until CS mode is entered.

Vehicles that had seen a full charge test included a Toyota Prius HEVs with a hybrid conversion kit. The kit was an extra battery to extend vehicle range [12]. Each Prius had a different battery capacity and design approach but operations were similar.

During the test the vehicle data shows that the control systems had repeatable and stable depleting results [12]. A. The tests conducted included a few cycles of UDDS one after the other and highway driving. THE FTP drive cycle cold and hot weighted utility factor efficiency was evaluated and had similar results among the different aftermarket components [12].

Chapter III: Methodology

Research Approach

The test vehicle described in the introduction is the platform for testing. The ERAU EcoCAR 3 vehicle has a physical model that can be used to develop different control strategies. Using the model and the research from the literature reviews, different control strategies have been implemented to develop a reduced emissions strategy.

The vehicle was also taken to the Transportation Research Center in Liberty Ohio to have dynamometer emissions measured. The cases run include:

- FTP-75
- 505
- UDDS
- Custom emissions mapping

The FTP-75 was used to measure cold start emissions with the exhaust after treatment of an upstream and downstream catalytic converter. The custom emissions mapping was measuring full powertrain emissions at various accelerator pedal positions to collect data at a specific load point.

E&EC Drive Cycle

The testing case drive cycle used to measure emissions is going to be the EcoCAR 3 Emissions and Energy Consumption drive cycle. This cycle is a combination of the FTP, HWFET, US06 Highway portion, and the US06 city portion.

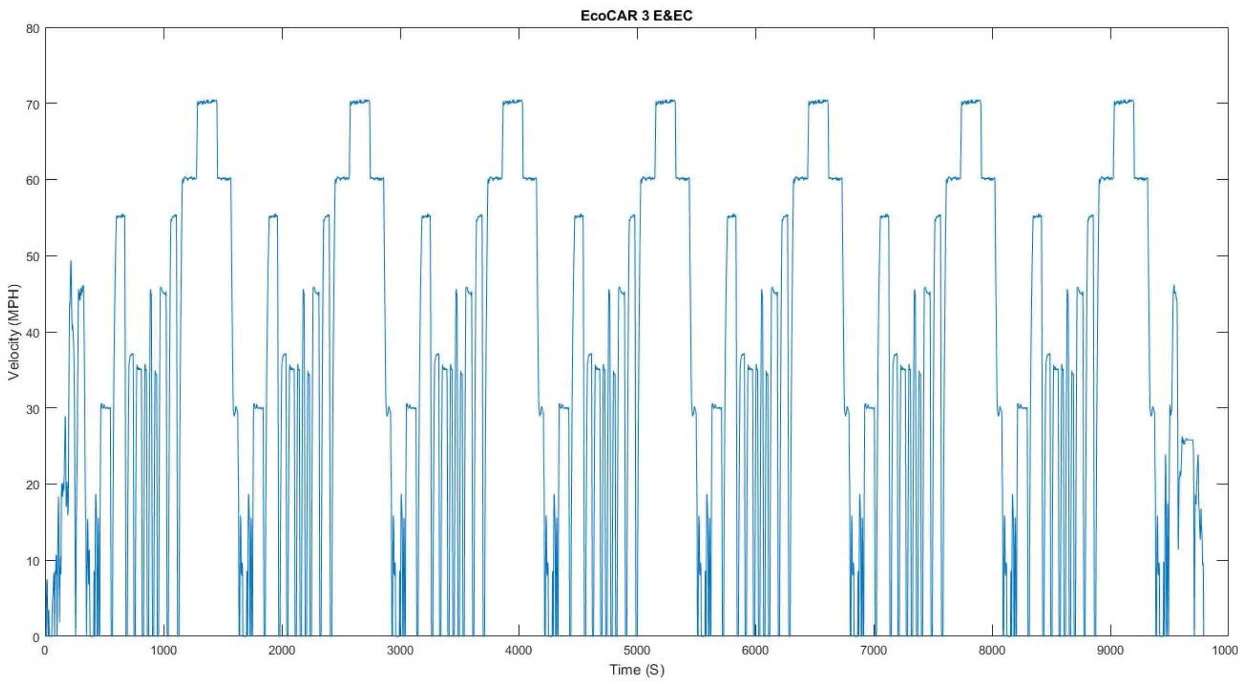

Figure 7 - EcoCAR 3 E&EC Drive Cycle

Figure 7 is the full E&EC trace that is run by the competition. The total distance of the cycle is 103.18 miles. This cycle includes the vehicle moving from the garage to the track and its return to the garage.

UF Weighting

Calculating the UF for the E&EC drive cycle is done at seven intervals. Within each interval GHG emissions, criteria emissions, electrical energy usage, and fuel consumption are UF weighted. The cycle's distances are:

Table 3 - E&EC UF Measurement Intervals

Interval 1 Distance	Interval 2 Distance	Interval 3 Distance	Interval 4 Distance	Interval 5 Distance	Interval 6 Distance	Interval 7 Distance
16.29 Miles	30.42 Miles	44.53 Miles	58.66 Miles	72.80 Miles	86.93 Miles	103.18 Miles

The first step of assessing the utility factor is to separate the data to each specific interval. This is done by simply extracting the data related to each distance variant stated above. The data is then averaged for the interval. A rate for the cycle is established of the averaged measured data over the distance of the interval. A cycle specific rate is then found.

Using the NHTSA data and a curve fitted equation from J1772 the UF can be assessed, and are shown in Equation 6.

$$UF = 1 - e^{-[C_1*(\frac{Distance}{399.9})+C_2*(\frac{Distance}{399.99})^2 ...+C_6*(\frac{Distance}{399.9})^6]}$$

Equation 6 - Utility Factor Calculations

Equation 6 is from SAE J2841 [2] and is how the UF is calculated to each of the seven intervals. A VMT weighting is found by subtracting each UF from the previous interval to find the weighting of each interval. The variables C_1 – C_6 are in Table 4and are coefficients that are curve fit from J2841 for the E&EC data.

Table 4 - UF Coefficients

C_1	10.52
C_2	-7.282
C_3	-26.37
C_4	79.08
C_5	-77.36
C_6	26.07

The measured data is then multiplied by the VMT number to get a fleet estimation for the current interval. Once each interval is weighted the results for each set of data is added up among the intervals.

$$Data\_set_{UF\ Weighted} = (UF_{current\ interval} - UF_{previous\ interval}) * Data\_Set$$

Equation 7 - VMT weighted Interval

Equation 7 is the equation to weight a single interval that is then summed with all the intervals to get an overall weighting for the vehicle.

- *Data_set* is the set of data being analyzed for the current interval
- $UF_{current\ interval}$ is the current interval being tested
- $UF_{previous\ interval}$ is the data set interval that was previously analyzed

The $Data\_Set_{UF\ Weighted}$ data is then summed among the 7 cycles. The sum of the seven cycles is the final values of emissions, both GHG and criteria, and fuel economy, both electrical energy and fuel used.

Plant Model Development

The plant model used has two parts. An initialization script in Matlab to assign each variable and a Simulink physics model. Each component was modeled based on manufacturer information provided and measured data.

Engine Model

The 2.4L 4 cylinder Ecotec engine from the ERAU EcoCAR 3 vehicle discussed in the introduction was modeled by Mathworks and provided to the EcoCAR 3 team. This model inputs torque request, mode, and engine rpm. Torque request is sent from the driver model and is the APP but the engine model provided by GM requires a throttle position. This is due to the method for looking up emissions and torque.

The model looks at throttle position to calculate airflow into the engine. The model then has a series of lookup tables for emissions, fuel usage, and output torque that need airflow in the intake and engine speed to output values.

The GM model is derived from an engine on an engine dynamometer. The emissions are hot soaked treated. The cold start emissions are not captured accurately with this model.

The model needed an additional idle so that at the various stopping portions the vehicle could idle in some mode. The drive cycles being used for this paper require the vehicle to stop and engine to idle. To prevent the engine from just shutting down while observing non start/stop capabilities a serious of switches and rate limiters maintain engine idle speeds when vehicle velocity is zero. When start/stop is possible, the engine will then power down and start up based on torque demand and mode.

The engine also has an idle torque that would not allow the vehicle to achieve 0 mph during testing. To compensate for this a set of logic was added so that when the driver model applies the brakes the engine would apply idle torque but the vehicle would not move.

Electric Motor Model

The vehicle has a traction motor and generator both of which are the Bosch IMG electric machines. Torque, power, and efficiency curves are proprietary however the method to model the motor will be explained. The SCU sends a torque request to each component depending on the strategy. Both motors are modeled the same with the capability to apply torque and generate electricity. In regenerative braking, parallel operations, or just charge depletion mode both motors need the capability to apply positive and negative torque.

For the motor to apply torque, whether it be positive or negative, motor speed and a torque request are inputs into the model. The torque of the motors is a look up table of the input speed and the HV bus voltage available for use. Based on a power command coming into the IMG block, the motors are also power limited by the batteries. If the torque request is positive then a positive torque is produced. If a negative request comes in the motor will enter regenerative braking.

Input powertrain speed is entered into a lookup table with voltage to output the highest possible torque available. The motor torque is then compared to requested torque to determine if the requested torque can be met. In regen the requested torque and motor torque are compared to see which value is the smaller possible torque. Positive torque compares requested torque to the motor torque and the greater of the demanded and possible is used.

The motor torque is then output based on the capabilities and is converted to power with Equation 8.

- $T_{lookup\ table}$ is the torque the motor is outputting from the torque lookup table based on voltage and motor speed
- $S_{motor\ speed}$ is the speed at which the motor spins
- η is the current efficiency of the motor. The motor efficiency is a look up table that inputs RPM and current torque.

$$P_{motor} = \frac{T_{lookup\ table} * S_{motor\ speed}}{c}$$

Equation 8 - Motor Power Calculation

The motor power is then compared to the power output of the HV bus. The power is checked against the power the ESS can provide the motor, thus power limiting the motors. Negative torque is compared as well but for a higher power output. Ideal power from both scenarios is then back calculated to find the torque output of the motor shown in Equation 9.

$$T_{motor\ output} = \frac{P_{ess} * \eta_{motor\ efficiency}}{S_{motor\ speed}}$$

Equation 9 - Motor Output Torque

- P_{ess} is the power the battery can provide to the motors

This architecture has two of the same electric motors in series with the engine there for both motors are modeled the same and represented in Figure 8.

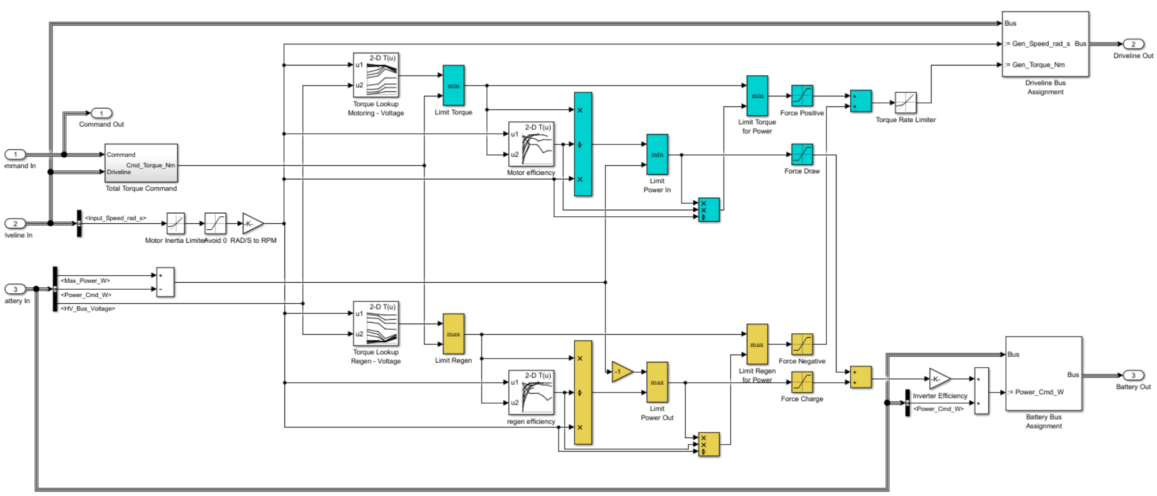

Figure 8 - Bosch IMG Motor model.

Transmission and Final Drive Model

The GM 8L90 transmission model includes a torque converter for slip of the powertrain to the wheels. Combined torque is multiplied by a torque multiplier factor based on the slip ratio to simulate the slip of the powertrain until the torque converter locks up.

To shift gears the transmission uses a multiport switch of gear ratios and multiplies total powertrain torque by the ratio.

Table 5 - GM 8L90 Gear Ratios

First Gear	Second Gear	Third Gear	Fourth Gear	Fifth Gear	Sixth Gear	Seventh Gear	Eighth Gear
4.56	2.97	2.08	1.69	1.27	1.00	0.85	0.65

The multiport switch inputs a gear command from the shift logic of the SCU. GM provided the ERAU EcoCAR 3 team the stock shift logic. The transmission requests zero torque briefly between shifts so when the vehicle commands a shift torque is changed to zero briefly with a time delay until the new gear is achieved. Input speed is also multiplied by gear ratio to estimate vehicle speed. Figure 9 is the transmission model wired up in Simulink.

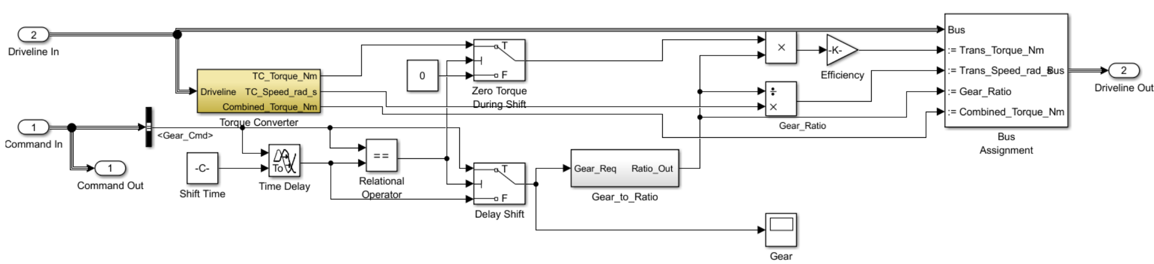

Figure 9 - Transmission Model

The final drive is calculated by multiplying the torque and speed out of the transmissions by the final drive ratio of 2.85 and the final drive efficiency. The tractive force calculation is represented in Equation 10. Figure 10 is the final drive model. Axle speed and axle torque are then used with the vehicle glider model to model vehicle speed.

$$F_{tractive} = \frac{T_{transmission} * FD_{ratio} * \eta_{final\ drive\ efficiency} * \eta_{trans\ efficiency}}{R_{wheel}} + F_{Braking}$$

Equation 10 - Tractive Force Equation

- $F_{tractive}$ is the tractive force of the powertrain in Newton
- $T_{transmission}$ is the torque output of the transmissions
- R_{wheel} is the radius of the wheel in meters
- FD_{ratio} is the final drive ratio of 2.85
- $\eta_{final\ drive\ efficiency}$ is the efficiency of the differential at 0.95
- $\eta_{trans\ efficiency}$ is the transmission efficiency
- $F_{Braking}$ is the brake force calculated in the glider model

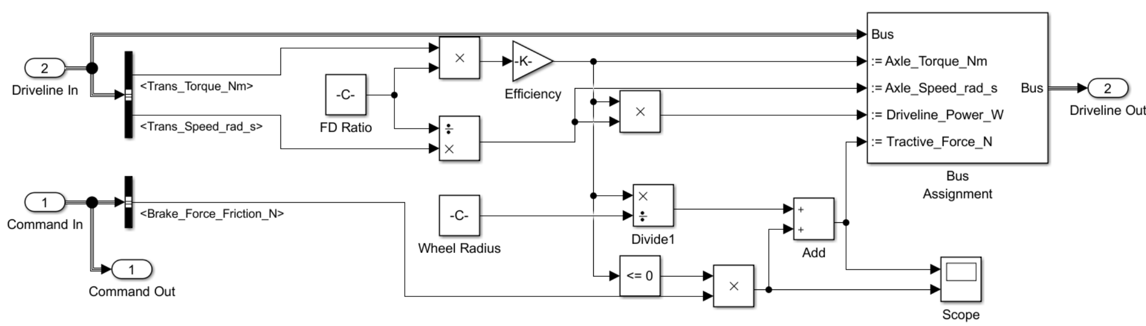

Figure 10 - Final Drive Model

ESS Model

The ESS being used is an 18.9kWhr A123 lithium ion ESS. The model calculates the change in SOC of the vehicle. The SOC dictates the power available to the motors and is used with a look up table to find HV bus voltage.

To calculate the SOC, commanded power is used with the accessory load on the HV bus due to the DC/DC converter. The change in SOC is calculated in Equation 11.

$$SOC = \int_{18.9kWhr}^{\Delta PW} -P_{commanded} * \eta_{battery\ efficienccy} - PW_{commanded} - L_{acc}\, dt$$

Equation 11 - Dynamic SOC Capacity

- *SOC* is the changing capacity of the ESS based on usage
- $P_{commanded}$ is the power needed to meet the torque demand
- ΔP is the change in power requested from the previous time step
- $H_{battery\ efficiency}$ is the efficiency of the battery
- L_{acc} is the loss of power due to the accessories

To find the SOC the dynamic capacity is divided by the maximum capacity to get a percentage of remaining capacity. The SOC is then fed into a look up table of battery SOC against max power output of the battery. Max power of the ESS is now known and the accessory load is subtracted to account for the available power to the motors.

The ESS limits power to the motors as well. A look up table of the max power based on SOC is used to output the max power. This will power limit the motors and prevent the model from drawing more power than the ESS is capable of supplying.

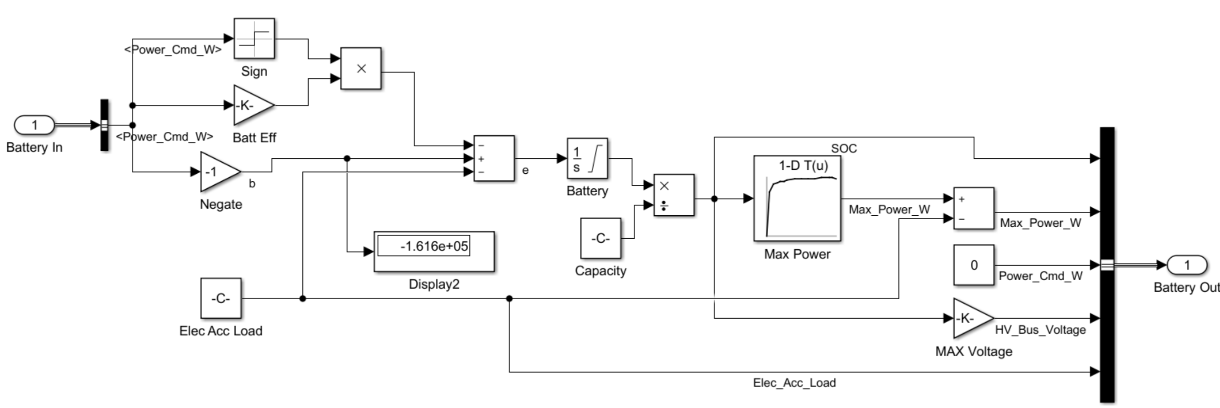

Figure 11 - ESS Model Simulink

Glider Model

The glider model calculates the dynamics of the powertrain. Torque at the axle is calculated by multiplying the tractive force by the wheel size. Power at the wheels is calculated by multiplying the tractive force by the vehicle velocity. Tractive energy, propelled energy, and brake energy are found by integrating the tractive power. If the energy is negative then it issued to find braking force and if the energy is positive it goes towards accelerator pedal position.

$$E_{propelled/brake} = \int F_{tractive} * V_{vehicle\ speed} dt$$

Equation 12 - Wheel Energy Equation

- $E_{propelled/brake}$ is the energy at the wheels
- $V_{vehicle\ speed}$ is the speed of the vehicle

To calculate the force of the vehicle rolling aero loads, rolling resistance, and grade force need to be calculated. The equations are listed in Equation 13.

$$F_{grade} = MG * \sin(grade_{\%})$$

$$F_{aero} = 0.5 * \rho_{air} * C_d * V_{vehicle\ speed}^2$$

$$F_{rolling} = MGC_{rr}$$

Equation 13 - Force due to Grade (TOP); Aerodynamic Force (Middle); Rolling Resistance (Bottom)

- F_{grade} is the force due to a grade
- M is the vehicle mass 1922 Kg
- G is acceleration due to gravity
- $Grade_{\%}$ is the percentage of grade
- C_d is the coefficient of drag

- ρ_{air} is the density of air 1.2 kg/m^3
- F_{aero} is the load due to the aero dynamics
- $F_{rolling}$ is the rolling resistance force
- C_{rr} is the coefficient of rolling resistance 0.76

Using the tractive force, force due to grade, aero loading, and rolling resistance the rolling force of the vehicle is found. The rolling force can be used to find vehicle speed.

$$F_{rolling} = F_{tractive} - F_{grade} - F_{aero} - F_{rolling}$$

Equation 14 - Rolling Force

By integrating Equation 14 the vehicle velocity can be found. $I_{inertial\ mass}$ is the inertial mass that needs to be divvied by rolling force to get the vehicle speed. To get distance vehicle speed is integrated as well.

$$V_{speed} = \iint \frac{F_{rolling}}{I_{inertial\ mass}} dtdt$$

Equation 15 - Vehicle Speed Calculation

Figure 12 is the Simulink model associated with the glider equations. This model takes inputs from the transmissions and outputs to the driver and SCU model.

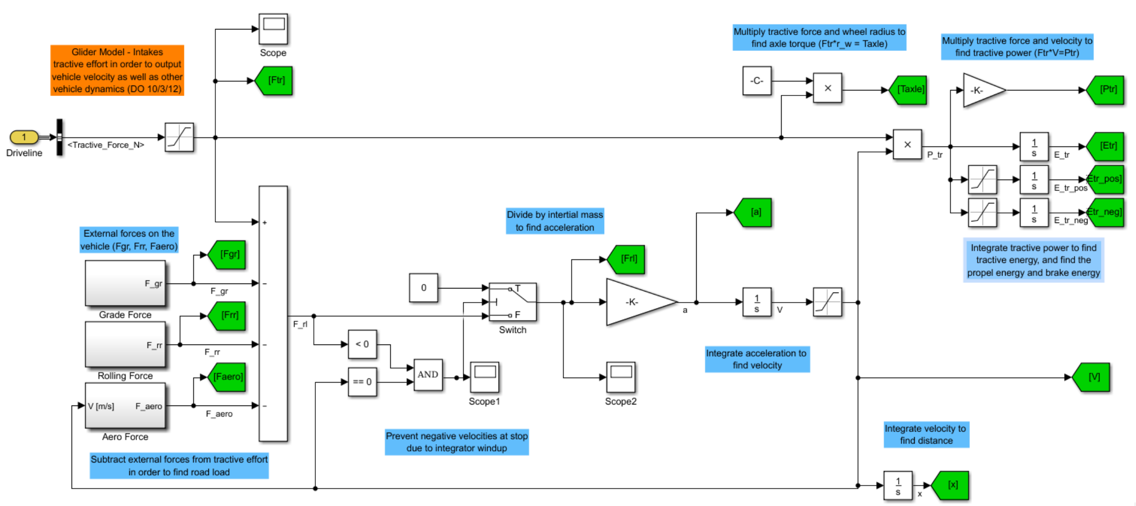

Figure 12 - Glider Model Equations in Simulink

Driver Model

The driver model uses the vehicle speed trace that is initialized to output APP and brake force. A PID controller is uses that inputs the velocity of the trace subtracted from the current vehicle speed. The PID out puts APP and the brake force.

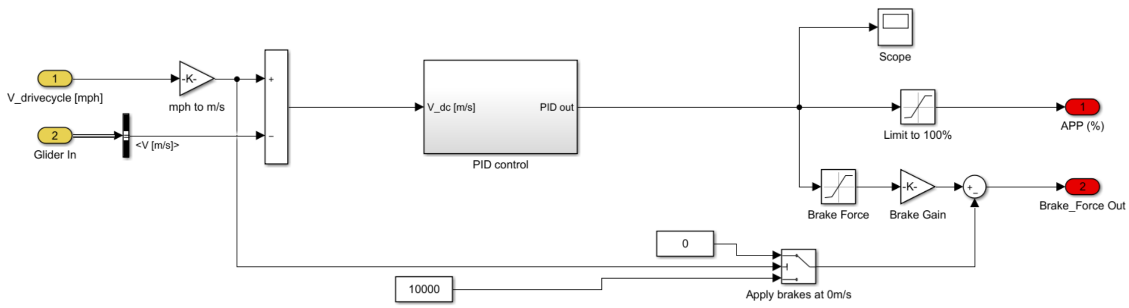

Figure 13 - Driver Model

Catalytic Converter Model

The engine model provided by Mathworks does not include cold start emissions but uses data after heat soaking the engine. The test vehicle has an upstream and downstream catalytic converter. The test vehicle had run the FTP-75 drive cycle at TRC in Liberty Ohio. This drive cycle coincides with modeling of cold start emissions until the catalyst is heat soaked.

For the sake of this model and development of a powertrain to reduce emissions assumptions were made of catalytic converter. The first assumption is that power lost in the engine is through heat in the cooling system, oil system, and heat in the exhaust.

Measurements of power loss versus power from heat at the catalytic converter were taken. This was done by measuring the engine torque, engine rpm, and catalyst temperature at a constant 150 Nm. The data from the dyno run is captured in Figure 14.

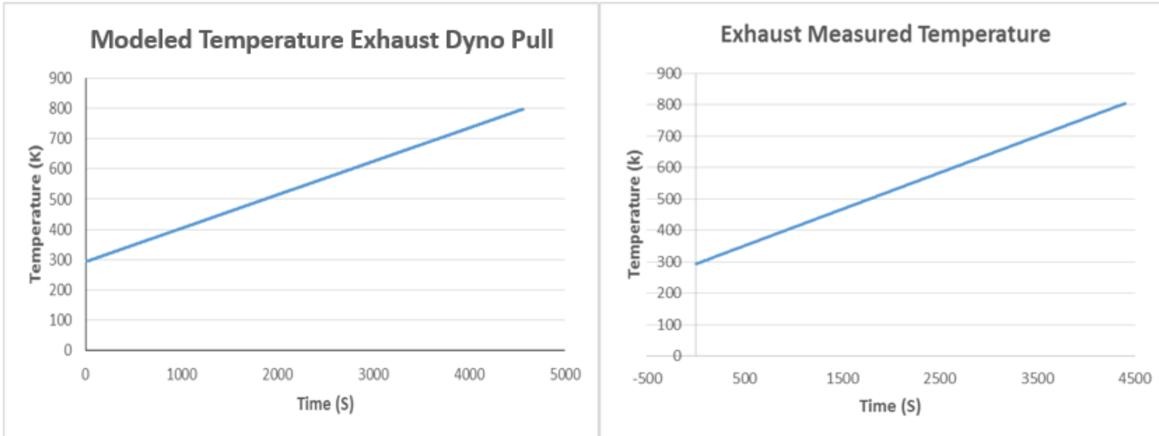

Figure 14 - Measured Catalyst Warm Up Data Against Modeled

With the measurements of torque, engine speed, and fuel usage the efficiency can be found and used to find lost power.

$$PW_{ICE\ lost\ power} = \left(1 - \frac{\dot{m}_{fuel\ flow} * HV_{E85}}{T_{ice} * S_{ice}}\right) * T_{ICE} * S_{ICE}$$

Equation 16 - Power Lost To Engine

- T_{ice} engine torque at the crank shaft
- S_{ice} is the engine speed
- $\dot{m}_{fuel\ flow}$ is the mass flow rate of fuel into the engine
- HV_{E85} is the heating value of E85
- PW_{ice} is the power lost through the engine

Equation 16 calculates the total power loss of the engine. This was measured compared to the temperature in the catalyst. Knowing the volumetric efficiency of the ICE the mass flow rate through the exhaust is known. Solving for the power of each component of the emissions the power generated at the catalyst can be found.

$$Q_{HC\ NO_x\ CO\ CO_2} = \dot{m}_{exh} * C_{HC\ NO_x\ CO\ CO_2} T$$

Equation 17 - Power Due to Exhaust Heat

- $Q_{HC\ NOx\ CO\ CO2}$ is the power lost from each gas independently
- $\dot{m}_{exh}$ is the mass flow rate through the exhaust
- $C_{HC\ NOx\ CO\ CO2}$ is the specific heating value of each component of exhaust
- T is the instantaneous temperature measured at the catalyst

All the power produced from each of the exhaust gases are summed to get a combined power. In the Catalyst. Equation 17 and Equation 16 yielded a look up table that is graphed in Figure 15. The table uses the power loss from the engine in the model to look up the power due to heat in the catalyst. As power loss in the engine increases power into the catalyst increases.

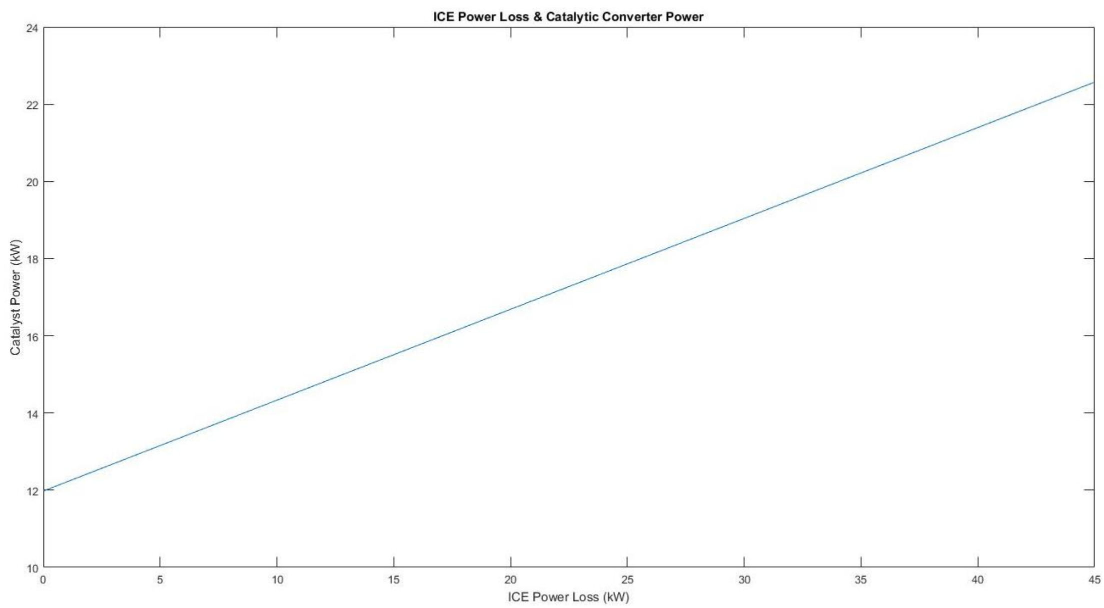

Figure 15 - ICE Power Loss against Catalyst Power

Using data from Equation 17 a look up table of energy in the Catalyst against the temperature of the catalyst can be created. The look up table is shown in Figure 16. The power going into the Catalyst to get temperature is not instantaneous. When the engine is not running then the catalyst cooldown is from convection with air of the car moving and radiation. Power of convection and radiation is removed from the exhaust energy.

Therefore the power term was converted to energy by multiplying the time step of data collection by the power term. The Catalyst power is integrated to find the energy in the catalyst at the given point..

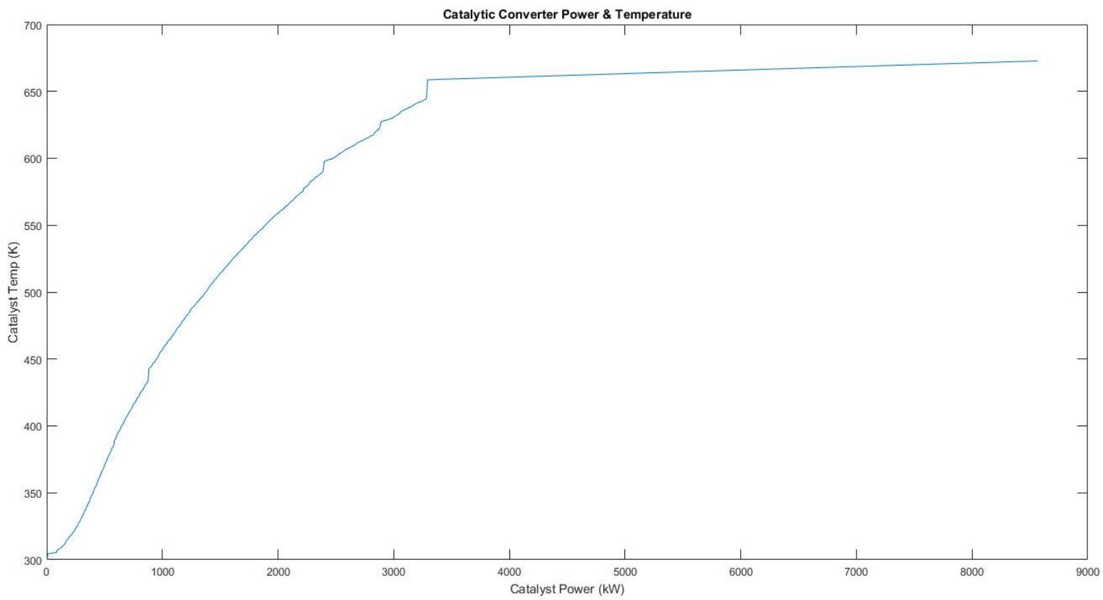

Figure 16 - Catalyst Power against Temperature

As the power of the catalyst increases the temperature increases. Temperature was measured using thermocouples on the catalyst and exhaust pipe in and out of the catalyst. The temperature of the pipe is the assumed proxy for temperature of the exhaust gases.

The catalyst efficiency was derived from model data and measured data. The Camaro was tested at TRC with a treated exhaust. A downstream and upstream CAT was present. The engine model had run the FTP-75 cold start emissions to measure treated data.

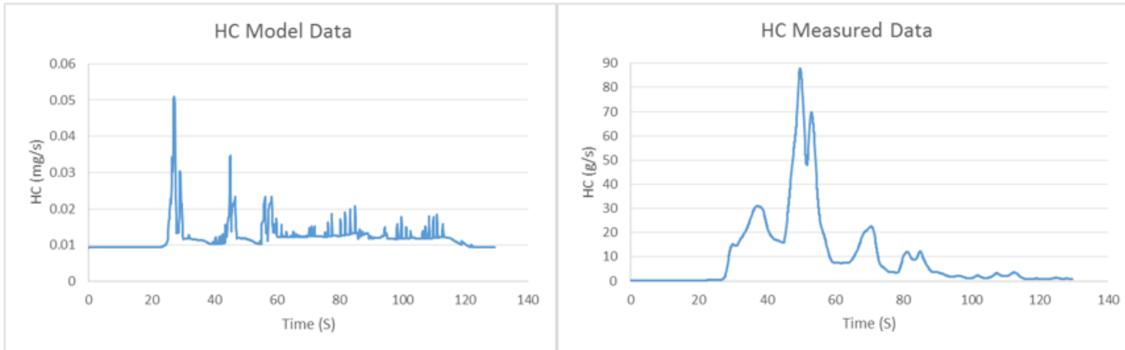

Figure 17 - Model and Measured HC Data

Figure 17 is the measured and modeled data cold start emissions from the first 120 seconds of the FTP-75. The measured data is higher than model data. The engine model look up tables were measured from a hot soaked treated exhaust. To create the efficiency of the cold start an efficiency of measured over modeled was created until light off is achieved.

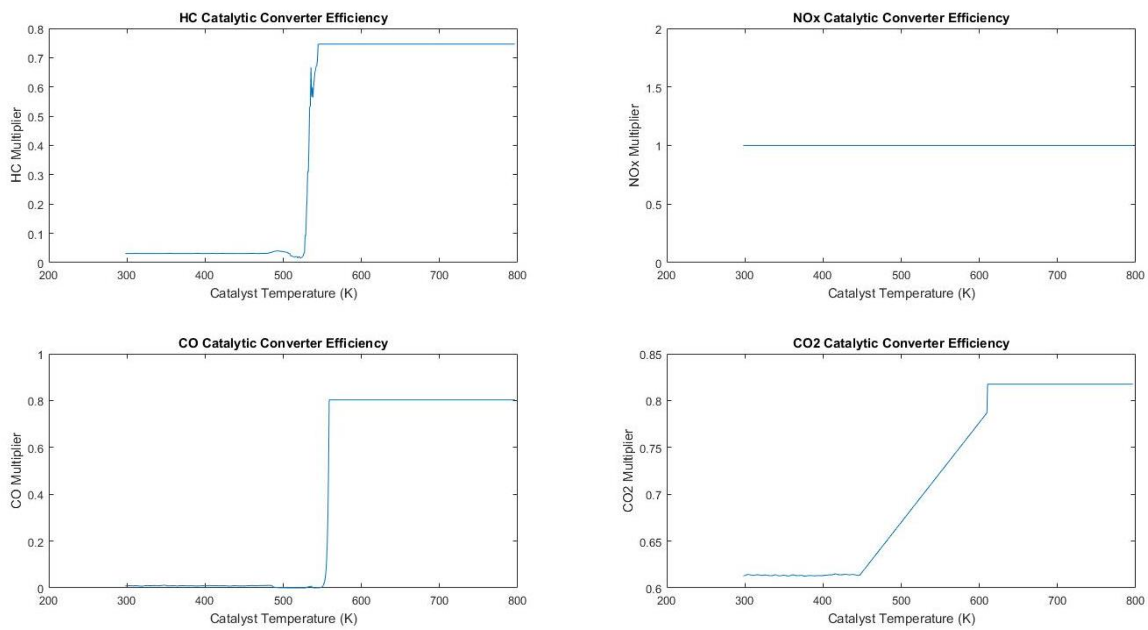

Figure 18 - Efficiency against Temperature of Catalyst

Figure 18 represents the efficiency accurately. At 350 °C the catalyst achieves light-off and is at its most efficient operating point. This is why the data trends towards a steady state.

Supervisory Controller Development

The SCU is the primary variable to change for the development of a controls strategy to reduce emissions. Multiple methods of maintaining light-off temperatures in the catalyst and different loading options are tested and UF weighted.

The default manufacturer method for a PHEV is currently a maximum depletion strategy. CD mode range is consumed immediately in the cycle and CS is engaged when SOC is at a point where functionality against usage is questionable.

Maximum Depletion Accessory Load Strategy

The maximum depletion strategy is the most common strategy in advanced vehicle technology competitions as well as in industry. This mode is the Maximum Depletion Accessory due to the fact that when the vehicle enters CS mode only the power needed to power the vehicle functionality and accessories is recaptured. The strategy is one in which the vehicle has a set threshold for CS mode based on SOC. The maximum depletion strategy for this vehicle includes a CS and 2 different CD modes.

With two electric motors one motor or both motors can be used to drive the vehicle. Based on the power demand needed to satisfy the drive cycle one motor can be used. The motors and engine can be engaged and disengaged based on the clutches between the torque producing components. This controller will output the mode in which the vehicle is in and will send a state request to the components. This state request will have the torque producing components and clutches enter operational modes.

Table 6 - Max Depletion Table of Equations

	Mode (#)	ICE	Generator Motor	Traction Motor
Single CD	1	$T_{S/CD} = 0$	$T_{S/CD} = 0$	$T_{S/CD} = APP_{request}$
Dual CD	2	$T_{S/CD} = 0$	$T_{D/CD} = 0.5(APP_{request})$	$T_{D/CD} = 0.5(APP_{request})$
Parallel CS	3	$T_{CS} = APP_{request} + \frac{P_{acc}}{S_{input}}$	$T_{CS} = 0.9 * \left(\frac{-P_{acc}}{S_{input}}\right)$	$T_{CS} = 0.1 * \left(\frac{-P_{acc}}{S_{input}}\right)$
SOC CS	25 %			

- $T_{S/CD}$ is the torque request of the component in single CD mode
- $T_{D/CD}$ is the torque request of the component in double CD mode
- T_{CS} is the torque request of the component in double CD mode
- $APP_{torque\ request}$ is the torque request sent to the SCU from the driver input
- S_{input} is the input speed of the powertrain into the transmission in Rad/S
- P_{ACC} is the electrical load of the electrical systems drawing current through the HV bus from the DC/DC converter

Table 1 is the equations used for the maximum depletion strategy. The SOC threshold for the strategy is 25%. This is due to the limitation of the HV components on the HV bus to prevent failures.

In CD mode the engine is off and fuel is not consumed. The generator and motor split torque in dual CD mode to achieve a higher torque when needed. Maximum torque in a single motor is 347 Nm but combined can be up to 694Nm. This mode is only used as needed. If no more than 347Nm of torque is needed the second motor does nothing.

In CS mode the ICE is trying to load follow with the vehicle. This requires the engine to supply more torque then necessary to drive to compensate for accessory usage. The engine operates at a higher torque and propels the car. The generator is applying torque with the ICE while the traction motor is applying negative torque to recapture energy from accessories.

Charge Preserve SOC Strategy

This strategy begins with a CD mode range maximum depletion. Once CP SOC is entered rather than load following the powertrain will run an engine optimal case. An engine optimal case uses the torque request by the driver in a look up table of the most efficient torque values at the given RPM. By running the engine at the optimal efficiency less fuel is consumed and there for less emissions produced.

To run the engine in an optimal load case first a look up table of RPM against optimal torque values had to be generated. To do this an efficiency plot of the engine was made.

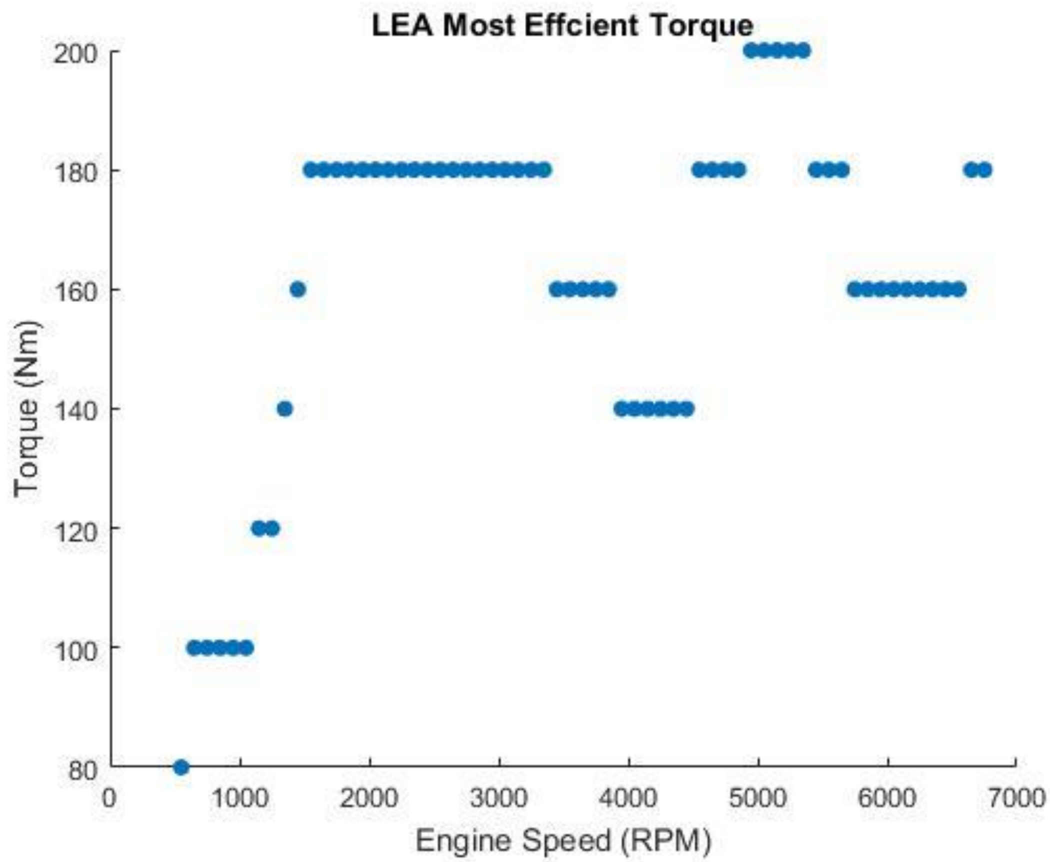

Figure 19 - LEA E85 Optimal Torque

Figure 19 is a plot of the most efficient operating points of the engine. The model interpolates between the points to operate the engine at the most efficient torque based on engine speed. The engine is also limited from entering a negative torque or engine braking.

The Electric motors then calculate a torque to apply to the powertrain, either positive or negative. Table 7 is the equation breakdown when in CP SOC mode. Similar to Max depletion the initial CD mode has no engine operation and can go between a single and double motor strategy.

Table 7 - CP Mode SOC Table of equations

	Mode (#)	ICE	Generator Motor	Traction Motor
Single CD	1	$T_{S/CD} = 0$	$T_{S/CD} = 0$	$T_{CD/CP} = APP_{request}$
Dual CD	2	$T_{D/CD} = 0$	$T_{D/CD} = 0.5(APP_{request})$	$T_{CD/CP} = 0.5(APP_{request})$
Single CP	3	$T_{CP} = T_{ICE}$	$T_{CP} = 0.9(APP_{request} - T_{ICE})$	$T_{CP} = 0.1(APP_{request} - T_{ICE})$
Dual CP	3	$T_{CP} = T_{ICE}$	$T_{CP} = 0.5(APP_{request} - T_{ICE})$	$T_{CP} = 0.5(APP_{request} T_{ICE})$
SOC CP	25 %			
SOC CD	30%			

- T_{ICE} is the optimal torque from the look up table
- $T_{S/CD}$ is the torque of the component in single CD mode
- $T_{D/CD}$ is the torque of the component in dual CD mode

A PHEV scores a higher UF weighted fuel economy when a max depletion CD range is used. Maintaining the CD range should prevent any fuel economy disturbances in fuel consumption. This vehicle is estimated at approximately 35 miles of CD range.

This CP SOC mode strategy focusses primarily on the SOC of the vehicle currently. Once the vehicle enter CP SOC mode at 25% SOC the vehicle will remain in the mode until the SOC returns to 30%. Once at 30% SOC the vehicle will reenter CD mode, either single or double, and consume electrical energy until SOC reaches 25%.

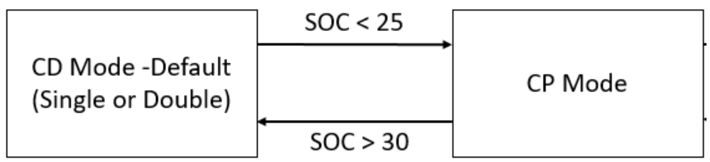

Figure 20 - CP SOC Mode Thresholds

CP SOC mode uses the motors and torque request to load the engine. In the event that the engine is operating at the optimal torque when torque is requested the motors will apply a minimal negative torque.

If the engine is operating at an optimal torque higher than the torque request then the motors will enter a negative torque state. This state will allow the vehicle to recapture charge. Figure 21 is a diagram of the inputs and outputs of the powertrain components torque requests. Input speed is dictated based on vehicle speed and there for the engine can use the optimal torque and power curve/ The motors compensate for the engine regard less of positive or negative torque.

The engine is limited to a minimum of 0 Nm of torque this is the lowest efficient operating torque. Preventing engine braking will benefit fuel economy due to the vacuum created from this effect. When the throttle is closed and the engine draws a vacuum the cylinder use more energy to overcome the vacuum pressure. Rather than engine braking regenerative braking will load the engine and serve the same purpose more efficiently by generating power.

If the engine torque operates at a lower value then the requested torque the motors will apply a positive torque and a negative torque. This will enter a traditional CS mode. The charge will be sustained until a better load point is reached.

When a negative torque is applied in this strategy the engine will recapture charge. This strategy does not take the exhaust into account. Strictly optimizing for fuel economy based on the torque requested to load the engine. A higher efficiency and load can result in lower emissions.

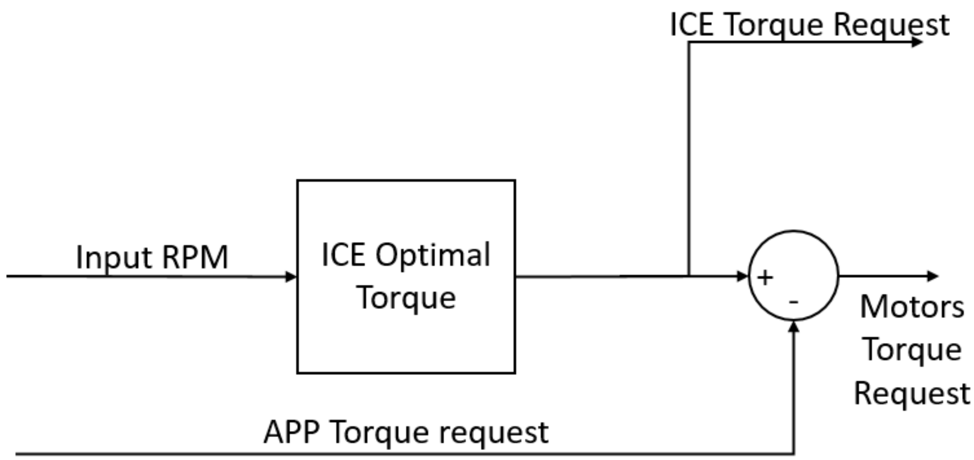

Figure 21 - CP Mode Motor and Engine Torque Breakdown

Charge Preserve Exhaust Gas Temperature

This CP mode focuses not only on SOC but maintaining light off temperatures within the catalyst. The equations in Table 7 are the same as CP SOC but the strategy and thresholds change. Figure 21 is the visual representations of the same questions in the CP SOC mode that hold true for CP Exhaust mode. This mode maintains the temperature in the Catalyst above light off so that the catalyst is always at peak efficiency.

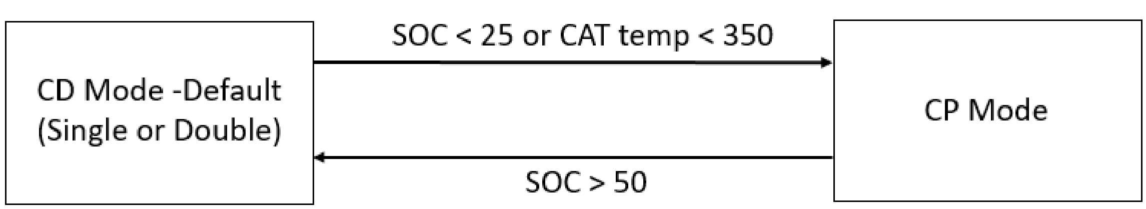

Figure 22 - CP Exhaust Mode Thresholds

The catalyst achieves light off at 350°C and will enter CP mode once the Catalyst drops below this threshold. The strategy still has a CD mode range and will not turn the

Engine on until the initial startup at 25% SOC. Once the vehicle enters CP Exhaust mode the engine will not shut down until 50% SOC. At this point if the catalyst is warm the engine will shut down and return to CD mode. Once CD mode is enter catalyst temperature will be measured and due to conduction and radiation cool. If the vehicle reaches 25% SOC or 350°C then CP Exhaust mode will be entered. Only one of the two criteria needs to be met.

The mode numbers are the same in Table 7 excluding the single and dual CD mode return to CD. An initial CD mode had to be instituted so that the engine does not immediately start up due to exhaust temperature. Once the engine starts initially the vehicle CD and CS mode modes are numbers 5 and 6 respectively. The same equations are used for the component torque requests as modes 1 and 2.

Chapter IV: Results

Max Depletion Results

The maximum depletion strategy followed the trace within a 1% accuracy. The trace is in Figure 23 and the vehicle drove the full 103 mile journey without any interruptions.

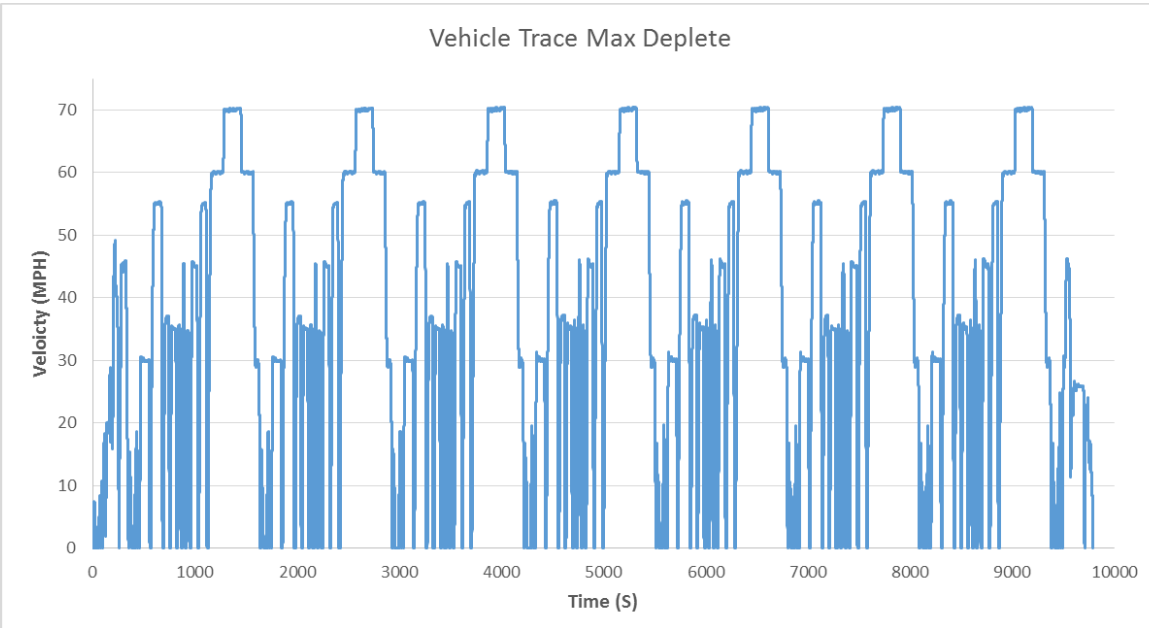

Figure 23 - E&EC Driven Trace Max Depletion

Max Depletion Fuel Economy

The max depletion controller operated as intended. Figure 24 is a graph of the SOC throughout the distance traveled. At 35 miles the vehicle entered CS mode allowing for 35 miles of CD mode. The controller responded correctly and sustained charge at the 25% threshold. The overall trend of SOC dropping the further the vehicle goes is as expected. Small spikes of SOC rising to 30 at points around 50, 80, and 90 miles are the points at which the vehicle maintained charge enough to reenter a single CD mode. This was due to the regenerative braking negative torque compounded with the negative torque to meet the minimum power demand to continue driving.

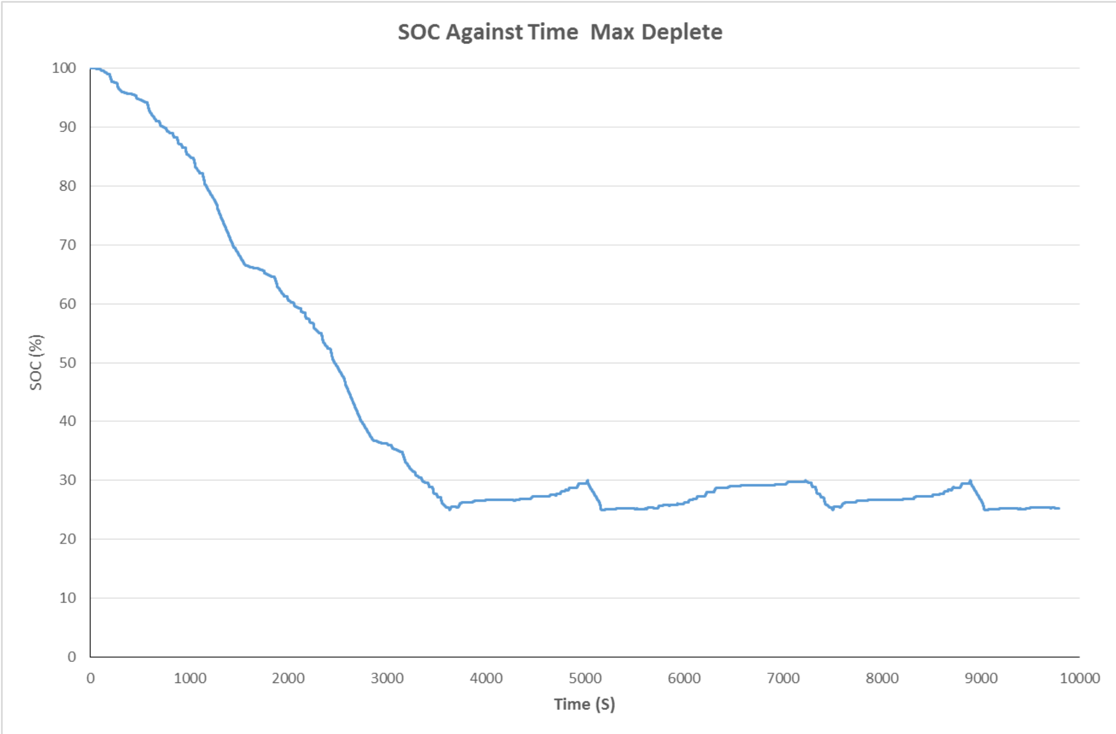

Figure 24 - SOC against Time Max Depletion

The vehicle mode switch is shown in Figure 25. The CD mode consisted primarily of a single motor CD strategy. This effectively means one motor can drive the car while the other is decoupled.

Throughout CS mode the vehicle would charge up to the 30% threshold and reenter CD mode. This reduced the use of the engine and overall fuel usage. The clutches are engaged and disengaged to shut the engine down and allow CD mode. However due to CD mode reentry at 30% SOC and CS mode activating at 25%. The longest duration of reentered CD mode was 4.5 minutes.

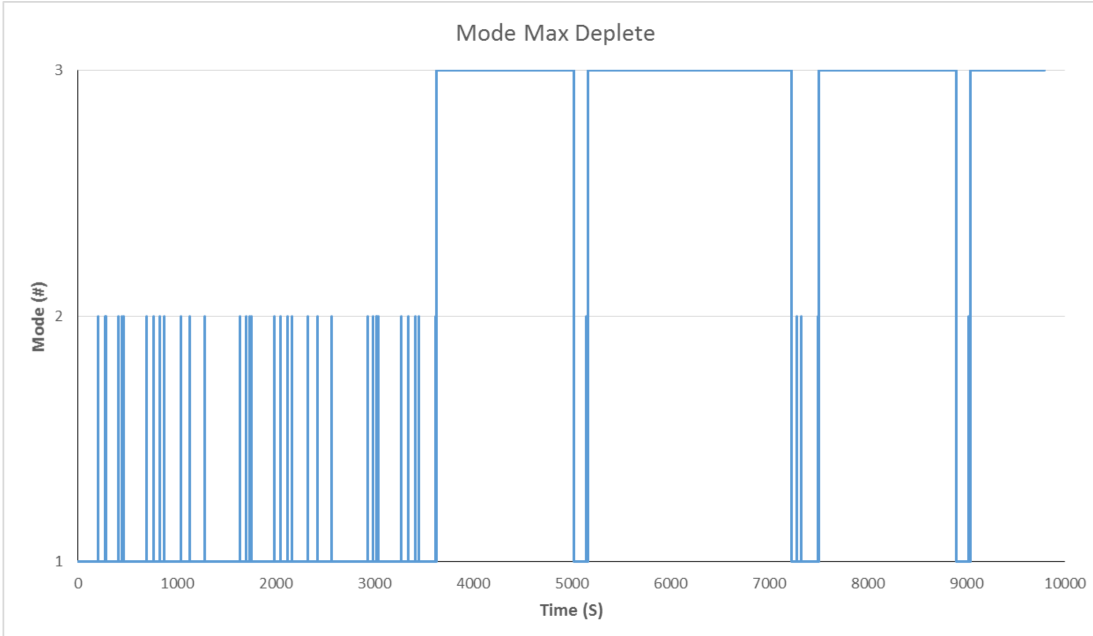

Figure 25 - Mode Switching Over Time Max Depletion

Figure 26 is the overall fuel usage. The fuel usage followed an expected trend of turning the engine on at the end of the CD range and increased throughout operation. Fuel was consumed over the 65 mile CS mode duration excluding the reentered CD modes.

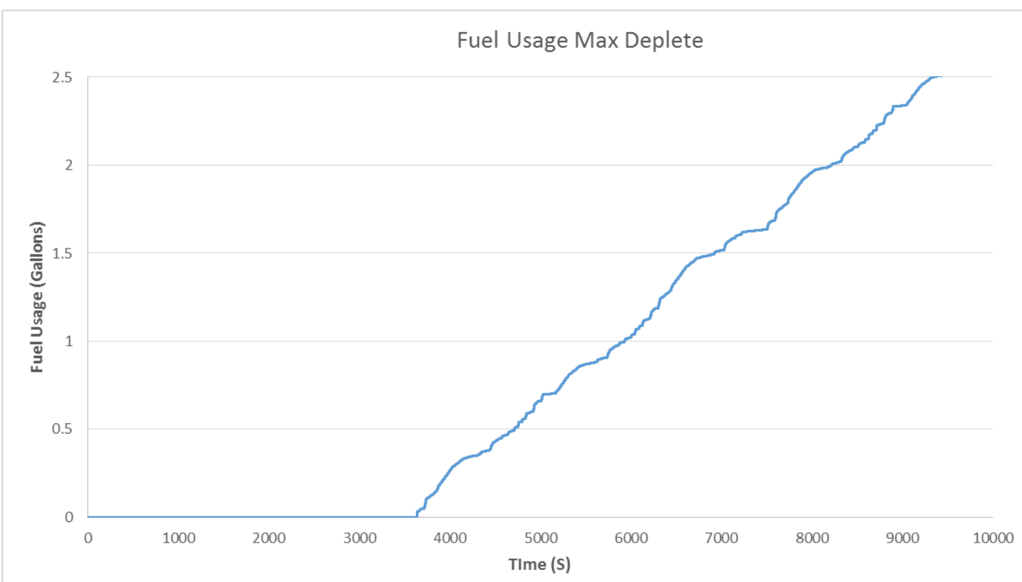

Figure 26 - Max Depletion Fuel Usage

Max Depletion Emissions

Figure 27 is a graph of the emissions summed based on time. At the beginning of the graph emissions are at zero. The vehicle was in CD mode so no torque was produced by the engine. As the cycle progressed the sum increased as expected.

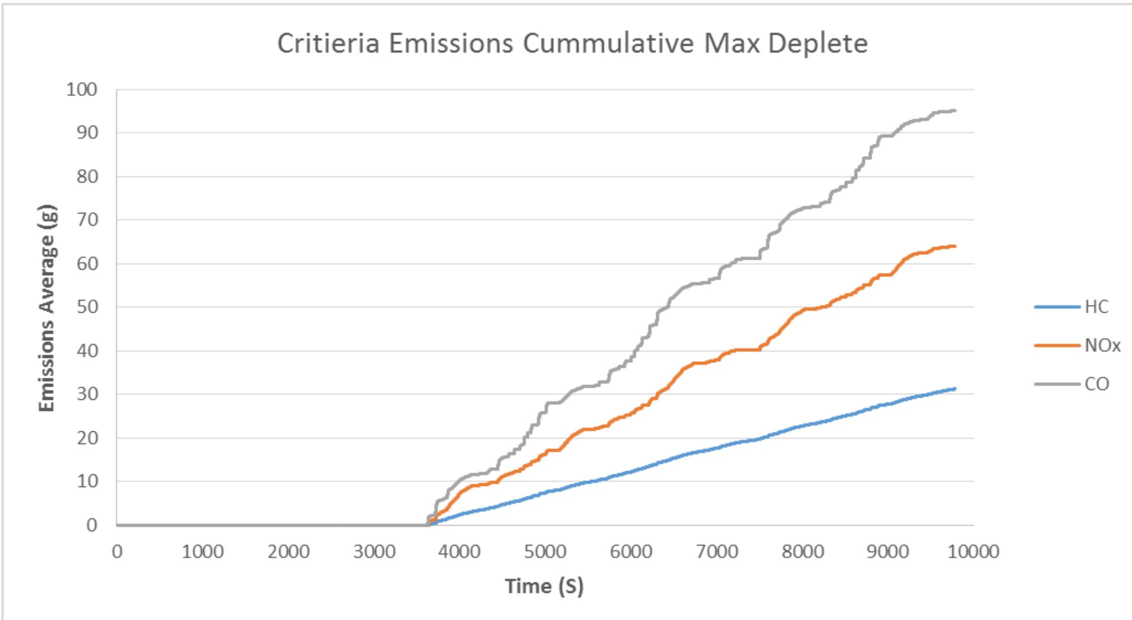

Figure 27 - Max Depletion Criteria Emissions

Figure 28 is data of the initial cold start of the engine. This data is the instantons rate at which emissions are produced based on the startup of the engine. The initial startup within the first second has low emissions. The fuel is being introduced into the cylinder to start combustion. This is the only cold start event in the maximum depletion strategy due to engine maintaining charge and continuously running.

The engine begins to add more fuel into the cylinder to achieve light off in the catalyst. More fuel leads to the large spike in emissions because the exhaust is not warm enough to achieve maximum efficiency. Once the catalyst is at the maximum efficiency possible at 350°C, the emissions achieve a steady state production rate. The exhaust maintains temperature the remainder of the cycle. The brief CD modes attest to 6.8% of the CS mode operation and do not let the catalyst cool down.

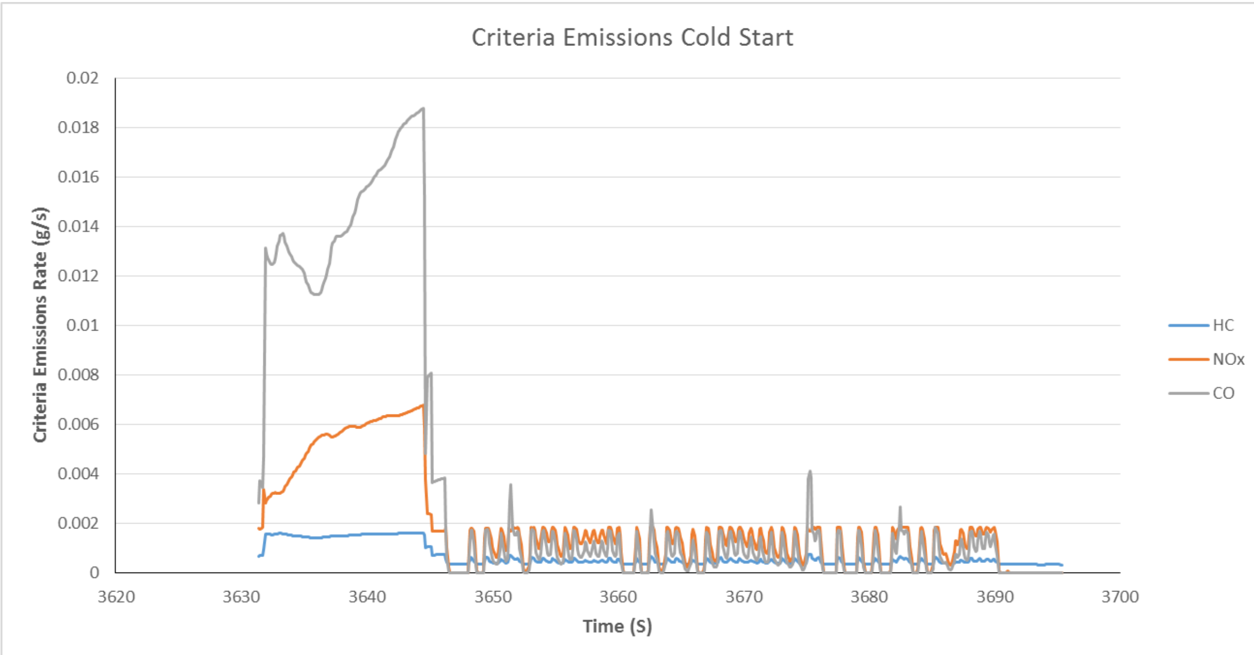

Figure 28 - Cold Start Emissions Spike Max Depletion

GHG emissions production is in Figure 29. The values for the production of CO_2 are higher than the criteria emissions. This is due to the fact that more CO_2 is produced than any other emissions. If the combustion was pure and no other elements were introduced to the burn then CO_2 would be the only emitted gas.

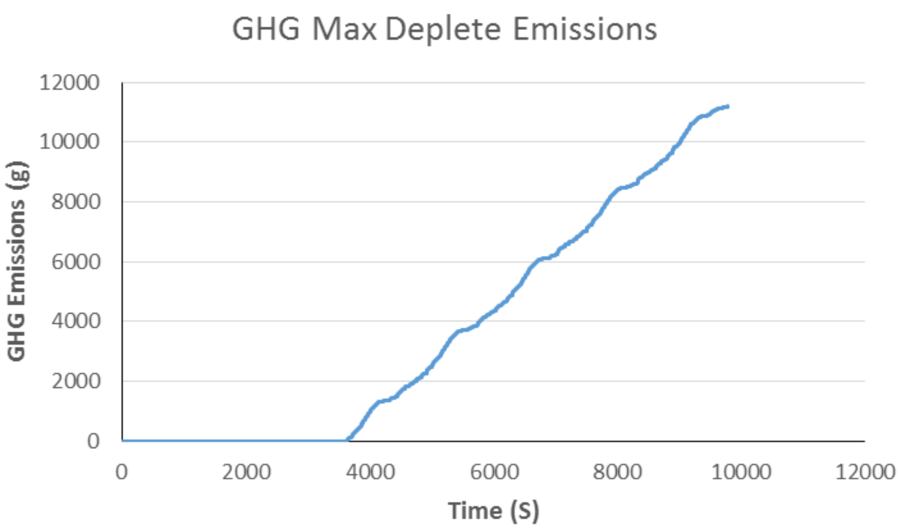

Figure 29 – Max Depletion GHG Emissions Production

Table 8 is the cumulative results of the cold start emissions data. NO_x emissions are higher due to the catalyst not achieving light-off. This same effect is shown on the CO_2 due to the criteria emissions not achieving light off and producing CO_2.

Table 8 - Cold Start Cumulative Emissions Max Deplete

Emissions	Total (g)
HC	0.413
NOX	31.79
CO	1.860
CO2	1331.9

UF Weighted Max Depletion E&EC

Figure 29 is the final table of values for the UF weighted emissions and energy consumption for the max depletion case. The corrected values shows that the criteria emissions were lower than the GHG emissions. This is to be expected based on the higher production of CO_2 that naturally occurs due to the fuel combustion.

More fuel energy was used then electrical energy. Based on the capacity of the ESS this is to be expected. This resulted in a total energy consumption of 0.279 kWh/km or 53MPGGE. Using less fuel and more electrical energy would result in better emissions and less energy consumed.

Table 9 - Maximum Depletion UF Weighted Emissions and Energy Consumption

Fuel Used (gal/mi)	Elec Used (gal/mi)	CO2 (g/mi)	CO (g/mi)	NOx (g/mi)	THC (g/mi)	Total Energy Consumed (gal/mi)	MPGGE E85
0.016	0.002	70.626	0.607	0.412	0.446	0.019	52.852

Charge Preserve SOC Strategy

The charge preserve SOC strategy had the vehicle drive efficiently and enter CS mode at 25%. The trace was followed within a half of a percent accuracy. Figure 30 is the velocity profile from the trace.

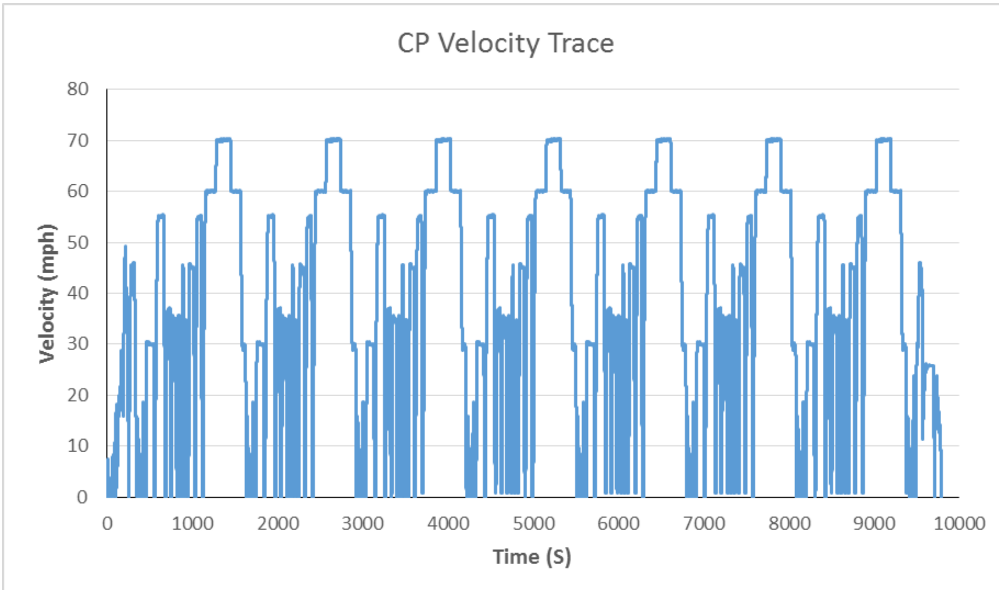

Figure 30 - CP SOC Mode Velocity Trace

CP Mode SOC Fuel Economy

Similar to the max depletion mode CP SOC mode was entered at 35 miles. The biggest difference however is the total miles driven in CD mode are approximately 56 miles. During the CP mode operation CD mode was re-entered 9 times total excluding the initial 35 mile CD mode. Figure 31 is the total mode switches throughout the cycle. Mode 1 is the single electric motor CD, mode is double motor CD, and 3 is the CP SOC mode.

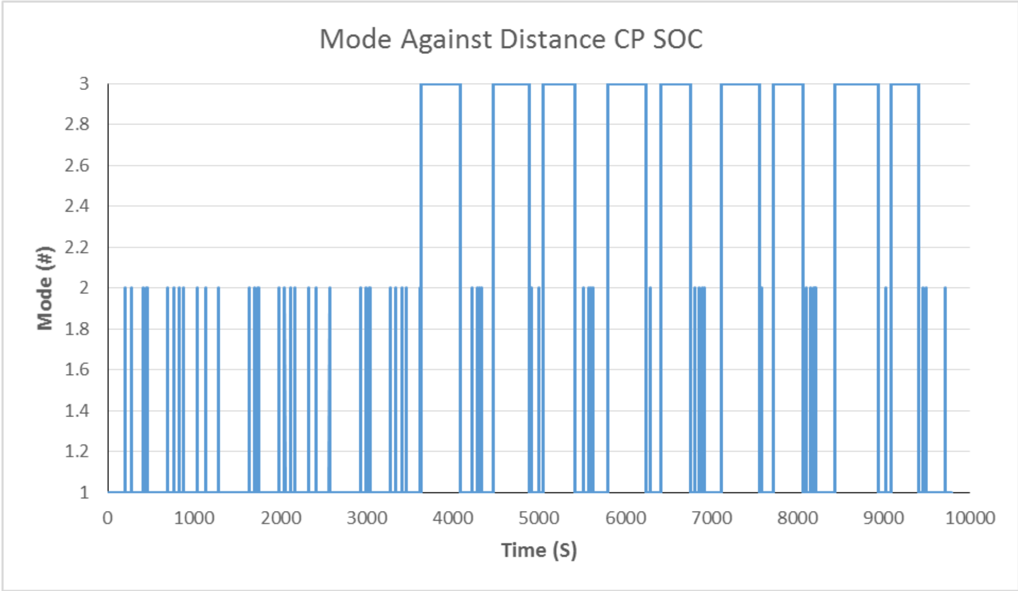

Figure 31 - CP SOC Mode Switches

The SOC changes demonstrate the CP mode charging capabilities. The engine operating at optimal torque could supply the needed torque to drive the vehicle most of the time. This means the motors spent a lot of time regening and charging up unto the threshold rapidly.

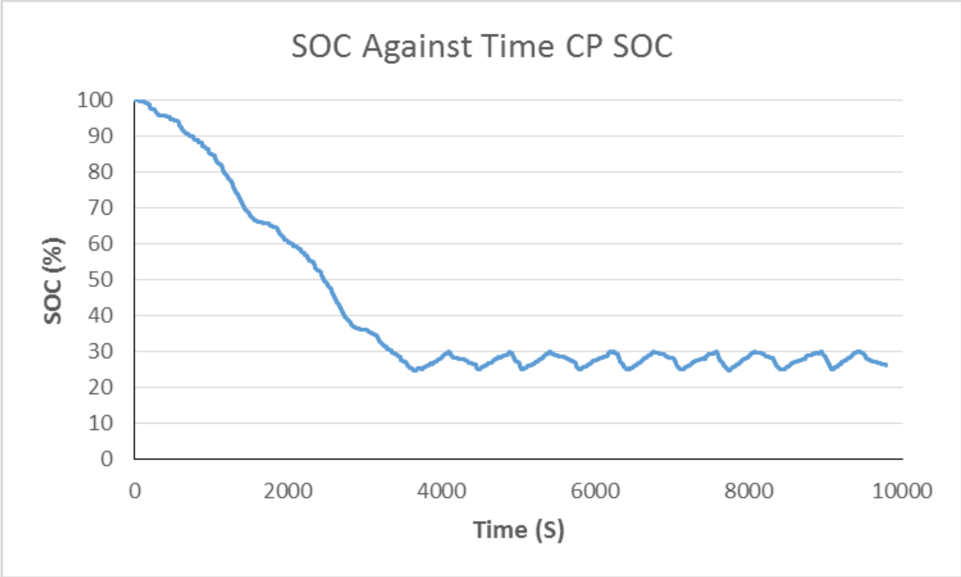

Figure 32 - CP SOC Mode Changes in SOC

The fuel usage increases with time but flat lines when fuel is not consumed. The flat lines in Figure 33 are the re-entered CD mode periods. Any period of increased fuel is the CP mode generating SOC. The total energy consumption was measured to be 0.46 kWh/mile a 2.47% difference from the maximum depletion case.

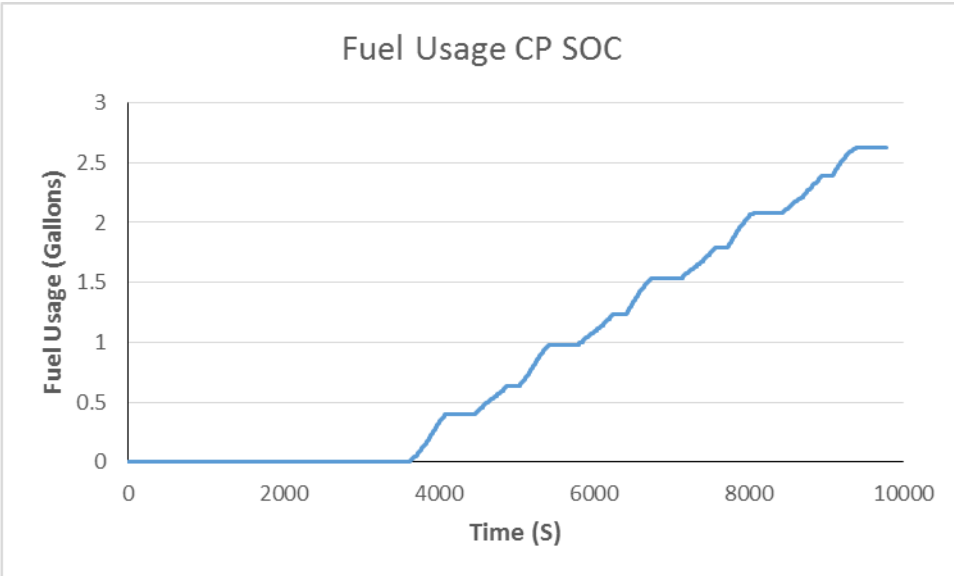

Figure 33 - Fuel Usage CP SOC Mode

CP Mode SOC Emissions

Overall emissions had decreased from the maximum depletion case. Figure 34 is the GHG emissions increasing throughout the cycle based on energy usage. Similar to the Fuel usage the portions of re-entered CD mode are flat lines on the plot.

The increased emissions relate to the engine load. The GHG increase is due to catalyst performance and the engine running at a higher load. The higher the operation of the engine the more CO_2 is created. This is proportional to the load. CO_2 is also created from Equation 5 due to the combination of criteria emissions in the catalyst. The slight increase of 16% was found in the model.

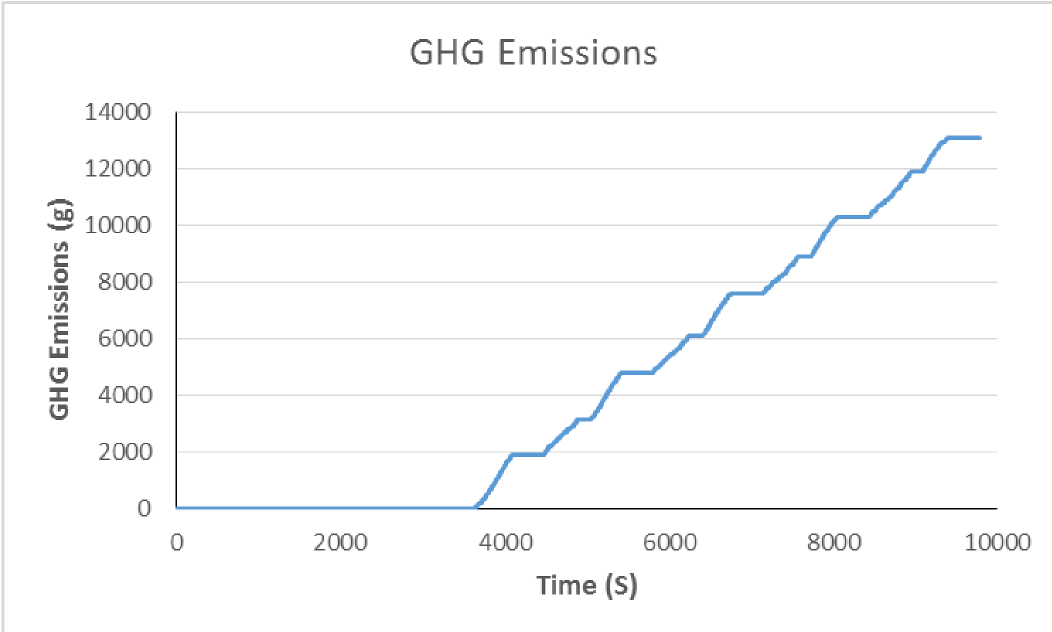

Figure 34 - GHG Emissions CP SOC Mode

The criteria emissions had a seen a smaller reduction compared to the max depletion case. Figure 35 is the summary of all three criteria emissions during the cycle. NO_x saw the biggest reduction by 67%. NO_x is highly dependent on the completeness of the burn with E85 and not the catalyst. Having a more complete burn with the higher efficiency operating point's yields fewer NO_x and higher separation of nitrogen and oxygen.

The HC emissions are decreased 13.2%. The engine is operating at higher points of operation and yield more fuel usage but better efficiency of the burn yielding fewer unburnt emissions. Running more efficiently yields less unburnt fuel. CO emissions are increased 17 % due to CO having a similar relationship with load as CO_2.

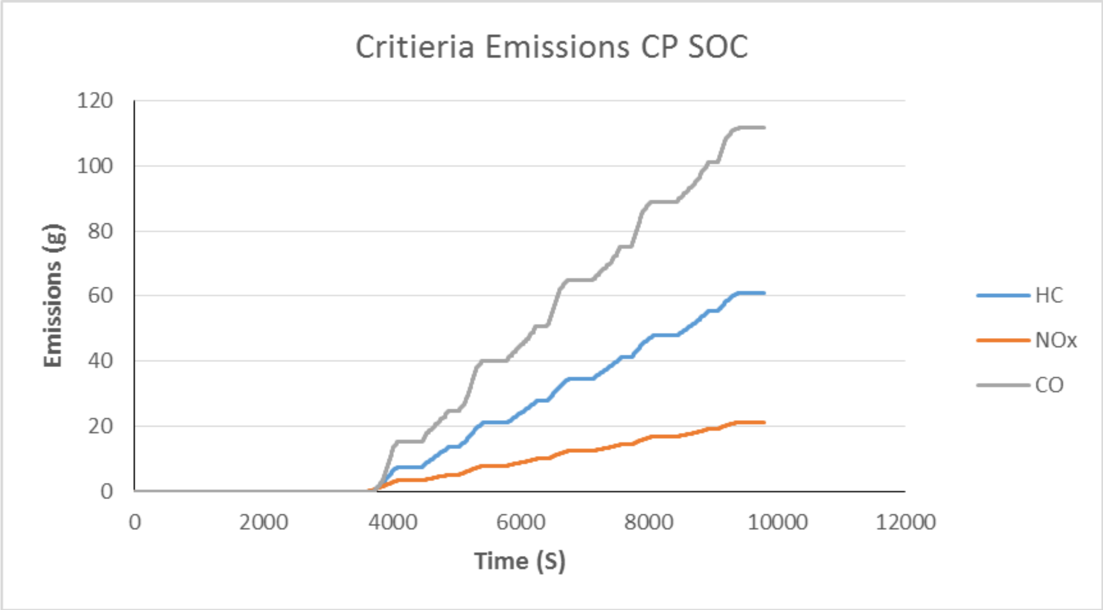

Figure 35 - CP SOC Mode Criteria Emissions

The CP SOC cold start is characterized in Figure 36. The engine has been run and the catalyst remains above light off due to the steady trend of emissions production. The emissions increase slightly but not at a rapid rate like the maximum depletion case.

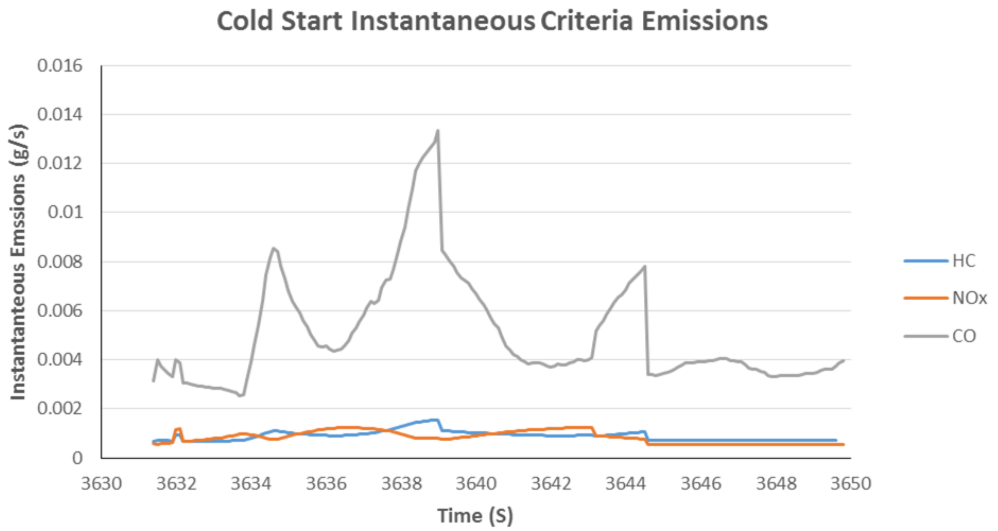

Figure 36- Thermally Soaked Cold Start CP SOC Mode

The exhaust temperature throughout the drive cycle in is Figure 37. The exhaust temperature follows the trends of engine operation and flat lines during re-entered CD mode instances.

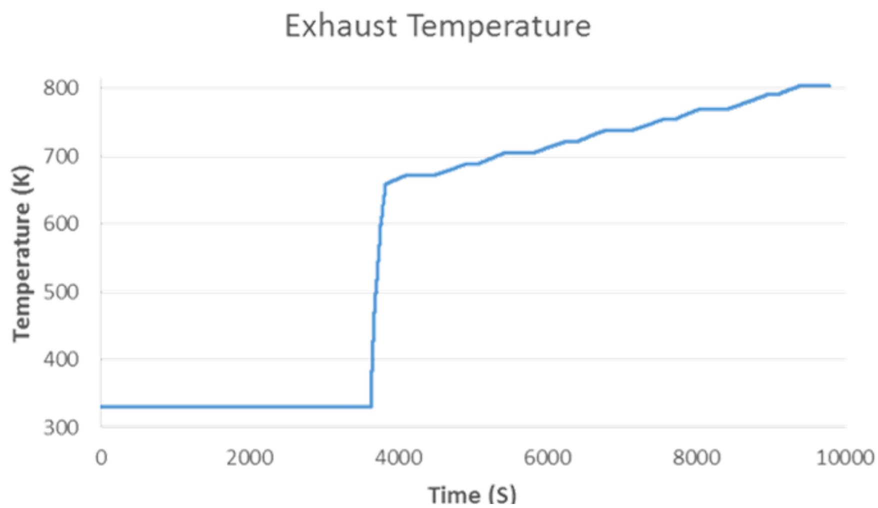

Figure 37 - CP SOC Exhaust Temperature through Drive Cycle

Figure 38 is the section of exhaust temperature in which the engine is operational. Using this data an exponential growth equation can be made and is in Equation 18.

$$Temperature = 389.71 * e^{0.003*Time}$$

Equation 18 - Exponential Temperature Growth

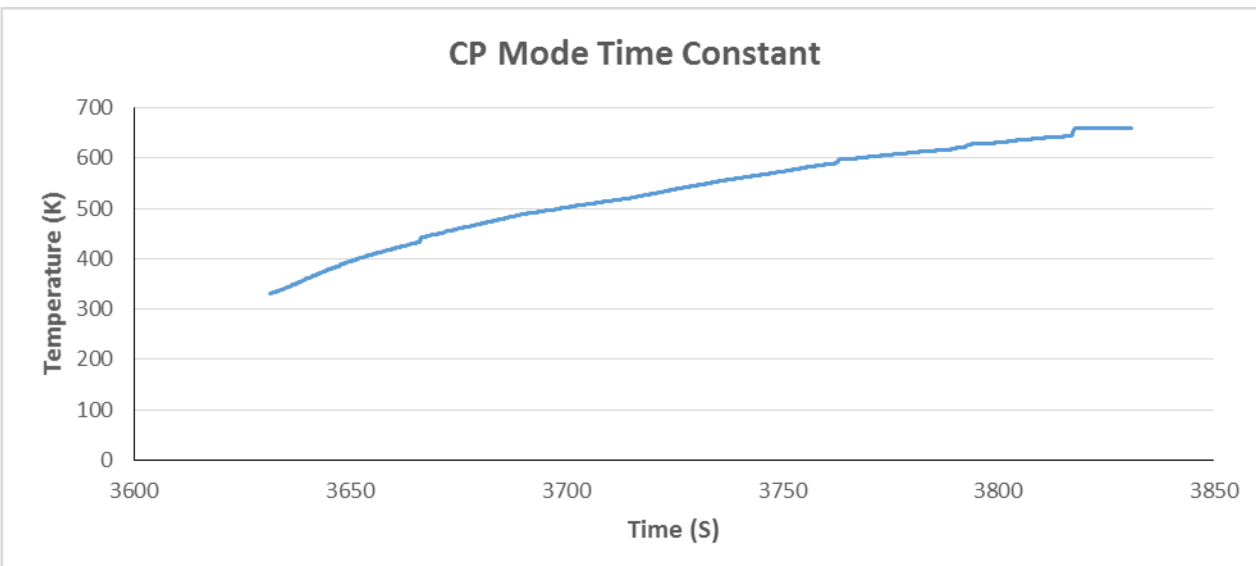

Figure 38 - CP Mode Temperature time constant

The time constant from Equation 18 is 120 seconds. This equation is used with the time at which the maximum temperature was measured and shown in Table 10. The maximum time for the first warm up period of the catalyst was compared as well as a time

60% through the initial warm up. The percent difference between the maximum warm up and modeled warm up was 4%. The time 60% through the warm up was within 6%.

Table 10 - Exponential Growth Temperature Calculation

Model		Time Constant	
Time (S)	3831	Time (S)	3831
Max Temp (K)	659.3	Max Temp (K)	686.2
Time 60% (S)	3751	Time 60% (S)	3751
Temp 60% (K)	574.5	Temp 60% (K)	539.8

UF Weighted CP SOC E&EC

Table 11 is the results of the UF weighted emissions and energy consumption results for the CP SOC mode. Interesting to note is the reduction in NO_X compared to the other emissions.

Table 11 - UF Weighted CP SOC Mode Emissions and Energy Consumption

Fuel Used (gal/mi)	Fuel Energy Used (kWh/mi)	Elec Used (gal/mi)	CO2 (g/mi)	CO (g/mi)	NOx (g/mi)	THC (g/mi)	Total Energy Consumed (gal/mi)	MPGGE E85
0.017	0.400	0.003	83.597	0.714	0.136	0.387	0.019	51.576

Equation 5 is the stoichiometric equations for NO_x production in a catalyst and converts NO_2 and CO into CO_2. Burning fuel at the most efficient operation points will yield a more complete combustion and there for less NO_x. Less NO_x going into the catalyst will yield less CO emissions.

Charge Preserve Exhaust Strategy

The CP mode exhaust strategy uses the same equations as the CP mode SOC strategy but with different thresholds. The vehicle will re-enter CD mode once 50% SOC is achieved. The vehicle then will deplete the battery until 25% SOC or the exhaust drops below 350°C. Once one of the two thresholds are met then the vehicle reenters CP mode.

The vehicle trace is shown in Figure 39. The trace was followed within 2% of the intended drive cycle.

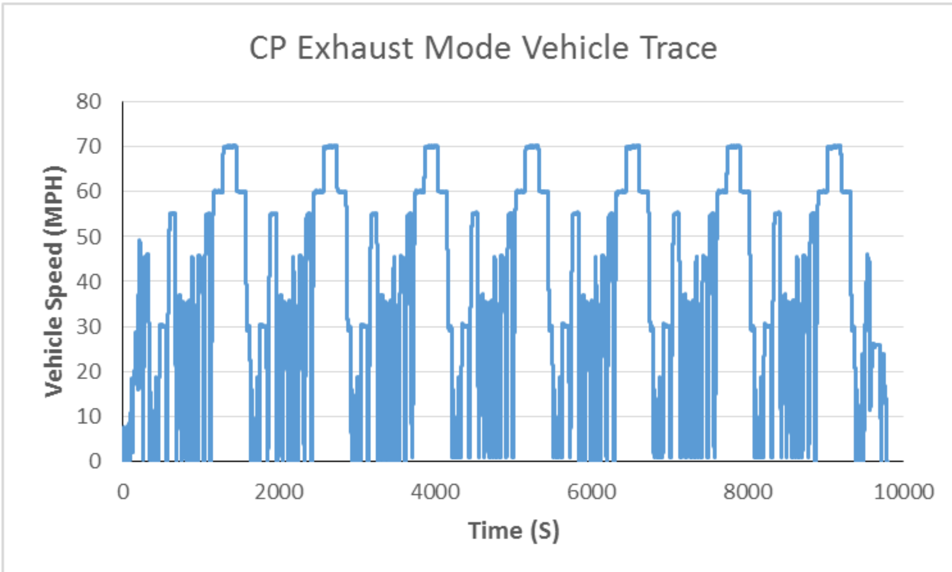

Figure 39 - CP Exhaust Mode Vehicle Trace

CP Mode Exhaust Fuel Economy

From the CP SOC mode and the maximum deplete strategy the vehicle exhibits more fuel usage evident in Figure 40. 13.5% more fuel was used from the maximum deplete strategy and 11% more than the SOC strategy.

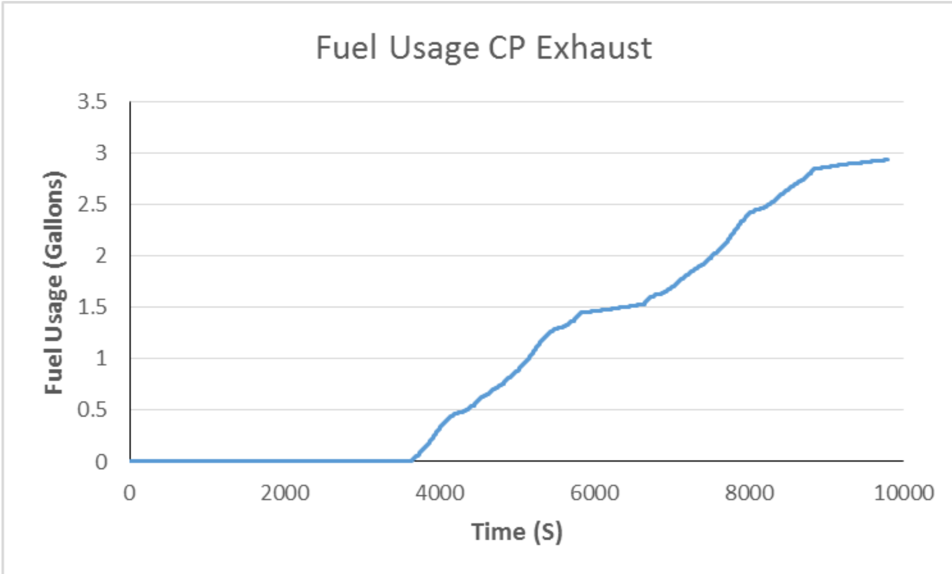

Figure 40 - Fuel Usage CP Exhaust Mode

The vehicle entered CP mode and would reenter CD less frequently than in the CP SOC 30 strategy. The SOC of the vehicle throughout the drive cycle is in Figure 41. Charging was very apparent and would achieve 50% SOC and deplete to 25%. The vehicle would run to the SOC threshold prior to the exhaust temperature reaching 350°C.

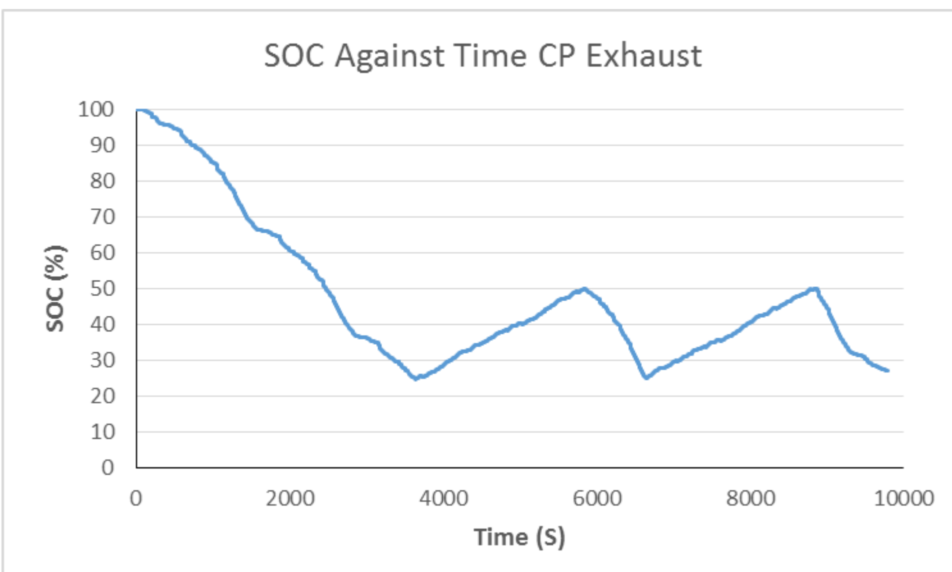

Figure 41 - CP Exhaust Mode SOC

Figure 42 is the changes in the modes and related directly to Figure 41. The vehicle reenters CD mode twice. The vehicle achieves 50% and depletes until 25%.

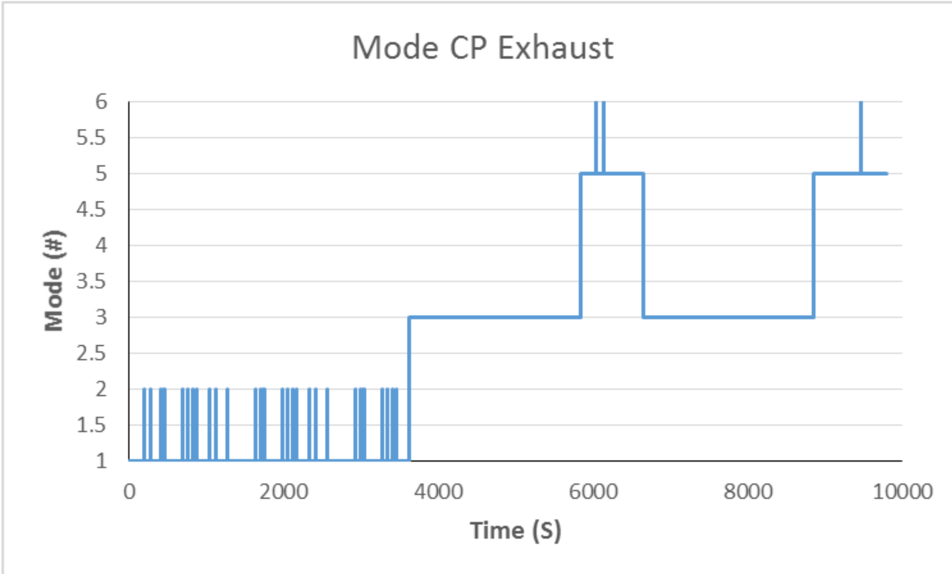

Figure 42 - CP Exhaust Mode Change in Mode

CP Mode Exhaust Emissions

The exhaust temperature increases as the engine is loaded and expected. The CP strategy loads the engine higher than the road load to generate electricity quicker. This creates more heat in the exhaust in which the vehicle achieves light-off temperature quicker. The exhaust gets heat soaked immediately and does not drop below light off temperature. The SCU only lets the vehicle re-enter CP at 25% SOC throughout the drive cycle and never due to the exhaust temperature.

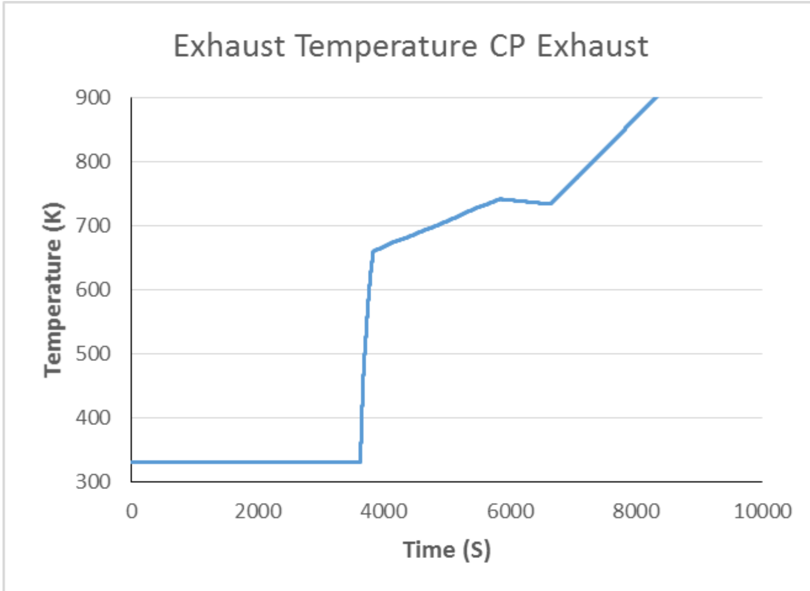

Figure 43 - Cumulative Exhaust Temperature CP Mode Exhaust

The vehicle running at a higher load and consuming more fuel then CP SOC modes results in higher GHG emissions but fewer than max deplete. Figure 44 is the cumulative results of GHG emissions and yields a 18.3% increase in CO_2 from the max deplete case. The CP SOC mode yields 23.1% more GHG emissions then the exhaust strategy. The engine runs at a higher load and for longer periods of time and results in higher emissions.

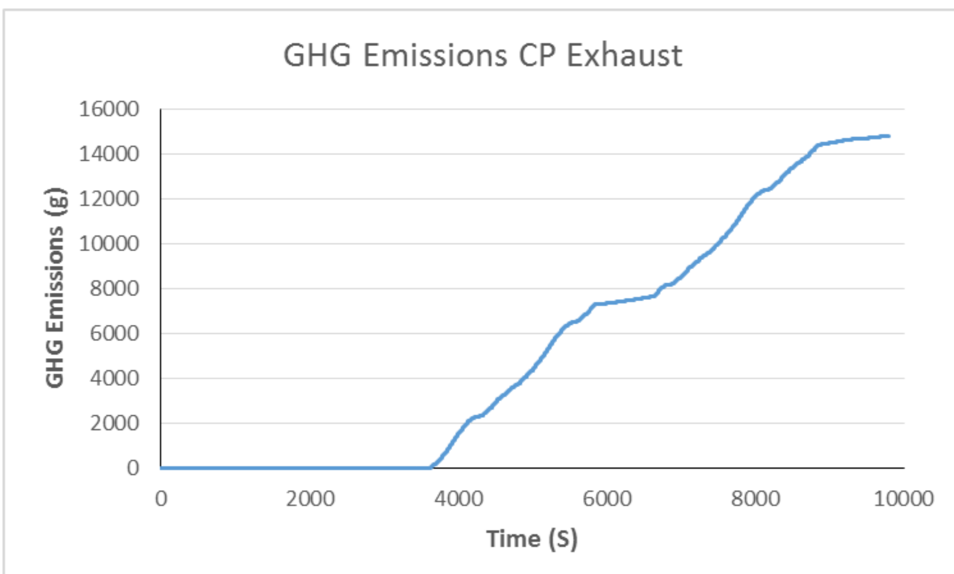

Figure 44 - GHG Emissions CP Exhaust Mode

Figure 45 sit the cumulative criteria emissions from the CP mode exhaust case. The HC follows a linear trend. This is due to the amount of fuel consumes and results in higher emissions of HC then both cases. Max deplete had 15% fewer HC emissions and CP SOC had 30% fewer emissions of HC.

CO emissions were relatively high due to the higher loading points through the drive cycle with this strategy. CO emissions had been increased 8% from the maximum deplete strategy and 23.1% from the CP SOC.

The NO_x emissions had decreased from the max deplete strategy due to the improved catalyst efficiency and dropped 65%. However from the CP SOC strategy the NO_x increased 10.79%. This is due to the engine running more and consuming more fuel.

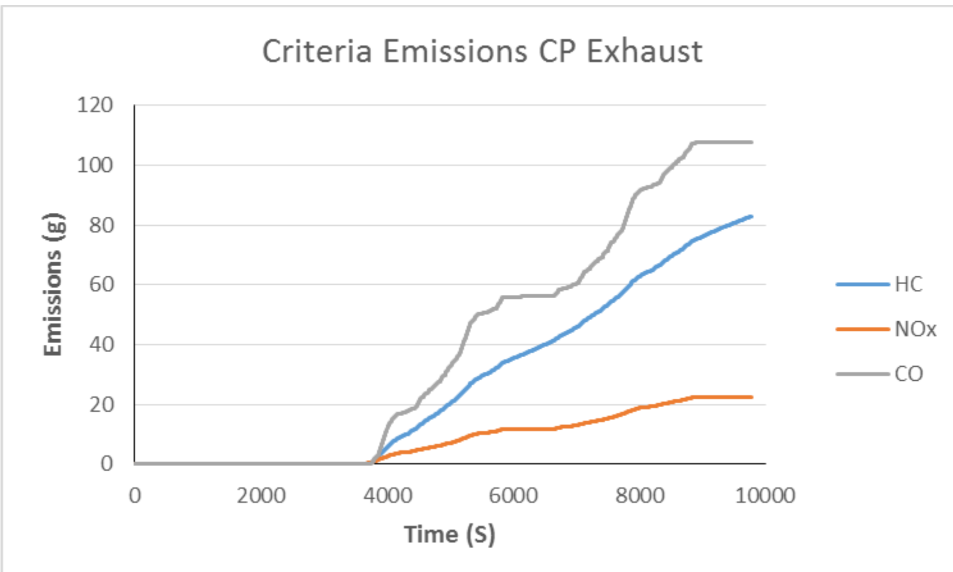

Figure 45 - CP Exhaust Mode Criteria Emissions

UF Weighted CP Exhaust E&EC

The UF weighted results are in Table 12. The overall fuel economy was reduced due to the engine running at higher operating points for a longer duration. The CD mode range was the standard 35 mile initial max depletion range but with re-entered CD mode a total of 55.5 miles total electric driven range. The total 46.5 MPGGE is reduced from the

Max deplete and CP SOC strategy due to higher fuel consumption. The emissions data had yielded slightly higher results then the CP SOC due to efficiency of the catalyst being achieved in both strategies. More fuel was used with the exhaust strategy and resulted in higher overall emissions of GHG and criteria.

Table 12 - UF Weighted CP Exhaust Mode Emissions and Energy Consumption Results

Fuel Used (gal/mi)	Elec Used (gal/mi)	CO2 (g/mi)	CO (g/mi)	NOx (g/mi)	THC (g/mi)	Total Energy Consumed (gal/mi)	MPGGE E85
0.019	0.003	94.623	0.686	0.144	0.521	0.022	46.499

Chapter V: Conclusion, and Recommendations

Conclusion

Overall the three strategies are summarized in Table 13. Max depletion is a strategy that benefits fuel economy the best. Criteria emissions has the biggest benefit from a CP strategy due to the engine running at strictly optimal torques. The fuel is getting burned ideally and the engine is being loaded to the point where SOC is charged rapidly. A maximum depletion strategy is using just enough energy to keep the car moving but CP mode allows for further CD mode operations.

The catalyst maintained temperature and was kept at light off. This resulted in the reduction of criteria emissions and a slight increase in carbon based emissions. GHG emissions are proportional to the load and yielded higher emissions. The catalyst also changes criteria emissions by combining HC and NO_x emissions into CO_2.

Table 13 - Strategy Side by Side Results

Strategy	Fuel Used (gal/mi)	Elec Used (gal/mi)	CO2 (g/mi)	CO (g/mi)	NOx (g/mi)	THC (g/mi)	Total Energy Consumed (gal/mi)	MPGGE E85
Deplete	0.016	0.002	70.626	0.607	0.412	0.446	0.019	52.852
CP SOC 30	0.017	0.003	83.597	0.714	0.136	0.387	0.019	51.576
CP Exhaust	0.019	0.003	94.554	0.686	0.144	0.521	0.021	46.513

Table 13 is the side by side numbers each strategy yielded in fuel economy and emissions. The CP Exhaust strategy SOC threshold was much higher than the CP SOC strategy to re-enter CP mode based on temperature. The controller never re-entered CP mode due to the temperature but due to the 50% SOC limit. This consumed more fuel then the other two strategies due to the engine attempting to charge the batteries to a higher threshold.

Table 14 - CAFE 2025 Standards Comparison

Emissions	Standard (g/mi)	Max Deplete (g/mi)	CP EXH (g/mi)	CP SOC (g/mi)	Max Deplete (%)	CP EXH (%)	CP SOC (%)
CO	1.7	0.607	0.686	0.714	-35.71	-40.36	-41.98
NOx	0.2	0.412	0.144	0.136	205.85	-71.78	-67.91

Table 14 includes the comparison of all three strategies against the CAFE 2025 standards. The CO emissions of the Max Depletion strategy were higher than the standard by 200%. The CP SOC strategy had the best results when compared to the CAFE 2025 standards.

Table 15 is the percent differences of the CP modes compared to the maximum depletion strategy. Overall the CP SOC mode had the most significant impact as far as not compromising fuel economy and emissions reduction.

The CP SOC 30 energy consumption was reduced by 2.41% from the maximum deplete strategy. CP Exhaust strategy is a large reduction on energy consumption of 11.99%. Non-carbon emissions had benefitted the most by the strategy. Due to the catalyst performance and optimal torque the vehicle produced less non-carbon emissions but higher carbon emissions due to the reactions in the catalyst.

Table 15 - Percent Difference CP Strategies Compared to Max Deplete

Strategy	Fuel Used (%)	Elec Used (%)	CO_2 (%)	CO (%)	NO_x (%)	THC (%)	Total Energy Consumed (%)	MPGGE E85 (%)
CP SOC	2.5	2.03	18.4	17.6	-67.01	-13.30	2.47	2.41
CP Exhaust	14.5	7.31	33.9	13.03	-65.1	-16.76	13.63	11.99

The maximum depletion strategy is a higher fuel economy strategy with a CP strategy strong in emissions reduction. The ERAU EcoCAR 3 team should take the CP

SOC strategy the next step further in testing due to the minimal impact on fuel economy and high impact on criteria emissions. A CP strategy can be used to reduce criteria emissions and maintain the fuel economy.

Future Works

Work that can be continued from this includes, more measurements on the car in real-time, a more robust model, and more analysis. The catalytic converter model is very basic and could be more robust. To enhance this model a more detailed vehicle and exhaust CAD model should be analyzed with CFD underbody implications. CFD in the exhaust should be modeled as well to get a more detailed heat transfer model.

The EcoCAR platform is a perfect platform to test the theories of this model and thesis so testing on the Camaro with the CP and Max depletion strategy should be measured and compared. To do this an exhaust gas temperature sensor should be placed pre-catalyst to get the exhaust temperature. The temperature can be monitored to maintain catalyst light off either through preheat or the powertrain. A catalyst preheat would be beneficial to this strategy to maintain temperature for reductions in cold starts.

Appendix A

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