AuE 6610

Advanced and Electrified Powertrains

Group Project

Feasibility of a Series Hybrid Dodge Hellcat and SOC-based Control Strategy

Submitted By:

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OBJECTIVE:

The objective of the project is to attempt to design and model a series hybrid powertrain that can meet the performance characteristics of a Dodge Hellcat Challenger in terms of 0–60-time, maximum speed and torque while reducing the fuel consumption. This project assesses if a series hybrid can match the Hellcat within a comparable performance and cost bracket. Other hybrids of similar performance are also compared.

The project also attempts to devise a control strategy to operate the engine as a function of State of Charge (SOC) of Battery to reduce the battery's Depth of Discharge and thus increase the battery life.

VEHICLE APPLICATION:

The suggested powertrain will appeal to young professionals that enjoy high performance vehicles but are also environmentally conscious. It would provide both, a close 0-to-60 time and maximum speed as a conventional Dodge Hellcat but with increased fuel efficiency. The proposed series hybrid Hellcat would be most suited for driving around in the city but would also retain the Hellcat's performance characteristics to provide satisfactory power and feel to the driver.

MARKET ASSESSMENT:

I. Market Assessment of Dodge Hellcat:

The muscle car segment is experiencing a steady decline in sales. However, the Dodge Hellcat is the only exception continuously growing in sales year to year. Since the start of the 2015 calendar year, Dodge has sold 323,093 Challengers, which accounts for an average of 64,619 units sold each year. Dodge's target audience for the Challenger comprises of young American buyers who want a bigger, more luxurious, and more expensive car.

The cost of a Dodge Hellcat as of December 2021 could range from $76,000 for the Hellcat Widebody to $84,645 for SRT Hellcat Redeye Widebody.

II. High level market analysis of hybrid vehicles:

A vehicle with two variants, one hybrid and the other conventional combustion engine has a general price difference in the range of 12-20% with the hybrid costing more than the conventional vehicle. Other hybrid vehicles with similar performance characteristics to the Hellcat are listed in the table below. Hybrids usually cost more than typical internal combustion engine vehicles. However, it is also interesting to note that the University of Michigan Transportation Research Institute (UMTRI) found out that the cost of ownership of a hybrid vehicle is around $485 per year to drive as against $1,117 for gas powered vehicles. There is a potential trade-off for purchasing a hybrid vehicle that reduces maintenance costs over the long term.

Vehicle	0 to 60 mph time	Top Speed	Cost
2019 Dodge Hellcat	3.6	186	$76, 000
2015 BMW i8	3.8	155	$148,500
2018 Porsche Panamera	3.7	190	$85,000
2017 Acura NSX	3.1	191	$158,000

REPRESENTATIVE DRIVE CYCLE:

For the given vehicle application, the closest standard representative drive cycle would be the **US06, SFTP (Supplement Federal Test Procedure)** drive cycle. The details of this cycle can be summarized below:

Parameter	Drive Cycle Value
Maximum Speed	129.3 kmph
Distance Travelled	12.89 Km
Maximum Acceleration	+3.76 m/s^2
Maximum Deceleration	-3.08 m/s^2
Duration	600 seconds
Average Speed	77.08 kmph
Maximum Acceleration Power	73 kW

To test the control strategy the vehicle is driven on both the US06 drive cycle as well as the UPA UDDS (LA4) drive cycle. The **UPA UDDS (LA4)** cycle considers a city drive cycle while the US06 drive cycle considers an aggressive driving style. These drive cycles provide insight on the performance of the proposed series hybrid vehicle for highway driving and more conventional city driving.

PROPOSED ARCHITECTURE:

The conventional Dodge Hellcat uses 6.2 L, V8 Engine. The engine has a maximum torque of 815 Nm and delivers a horsepower of 707 HP.

The proposed architecture for this project is a **Series Hybrid powertrain**. To ensure the market relevance of the proposed hybrid architecture, the following performance metrics were matched with the original Dodge Hellcat:

- **0-60 mph time:** 3.6 seconds
- **Maximum Vehicle Speed:** 190 mph

The above factors were critical in determining the electric motor size chosen to drive the hybrid vehicle. Due to limitation in information resources available, an available motor was upscaled by a factor of three to match the Hellcat's 0 to 60 time. The max torque of the upscaled motor is 780 Nm. A motor with a close terminal power was found on the website: EVWest.com. This motor has a rated torque value of 760 NM.

The powertrain components in our analysis have been sized as follows:

- **Electric Motor:** Max Torque 780Nm
- **Combustion Engine:** Naturally aspirated 1.6 L, 4-cylinder engine
- **Battery Pack:** 200 cells in series and 10 strings in parallel.

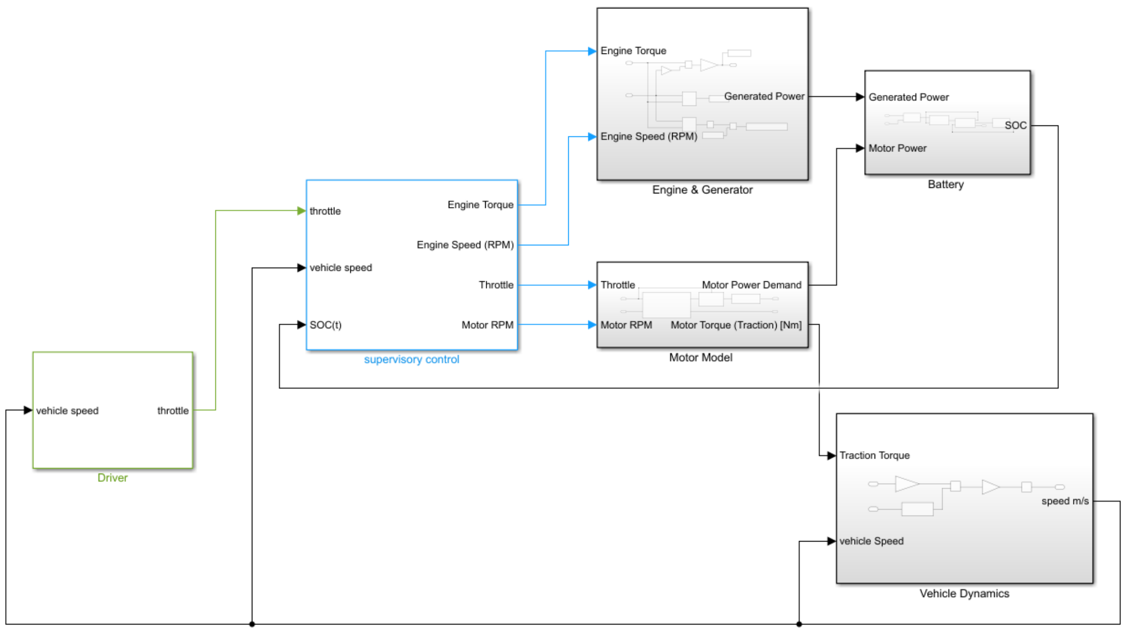
Novelty of Proposed Architecture

Keeping in mind that the State of Charge (SOC) and Depth of Discharge (DOD) play a vital role in the range and life of the battery, a different approach was taken to run the engine in this series hybrid architecture. Instead of running the engine at a single operation point (often corresponding to the lowest BSFC), the operational points of the engine were determined based on the State of Charge of the battery. A control logic was developed that ran the engine as a function of SOC. This approach was taken to keep the State of Charge of the battery at a healthy level, to reduce Depth of Discharge for better battery life, and to limit the use of engine as needed.

MODEL:

A Simulink model was developed to simulate the vehicle performance of both the combustion engine vehicle as well as the series hybrid vehicle. The model of the series hybrid vehicle consists of the following subsystems:

- Driver module
- Supervisory control
- Engine and generator module
- Electric motor
- Battery module
- Vehicle dynamics module

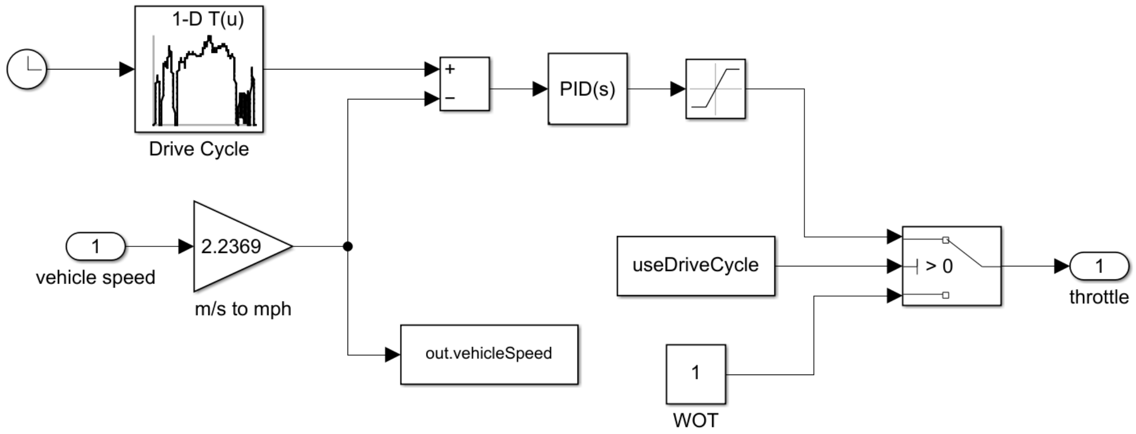


Overall Model

Description:

- The driver module considers the drive cycle demand and the current vehicle speed to determine the throttle input.
- The supervisory control module considers the throttle demand, the State of Charge of battery and the vehicle speed to determine the operational points for both the engine as well as the motor.
- The engine module considers the operational speed and torque demand as requested by the supervisory control to charge the battery through a generator. For simplicity, the engine and the generator are coupled in this module that considers the generator efficiency as well.
- The motor module also considers the operational speed and torque demand as requested by the supervisory controller. The output of the motor is used to drive the vehicle.
- The vehicle dynamics module considers the road load pertaining to frictional losses and aerodynamic drag.
- The battery module considers the power demanded/generated by the engine and the motor to either charge or discharge the battery. Furthermore, the battery module simulates a coolant-based temperature control for the battery pack. Finally, the subsystem calculates the SOC and Depth of Discharge of the vehicle.

Driver Module:

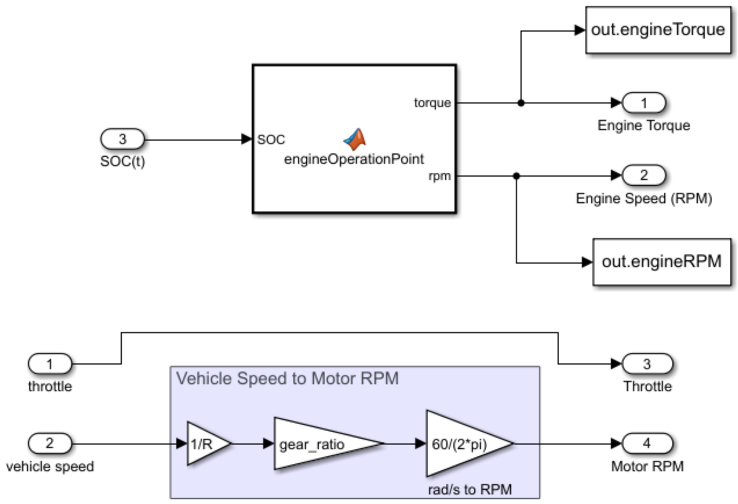


Driver Module

The driver module uses a PID controller to compare the drive cycle speeds with the vehicle speed to determine the required throttle. To determine the 0-60 time for the car, an additional case of wide-open throttle (WOT) has also been built into the driver module.

Supervisory Controller:

The supervisory control module considers the throttle demand, the State of Charge of battery and the vehicle speed to determine the operational points for both the engine as well as the motor.



Supervisory Control

In a series hybrid vehicle, as the motor drives the wheels, the motor needs to take care of the torque and speed demand. The supervisory control runs the motor as per the demand. However, as the engine is not directly coupled to the wheels, the engine can be run independent of the vehicle speed. For the project, the engine operation points have been determined based on the State of Charge of the battery.

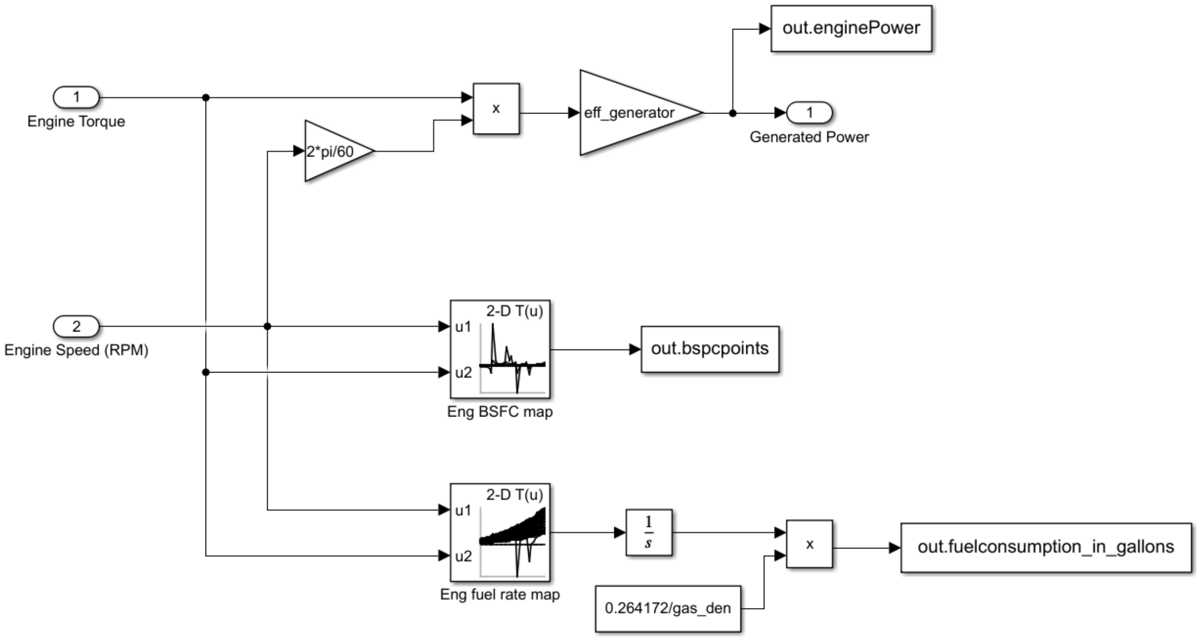
In essence, the following logic and cases are used to determine the engine operational points

1. **When SOC > 0.9:** The engine turns off. The battery is sufficiently charged to meet power demands and can accommodate brief periods of further charging due to regenerative braking.
2. **When 0.8 < SOC < 0.9:** Engine runs at low power level as battery is already in a good state of charge. This engine operation point is not as efficient as the lowest BSFC value but is suitable for generating lower power.
3. **When 0.6 < SOC < 0.8:** The State of Charge is in the moderate region. We don't need to rush to charge the battery, but the rate of charging shouldn't be too slow either. Therefore, the engine is run at the best BSFC point. This reduces the fuel consumption significantly.
4. **When SOC < 0.6:** To prevent significant reduction in battery life, we have imposed a minimum SOC restriction of 0.3. Therefore, below 0.6, the SOC has been considered low. Therefore, the engine is run at maximum power. This would help charge the battery faster. This situation would occur when the driver is demanding high power (in cases of wide-open throttle). Running the engine at maximum power would help reduce the depth of discharge during these conditions and thus would help increase battery life.

For the purpose of this project, since the US06 drive cycle is not causing a significant change in SOC levels, the above cases have been altered to demonstrate the effect of operating the engine as a function of SOC. The conditions used for this model are:

1. **When SOC > 0.7:** The engine turns off.
2. **When 0.64 < SOC < 0.7:** Engine runs at low power levels.
3. **When 0.6 < SOC < 0.64:** Engine runs at the best BSFC point
4. **When SOC < 0.6:** The Engine runs at higher power levels

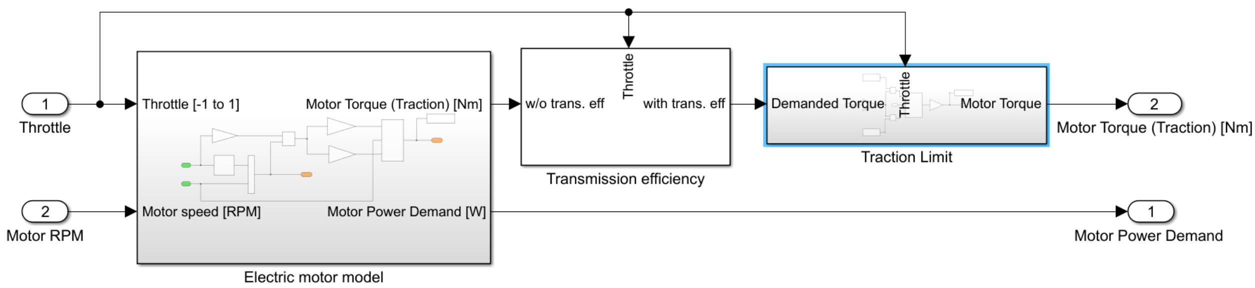
Engine and Generator:



Engine/Generator Module

The engine module takes as input the speed and torque requested by the supervisory control to generate the power required to charge the battery. To understand the operational points and determine the fuel consumption, necessary lookup tables were used from previous assignments. These tables are specific to the engine used in this analysis.

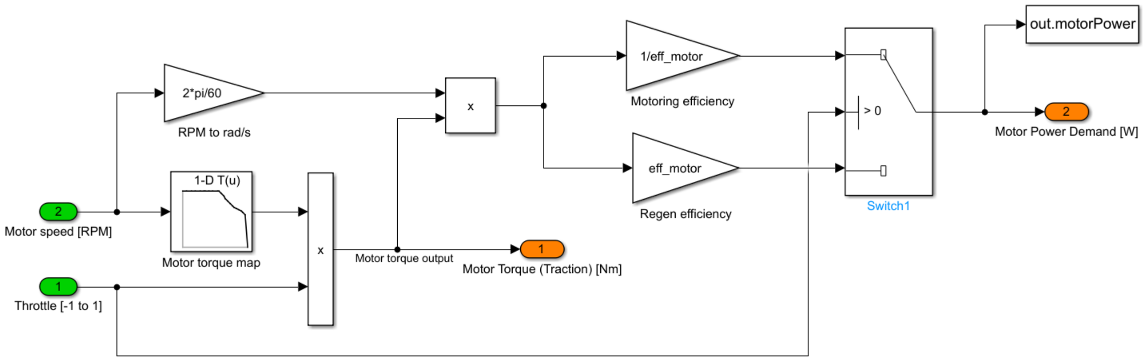
Motor:



The motor takes into the account the throttle and speed demanded by the supervisory controller. Correspondingly, the torque and power of the motor are calculated. Since this is a series hybrid architecture, the motor needs to be sufficiently large enough to run the vehicle. In this case, it needs to match the engine of a Dodge Challenger Hellcat.

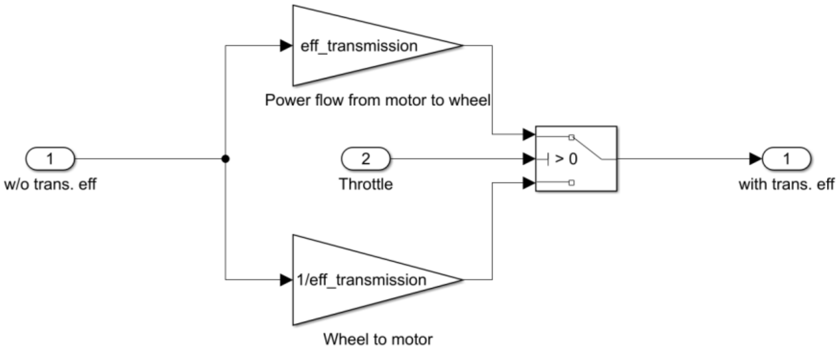
The individual sub-systems in the Motor module have been elaborated below:

- **Electric Motor model**



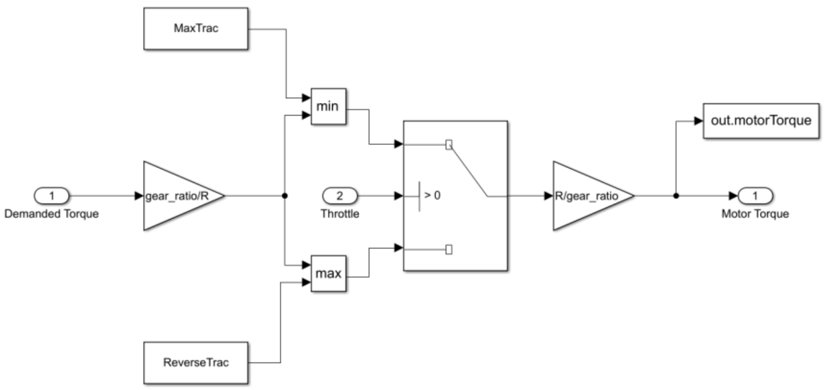
The subsystem calculates the motor torque corresponding to the throttle input provided by the driver. Correspondingly, the required power by the electric motor is also calculated keeping the motor efficiency in mind.

- **Transmission Efficiency**



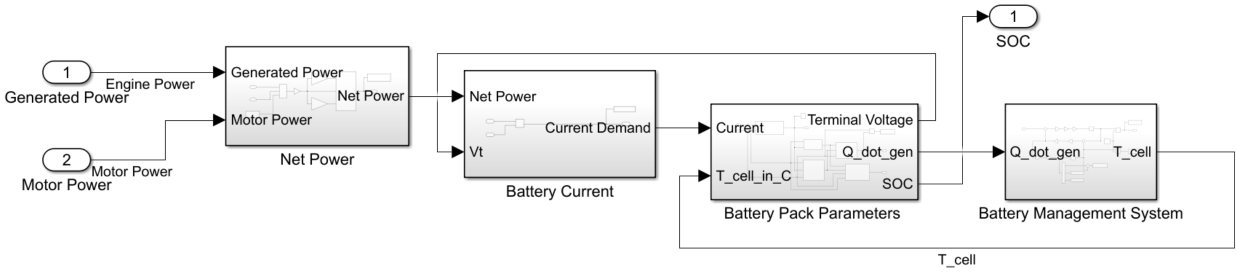
The transmission efficiency subsystem considers the inefficiencies of the transmission and reduces the motor torque accordingly.

- **Traction Limit**



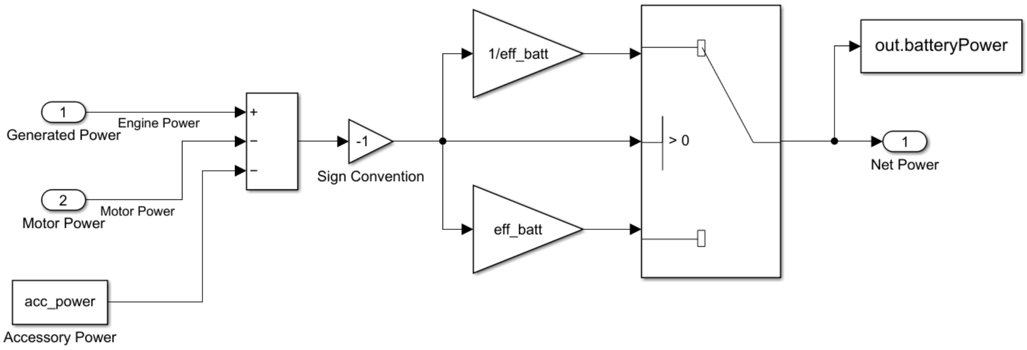
The Traction Limit subsystem ensures that the torque supplied by motor does not exceed the traction limit.

Battery:



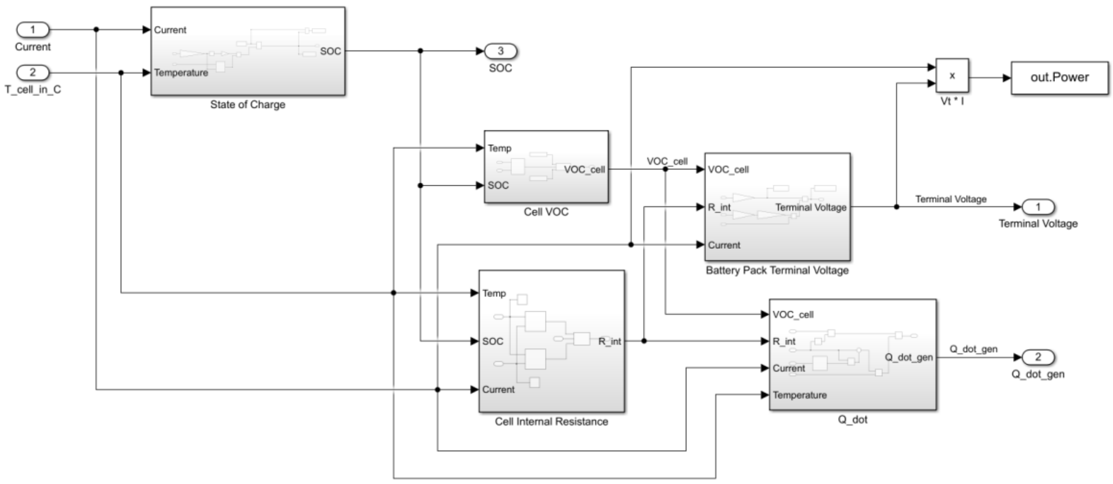
The Battery subsystem considers the power generated by the engine as well as the power required/recuperated by the electric motor. Correspondingly, the Simulink model goes on to calculate the following variables:

- **Net Power**



The net power charging or discharging the battery pack is calculated. While doing so, an assumed power requirement for electrically run accessories (air conditioning, etc) is also considered

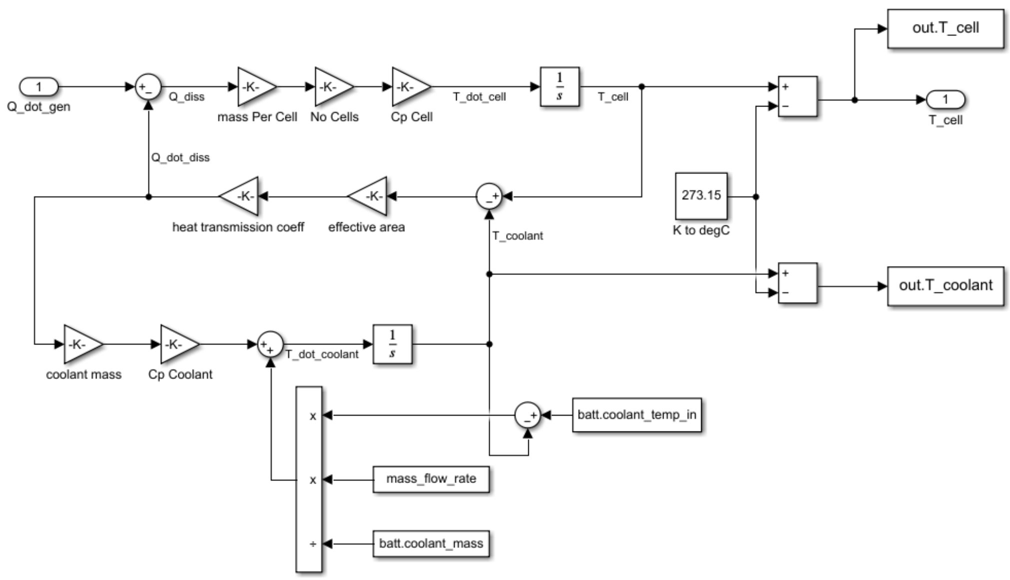
- **Battery Pack Parameters**



The Battery Pack Parameters block calculates all the essential parameters pertaining to a battery pack, such as:

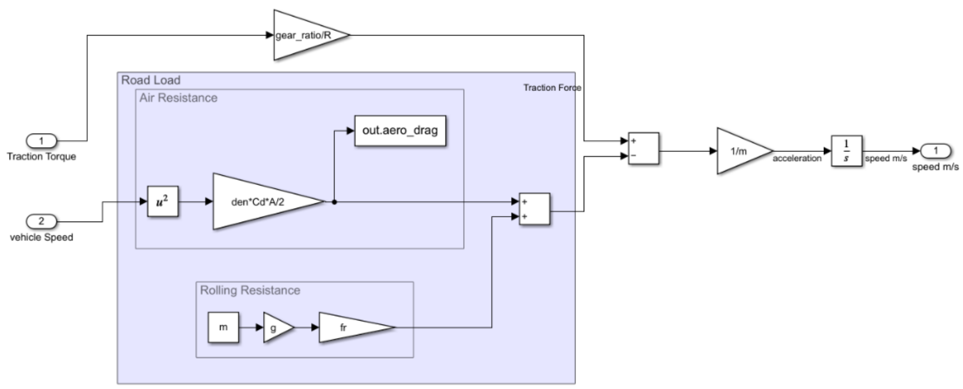
- Open Circuit Voltage (VOC)
- Internal Battery Resistance
- Terminal Voltage
- Heat Generated
- Power

- **Battery Management System**



The Battery Management System takes as input the heat generated in the battery pack and employs a coolant-based temperature control to prevent the battery pack from overheating.

Vehicle Dynamics Model:



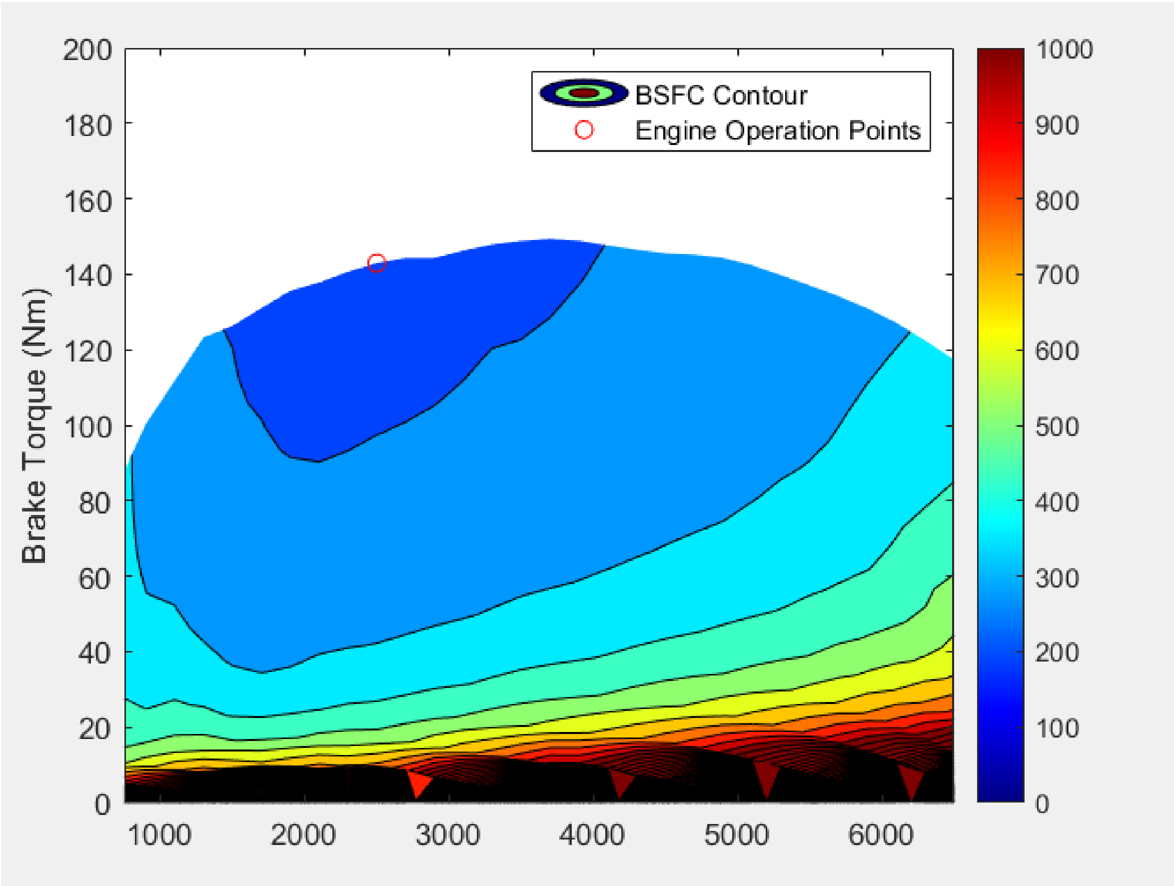
The vehicle dynamics model considers the road load i.e., the aerodynamic drag and rolling resistance to provide the final vehicle speed.

RESULTS:

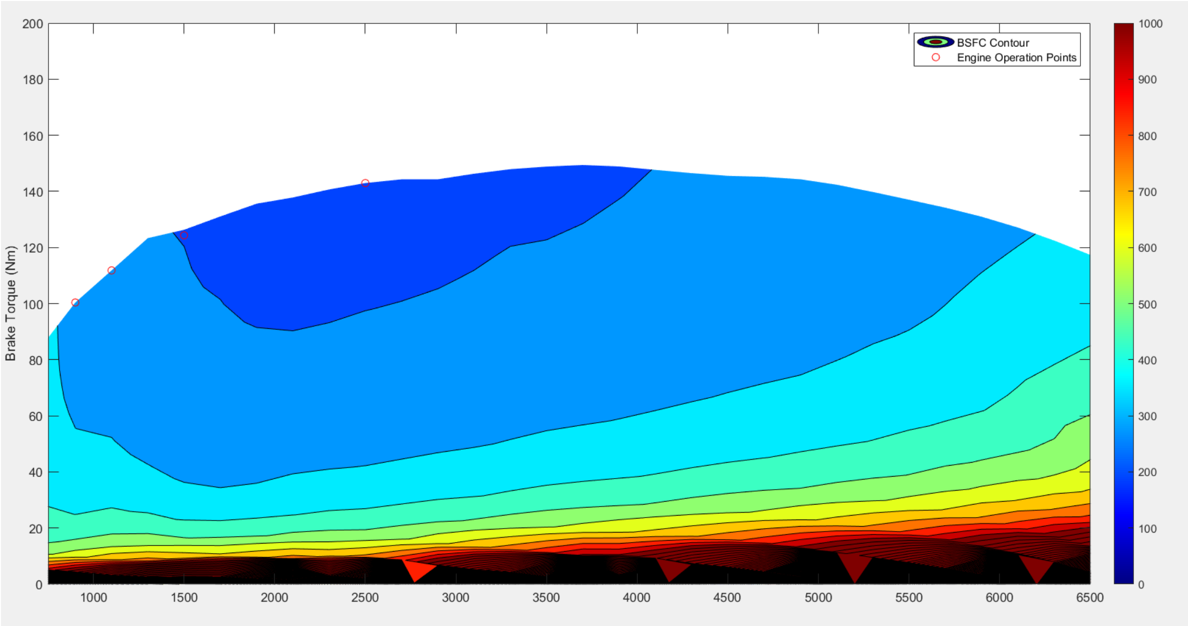
1. SOC-based Control Strategy

An important part of our project analysis is to determine whether using a multiple engine operation point strategy is more advantageous over running the engine at only the most efficient BSFC point. This analysis can be summarised by the following graphs:

1. Engine Operation Points

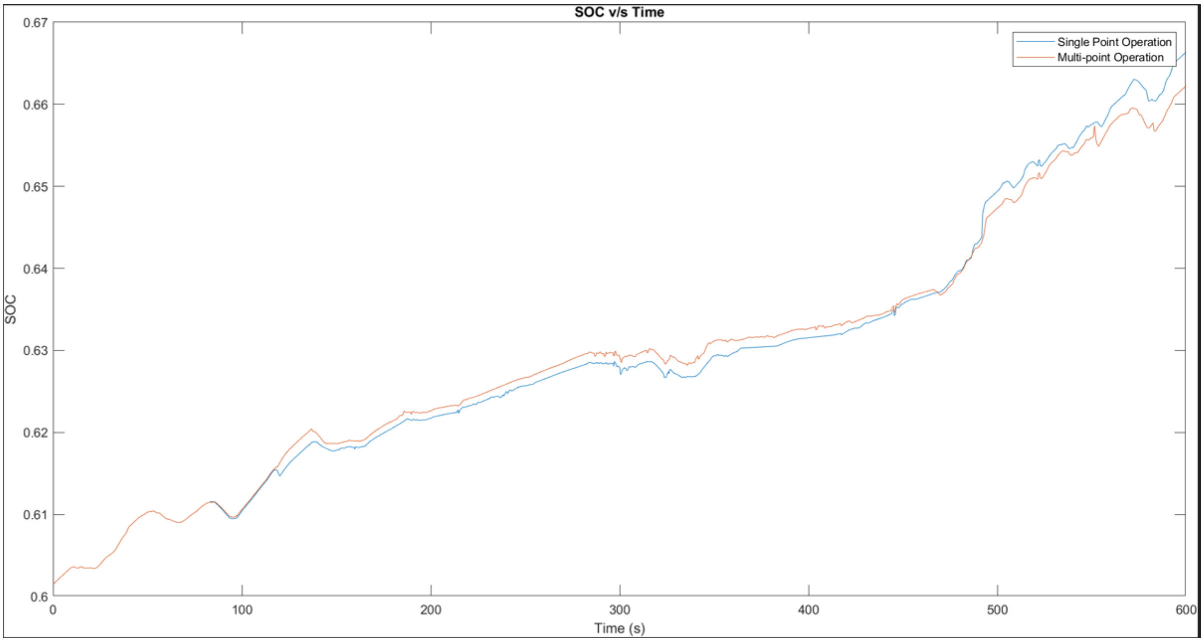


Engine Operating at only the best BSFC point



Engine Operation Points for SOC based control strategy

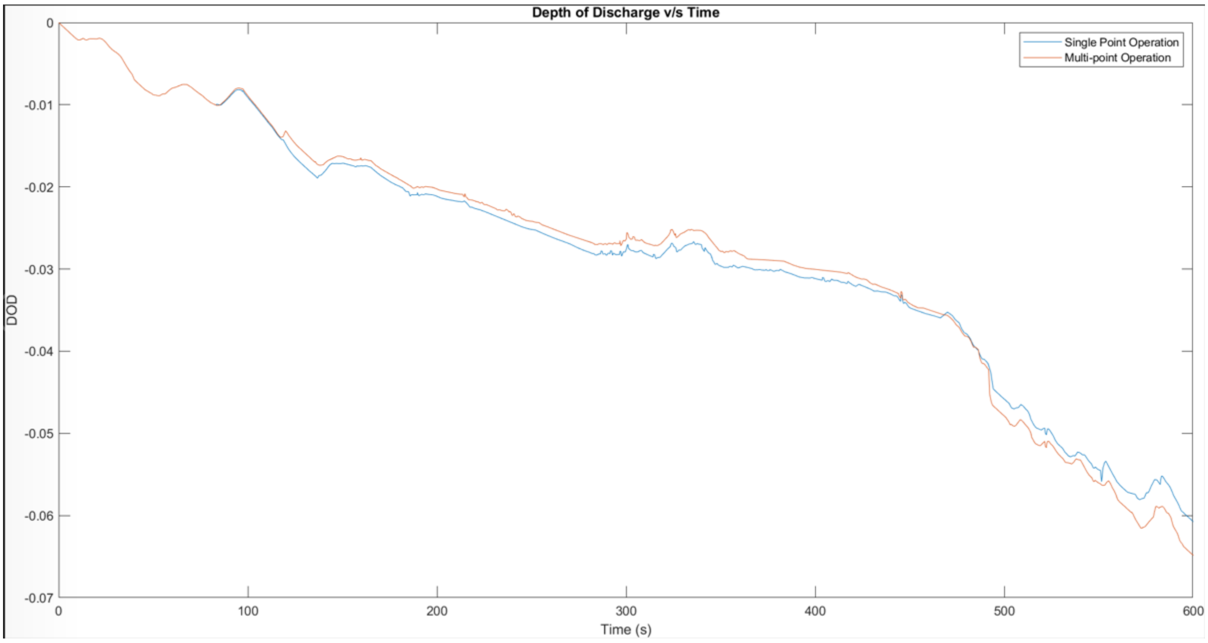
2. **Comparison of State of Charge of battery for different engine control strategies**



It can be observed that the rate of increase of SOC case of SOC based control strategy is higher than the single point operation when the state of charge is lower. This is because the engine is now running at higher power in order to charge the battery faster. However, as the SOC increases, the rate of increase decreases as compared to the single point operation. This is because the engine is now running at a lower power as it realizes that the state of charge is in a better stage and additional power is no longer required.

3. **Comparison of Depth of Discharge of battery for different engine control strategies**

The main aim of this SOC based control strategy is to reduce the depth of discharge as the depth of discharge plays a vital role while determining the battery life. The following plot is a comparison between the depth of discharge of the battery in both cases.



It can be observed that the depth of discharge in the case of a SOC based control approach is lesser than that of a single point engine operation. As the depth of discharge if less, the battery life would also be greater.

Fuel consumption analysis:

Fuel Efficiency	Single Point	Function of SOC
US06 Cycle Fuel Consumption	0.64 gallons	0.72 gallons
Gallons/mile	0.08 gallons/mile	0.09 gallons/mile

The overall gas consumption over the drive cycle was determined. As expressed earlier in the report, the total distance in the US06 drive cycle was 8 miles. The fuel economy in terms of gallons per mile were calculated for the two control strategies (single point v/s multipoint operation). Both strategies yield favorable results for fuel consumption per mile. Based on these calculated values alone, one could argue that operating the engine at a single point is the more favorable of the two options. However, the difference is not too significant. On the other hand, the State of charge is also an important factor to consider as the charts demonstrate that the battery can be charged more if the engine is allowed to operate in various operating points. This could potentially result in a longer electric range.

Battery life analysis

Battery Life	Single Point	Function of SOC
US06 Cycle	46726 miles	61288 miles

Cost analysis:

To compare if the tradeoff between battery life and fuel consumption is justifiable, cost analysis is done for both the cases:

- **Function of SOC**: As the battery would last up to 56288 miles, the total cost incurred till that day would be:
  Cost of new battery + (Life in miles x Cost of gas /miles per gallon)
  = $4435 + (61288 x $3/11.11)) = $20,984.41

- **Single Point Operation:** For the single point operation case, the same number of miles are taken into consideration. The total cost would be:
  $4435 + ((61288-46726)/46726*$4435) + (61288 x $3/12.5) = $20,526.27

From the above comparison, operating the engine as a function of SOC would be more economical as compared to running the engine at a single point. This difference would not be visible by merely taking the fuel consumption into account.

2. Hellcat Vs Series Hybrid Powertrain

	Original Hellcat	Series Hybrid Hellcat
0-60 time	3.6 sec	3.54 sec
Fuel Economy	12.5 mpg	12 mpg

The series hybrid not only matches the original Hellcat in terms of 0-60 time and fuel economy but also outperforms it slighly.

A comparison of the different powertrains can also be made. (The cost of the chosen battery is approximately $4435. This value was determined based on the number of cells and strings in parallel. The total energy was found in KWh and that number was multiplied by the current estimated costs of the battery. The current cost was $136/KWh.) Therefore, the total cost of the vehicle can be estimated as follows:

	Original Hellcat	Series Hybrid Hellcat
Engine	$21,807.00	$1,605.00
Transmission	$ 6,449.00	$0.00
Motor	$0.00	18,448.00
Battery	$20.00	$4435.00
Total	$21,807.00	$24488

It is safe to assume that hybrids are more expensive compared to the original Hellcat, but they are not vastly different. The powertrain costs are relatively similar.

CONCLUSION:

From the above results, it can be concluded that operating the engine as per the SOC levels proves to be more economical than operating the engine at a single point. The difference in cost could be more significant when the simulation is done for the entire range of SOC.

Scope for future improvement:

The control strategy can be a proper function of SOC rather than range based if-else conditions. A proper function-based strategy could further improve the overall cost of ownership of a series hybrid vehicle.

Overlap with other assignments:

The Simulink model of the proposed powertrain was constructed using past assignments from AUE 6610 (Advanced and Electrified Powertrains) as well as AUE 8810 (Automotive Systems Overview). From AUE 6610, the model for the Internal combustion engine was replicated and adjusted. In AUE 8810, a model for a pure battery electric vehicle was created. In this project, the goal was to create a series hybrid vehicle incorporating the IC engine and battery electric model from both AUE 6610 and 8810 respectively. A supervisory control subsystem was used to link the two models together. The challenge was then to size all the components appropriately to meet the objective of the report as well as the vehicle's intended application use.

In AUE 8810, the final group project is to optimize the cost of a proposed battery electric vehicle. The overlaps are from using the same models, but the powertrains and goals are different. In AUE 8810, the goal is to create a model of a vehicle to optimize profit based on zero-to-sixty-time, max acceleration, and range. It is also assuming the vehicle is purely battery electric. In AUE 6610, the feasibility of a series hybrid hellcat is tested and analyzed in various drive cycles. What took this project further was having to create a series hybrid model, not yet done in class. We also implemented the liquid cooling within the model.