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Hybridization of a Sports Utility Vehicle

Assignment report for the course TME095 Electric and Hybrid Vehicles

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Abstract

This assignment investigates the fuel consumption of a sports utility vehicle operating in a specific driving cycle using different powertrains. A conventional internal combustion engine, a series hybrid and a parallel hybrid powertrain is modelled using the QSS toolbox in MATLAB. Parameters in each model is optimised such that they can run through the driving cycle as expected and consume the least amount of fuel in the process. The result shows that with the custom driving cycle used which includes mixed driving in dense city traffic, rural roads and highways, the series and parallel hybrid powertrains have a lower fuel consumption than the conventional ICE. The parallel hybrid has the lowest fuel consumption of 6.591 L/100km because of a lower weight and higher regeneration efficiency as compared to that of series hybrid powertrain which has a fuel consumption of 7.567 L/100km. The results must not be taken literally since the models and driving cycle used are simplified and may not represent all different type of driving and vehicles. The results in this report are just to show the potential in lowering the fuel consumption that a hybrid powertrain can provide in this type of driving behaviour.

Contents

1. Introduction

Emission from transportation sector has been a one of the sources of greenhouse gas emission. There are collective efforts being made to reduce this. One of the measures is introduction of stricter emission regulations. Meeting these regulations just by modification of Internal Combustion Engine (ICE) is nearly impossible. This has led to a shift towards electrification of the vehicles. This assignment will investigate how fuel consumption of a Sports Utility Vehicles (SUV) differs using a conventional gasoline powered ICE compared to two types of hybrid powertrains i.e. series hybrid and parallel hybrid. One of the limiters is that each powertrain must complete the specific driving cycle. This will be done using a custom driving cycle and a software called QSS toolbox in MATLAB. With this tool, an ICE, series, and a parallel hybrid powertrain will be modelled, simulated, and optimized in order to obtain least fuel consuming vehicles.

2. Methodology

2.1 SUV basic parameters

The vehicle parameters are chosen based on the vehicles existing currently in market. SUVs such as the Volvo XC 90, Mazda CX-5 etc. Based on an average, the following parameters as presented in Table 1 are considered for the SUV design. These parameters will remain constant irrespective of the powertrain.

Table 1 Basic vehicle parameters

Vehicle Mass [kg]	Frontal Area [m^2]	Drag Coeff. [-]	Rolling Resistance Coeff. [-]	Rotating Mass [%]	Wheel diameter [m]
1920	3.087	0.35	0.02	4	0.739

2.2 Driving Cycle

The standard driving cycles such as the NEDC, WLTP and the FTP-75 cannot represent the exact driving situation for an SUV. Here a driving cycle has been defined considering that a person starts in a dense city driving condition for about 1000 seconds which is a modified New York driving cycle [1]. This is followed by some driving in outskirts of the city for about 4500 seconds which is a modified Gothenburg driving cycle which transitions to a highway driving cycle for 1000 seconds based on FTP highway cycle. The driving cycle ends with the driver entering a city limit. This gives an accurate representation of all situations involved with driving from dense city traffic to empty streets and highway-based driving. The maximum acceleration of the driving cycle is noted to be 2.66 m/s^2. The driving cycle is 74.32 km long and is presented in the Figure 1.

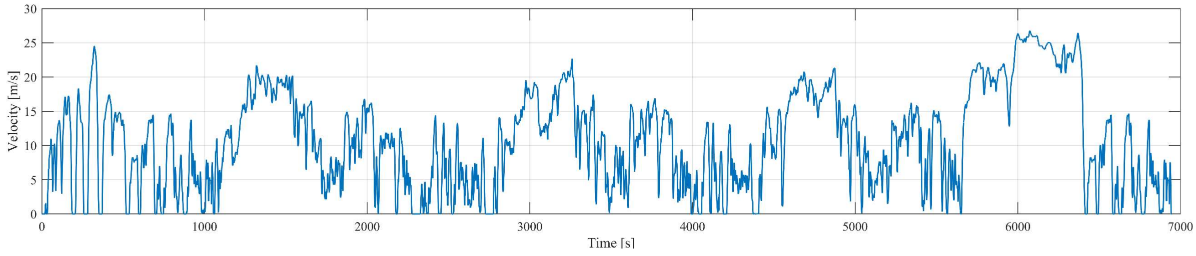

Figure 1 Custom driving cycle for an SUV

2.3 Conventional Internal Combustion Engine vehicle

The ICE based powertrain is the simplest in contrast to the hybrids. The architecture of a conventional ICE system is modelled as shown in Figure 7 of the Appendix. Both the series and parallel hybrids are based on this powertrain thereby enabling easy comparison of the performance variation resulting from hybridization.

2.3.1 Power of the engine and maximum speed of the vehicle

As mentioned in Section 2.1, the performance of the vehicle was based on the average performance of the vehicles in the SUV segment. The 0-100 km/h duration will therefore be 9.9 seconds resulting in an acceleration of 2.8 m/s^2. Thus, the power is as shown in equation below. This power is used to determine the maximum speed of the vehicle as shown below. Where C_r = 0.02 is the rolling resistance co-efficient, C_d = 0.35 is the drag co-efficient, m = 1920 is the mass of the vehicle, g = 9.81 is the acceleration due to gravity, A = 3.09 is the frontal area of the vehicle. Substituting these values in Equation 2 the maximum speed, V is found to be 210 km/h.

$$Power = m * a * v = 1920 * \frac{\left({}^{100}/_{3.6}\right)}{9.9} * \frac{100}{3.6} \approx 150kW \qquad (1)$$

$$Power = (C_r \times m \times g + 0.5 \times \rho \times C_d \times A \times V^2) \times V \qquad (2)$$

2.3.2 Gear box

A six-speed automatic gear box is selected, and the gear ratios and the differential gear were selected based on the average of the existing cars. These gear ratios are further optimized for obtaining the least fuel consumption possible. The optimization was carried out using the fminsearch function inbuilt in MATLAB with the custom driving cycle as presented in Section 2.2. The optimized upshifts occur at 9.63, 35.49, 46.87, 82.16 and 170.9 km/h while downshifts occur at 2.12, 16.03, 30.26, 60.06 and 97.96 km/h. The optimized gear ratios are shown in Table 2.

Table 2 Optimised gear ratios for a conventional ICE vehicle.

First	Second	Third	Fourth	Fifth	Sixth	Differential
3.67	2.49	1.79	1.32	0.94	0.69	3.89

2.4 Series Hybrid Vehicle

In this study, a series hybrid is considered. In this configuration the electric motor provides all the traction force while the engine-generator unit kicks in only when the State Of Charge (SoC) of battery reaches or is below the minimum specified. Once the engine has been started it is run until the SoC of the battery has reached the maximum limit specified and is then turned off. But if the power demand is above the set limit, the engine is run irrespective of the previous mentioned condition. Having the motor connected to the wheel enables regeneration of energy during braking. This has been achieved by modifying the engine model in the QSS blocks. The architecture of a series hybrid system is modelled as shown in Figure 8 of the Appendix.

2.4.1 Powertrain parameters

The addition of the motor, generator and the battery is assumed to increase the mass of the SUV by 250 kg. In order to meet the same requirement as of the ICE based as specified in Section 2.3, initial power of the Electric Motor (EM) was assumed to be 150 kW. Given that the motor has a high initial torque output, this will compensate the weight increased when doing a 0-100 km/h cycle. The maximum power of the ICE and Electric Generator (EG) was determined iteratively by trial and error and are presented in Table 3. For a hybrid battery, each cell in the battery having a nominal voltage of 3.8 V and a maximum current of 100 A, the number of cells in the battery pack was determined as shown below. Where N_s and N_p is the number of cells in series and parallel, respectively.

$$Max\ power\ required = 150 \times 10^3 = \ 3.8 \times Cells\ in\ Series \times 100 \times Cells\ in\ parallel$$

$$N_s \times N_p = 394.7 \approx 396 = 99 \times 4$$

Table 3 Various powertrain parameter for the series hybrid

EM Power [kW]	ICE Power [kW]	EG Power [kW]	No. in Series [-]	No. in Parallel [-]
150	48	35	99	4

Two simple transmissions are considered in this series hybrid configuration. Since the EM does not have any gears but is mounted before the differential, the overall effective gear ratio here will be 4.51. This number is chosen based on the value obtained during the optimisation of the parallel hybrid powertrain which is explained in Section 2.5.1. A single gear with a gear ratio of 1.15 and efficiency of 0.89 is mounted between the engine and generator to enable the generator to operate at it most efficient point.

2.4.2 Control Strategy

The control strategy of the series hybrid is based on the SoC of the battery. A maximum and minimum levels of SoC have been specified to be 60% and 30% respectively. The minimum is selected to be 30% just to have enough charge in the battery in case of a high-power demand occurs. The maximum limit is set to 60% to accommodate regeneration power if any occur and to avoid the engine constantly turning on and off. This will help avoid the energy demand to start the engine. The engine-battery control is as follows:

a. Regeneration is carried out up to 100% of the motor capacity during braking enabling charging of the battery. The engine is kept off when the regeneration is carried out.
b. When the SoC of the battery is above the max SoC the engine is always kept off. The engine stays off till the minimum SoC is reached the first time.
c. When the SoC of the battery has attained the minimum SoC limit or is below the minimum SoC limit, the ICE is turned on and runs at a speed of 2500 RPM and a torque of 75.4 Nm. This is in turn connected to a generator through a gear box which results in the motor operating at a speed of 2875, producing a torque of 73.67 Nm which charges the battery. If the power demand is higher than 60% of the maximum power the battery can supply, then the ICE is run at a speed of 3000 RPM and 95.25 Nm as the EM limits the maximum possible power. Since the engine can be run at any given point irrespective of the vehicle operating condition, we have the flexibility of running the engine at these conditions.
d. A memory block is used to remember if the engine is on in the previous iteration. This is used when the SoC is in between the minimum and maximum limits. When the memory block provides an output of 1 then the engine must be run until the maximum SoC limit has been reached.
e. When the output of the memory block is 0, this indicates the SoC has reached maximum limit of SoC and is to be discharged until the minimum limit is reached again. This cycle of charging and discharging repeats itself until the end of driving cycle.
f. When the SoC is in between minimum and maximum and the power demand is higher than 60% of the maximum power the battery can supply, then irrespective of previous condition of

the engine, the engine is run at 3000 RPM and 95.25 Nm. This is the most efficient point for balancing the difference in the operating regions of the motor and generator.

2.5 Parallel Hybrid Vehicle

This study considers a P3 parallel hybrid in which the electric motor provides majority of the traction force while the engine kicks in when either the SoC of battery is below the minimum specified or power demand is more than the capacity of the electric motor. The architecture of a parallel hybrid system is modelled as shown in Figure 9 of the Appendix.

2.5.1 Powertrain parameters

The addition of the motor and the battery is assumed to increase the mass of the SUV by 200 kg. Since we add only one motor and a smaller battery the mass increase is lower as compared to the 250 kg increase in the series. For meeting the acceleration requirements as specified in Section 2.3 the combination of ICE and EM must produce 150 kW. This can be done in multiple combinations but given that it is a non plug-in hybrid, and we need to charge the battery with either regeneration or the engine, we prefer to have a large engine and relatively a smaller motor. The capacity of each of these propulsion machines is determined iteratively and are presented in Table 4. For a hybrid battery, each cell in the battery has a nominal voltage of 3.8 V and a maximum current of 100 A. The calculation of number of cells is as shown below. Where N_s and N_p is the number of cells in series and parallel, respectively. Here a smaller sized battery is sufficient as engine provides power parallelly to the electric motor and can assist the drive. The parameters of the parallel hybrid powertrain are given in Table 4.

$$Max\ power\ required = 65 \times 10^3 = 3.8 \times Cells\ in\ Series \times 100 \times Cells\ in\ parallel$$

$$N_s \times N_p = 171.05 \approx 175 = 35 \times 5$$

Table 4 Various powertrain parameter for the parallel hybrid

ICE Power [kW]	EM Power [kW]	No. in Series [-]	No. in Parallel [-]
85	65	35	5

A six-speed gear box is coupled to the engine and is optimized using the fminsearch function inbuilt in MATLAB as described in Section 2.3.2. The optimized gear ratios are shown in Table 5. The optimized gear box has all ratios same as that of the gearbox in the conventional ICE with only change in the differential making it effective in terms of the cost for the manufacturer. For the electric motor we can run it without the gear but given that it is mounted before the differential the overall gear ratio will still be 4.51.

Table 5 Optimised gear ratios for engine gearbox in parallel configuration.

First	Second	Third	Fourth	Fifth	Sixth	Differential
3.67	2.49	1.79	1.32	0.94	0.69	4.51

2.5.2 Control Strategy

The control strategy is based on the power demand and the SoC of the battery. Similar to a series hybrid the maximum and minimum levels of SoC have been specified to be 60% and 30% respectively. The controller can be designed in many ways. Here, the simplest approach has been considered and is designed keeping fuel consumption as the variable to be optimised. The engine-motor control and power distribution is as follows:

a. Regeneration is carried out up to 100% of the motor capacity during braking enabling charging of the battery. This has been implemented within the EM block in QSS.
b. When the SoC of the battery is above the max SoC,
    i. If the power demand can be satisfied by the EM alone then the ICE is kept off and the EM supplies all the necessary torque.
    ii. If the power demand exceeds the power supplied by the EM at that given speed, the ICE is run to provide the excess torque requirement.
c. When the SoC of the battery is below the minimum SoC and the power demand is below the maximum power generated by the ICE at the given speed,
    i. If the sum of power demand and the maximum EM power at the given speed is less than the ICE power at that speed then, the EM is charged using the maximum possible torque and the ICE is run at a torque providing the total power requirement.
    ii. If the sum of power demand and the maximum EM power at the given speed is more than the ICE power at that speed then, the ICE is run at maximum torque for that speed while the EM is charged with the power remaining after meeting the power demand.
d. When the SoC of the battery is below the minimum SoC and the power demand is above the maximum power generated by the ICE at the given speed, then run the ICE at the maximum torque possible and the EM is run to provide the additional torque requirement. Although this will deplete the SoC of the battery even further, this high-power demand only lasts for few seconds.
e. When the SoC of the battery is in between the minimum and maximum SoC limits,
    i. If the power demand is less than 25% of the maximum EM power at that given speed, the EM supplies all the power while the engine is kept off. The reason for 25% limit is that the operating points beyond this will result in a lower efficiency.
    ii. If the power demand is greater than 25% of the maximum EM power at that given speed, then the ICE is run at 80% of its maximum power at the given speed as this is trajectory that provides the lowest fuel consumption. With this the power demand is met and the remaining power is used to charge the battery using the motor.
    iii. If the torque demand is greater than the maximum power the ICE can generate at the given speed, both the EM and the ICE are run to meet the power demand.

3. Results

All three powertrain configurations are tested using the custom driving cycle defined in Section 2.2. The results from each of the powertrains is compared below.

3.1 Performance

3.1.1 Conventional ICE based powertrain.

From Figure 2 it is evident that the engine operates mostly at low speeds and low torques. This is how most practical driving conditions are. But at some parts of the driving cycle the engine operates at wide open throttle condition. Although the engine is never used at the peak power points, a large engine has to be used as using a smaller engine will reduce the acceleration ability and the top speed.

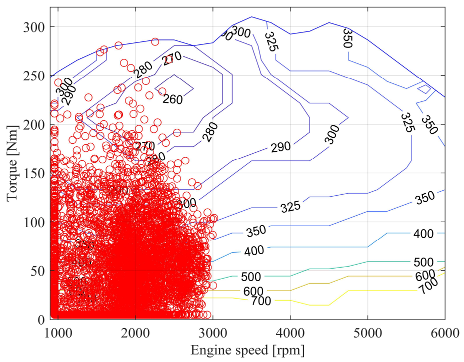

Figure 2 Engine map of ICE based powertrain.

3.1.2 Series hybrid powertrain

In the series hybrid powertrain, the ICE is operating only at two points as seen in Figure 3a. The engine is operating at the point having the lowest BSFC when charging the battery up to the max SoC. The other point is when the ICE is turned off because the SoC is above the max SoC and does not need charging the battery through the generator. The power demand in the driving cycle is not very high, but given that the driver requests a very high torque the engine is programmed to deliver a higher power output.

In Figure 3b the operating points of the generator is presented. In a similar way as the ICE the generator is only operating at two points since the power demand is limited within this cycle. But the generator is programmed to deliver a higher torque when the power demand exceeds 60% of what the battery can deliver. When charging the battery, it is running at the most optimal point that being around 2875 rpm and 76.1 Nm. The other point is when the engine generator unit is turned off as the maximum SoC limit is attained.

In Figure 3c the operating points of the electric motor is presented. As predicted with the driving cycle used, the maximum power is not used at any point. But a large motor is designed to meet the performance in terms of accelerations and top speed. This driving cycle does not test this, and the peak power is therefore not used.

The SoC during the driving cycle is presented in Figure 4. It is clear that the SoC is kept between the maximum limit of 60% and the minimum limit of 30%. Given that it is a non plug-in hybrid, in order to ease the comparison with the conventional powertrain the cycle starts at 42% SoC and ends with the same SoC, which is also one of the stated requirements.

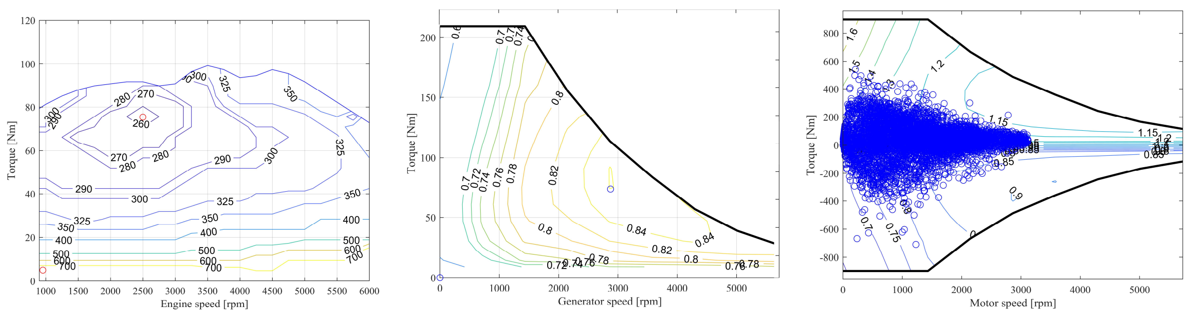

Figure 3 Operating points in a) Engine b) Generator c) Motor for a series hybrid powertrain

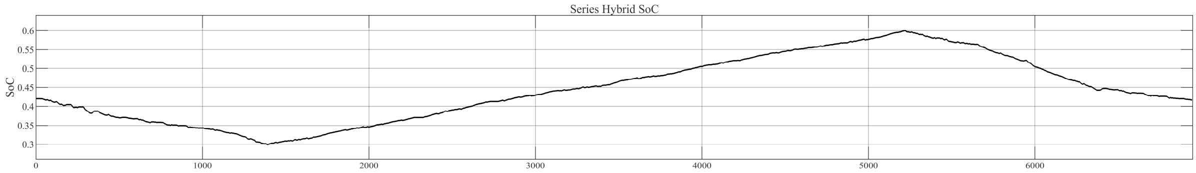

Figure 4 Battery SoC during the driving cycle for a series hybrid

3.1.3 Parallel Hybrid powertrain

In the parallel hybrid powertrain, the operating points for the ICE is presented in Figure 5a. The ICE is operating at more points than in the series due to the mechanical connection to the wheels. These operating points are observed to give the least fuel consumption as the engine operates in most efficient BSFC point for the given speed. In Figure 5b the Electric motor operating points is presented. This shows that with a parallel hybrid configuration the electric motor is used with a higher peak torque for recuperation than for propulsion. This is because of the use of a smaller EM and a bigger ICE. For propulsion, the motor is used only when the power demand is either very low or beyond the limits of the engine.

In Figure 6 the SoC during the driving cycle is presented. It is clear that the SoC is kept between the maximum limit of 60% and the minimum limit of 30%. in order to enable the comparison with the conventional powertrain the cycle starts at 45% SoC and ends with the same SoC, which is also one of the stated requirements.

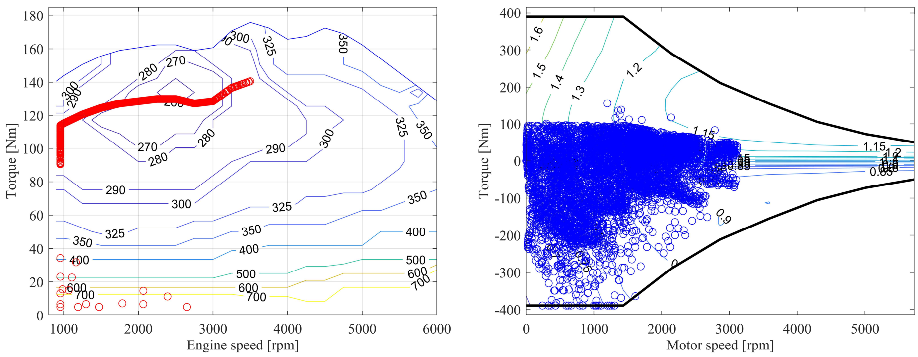

Figure 5 Operating points in a) Engine b) Motor for a parallel hybrid powertrain

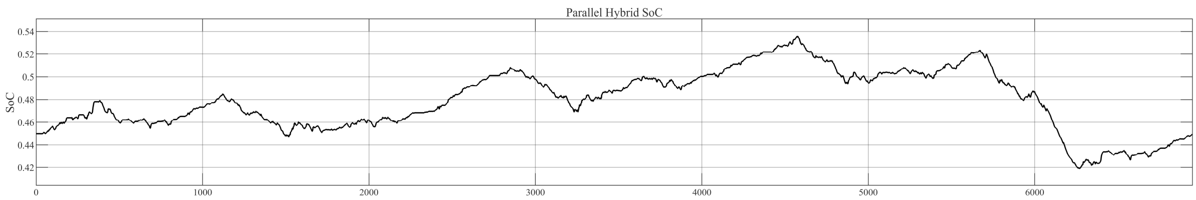

Figure 6 Battery SoC during the driving cycle for a parallel hybrid

3.2 Fuel Consumption

Since for both the series and parallel hybrid the SoC with which the driving cycle ends is same as that with which it is started, it is safe to assume that this will help compare all three powertrain setup on equal terms. The fuel consumptions of the different powertrains are presented in Table 6. As expected, a lower fuel consumption is achieved with both hybrid powertrains. Changing the powertrain from an ICE to a series hybrid will result in a 42.4% reduction while the reduction potential would increase to

49.8% is the ICE is changed to a parallel powertrain. The parallel hybrid has a lower consumption compared to the series powertrain. This is due to the fact that no losses when converting mechanical power to electricity is present.

Table 6 Fuel consumption (L/100km) of various power train configuration during the custom driving cycle

Powertrain configuration	Fuel Consumption [L/100km]	% reduction w.r.t ICE
ICE	13.13	-
Series	7.567	42.4
Parallel	6.591	49.8

Discussion & Conclusion

All three powertrains managed to run through the custom driving cycle and the resulting fuel consumptions are all reasonable. The various parts of the powertrain are modelled and optimised to obtain the least possible fuel consumption. Most of the engine operating points in the ICE configuration are relatively in the lower and mid-range of the torque speed diagram. This indicates that the powertrain can offer even higher acceleration given the driver requests any. Given the optimisation is done with fuel consumption in mind, the series hybrid the engine is run at the single most optimal operating point while a parallel hybrid is operated at the most optimal point for the given speed. The results of fuel consumption for each of the vehicles is just an indication and is not to compare with a real vehicles behaviour. But the difference in fuel consumption with this driving cycle and each powertrain is close to what real tests would be. This is due to the various limitations within the model. In the QSS toolbox there is some limitations, for example general maps being scaled, fixed rpm range of the engine, generator and electric motor, gear shifting based on speed alone etc. In a parallel hybrid model designed here the engine often turns on and off. There are losses associated with this both in terms of fuel consumption and mechanical damages to the starter motor. These losses are not taken into consideration. The results are depending on which driving cycle is used and what kind of driving the powertrain is optimised for. This in practice varies from driver to driver with some driving at full throttle always while the others may follow a pattern similar to the driving cycle. If the driver run long distances on highway it could be possible an ICE powertrain is most efficient with a low geared transmission and lower weight. In city driving that includes a lot of start and stops the hybrid could be the best option, using the electric motor when the ICE engine is not performing at the optimal point. With the custom driving cycle used in this assignment that includes mixed driving the parallel suits the best, since it combines a lower weight and without the high energy conversion losses that the series hybrid has. The series has a large motor which will not be operating at higher efficiency points during regeneration within the city limits whereas the parallel with its smaller motor can regenerate with higher efficiency due to the smaller motor as seen in Figure 3b and Figure 5b. The parallel uses a single 65 kW motor and a 9.975 kWh battery which is very small as compared to a 150 kW motor, 35 kW generator and a 22.572 kWh battery in the series hybrid configuration. The problem using the software and models used in this assignment is the simplification of the complex system in a real vehicle and driving cycles. The resulting numbers in this assignment is just indications and is not to be taken literally. But the trend of best improvement of fuel consumption being obtained in parallel hybrid can be deemed correct.

The conclusion is that based on the result of the analysis conducted for the driving cycle, one can clearly state that the parallel hybrid is the power train to go for not just in terms of fuel consumption but also with respect to of weight and the cost (as compared to the series hybrid).

Appendix

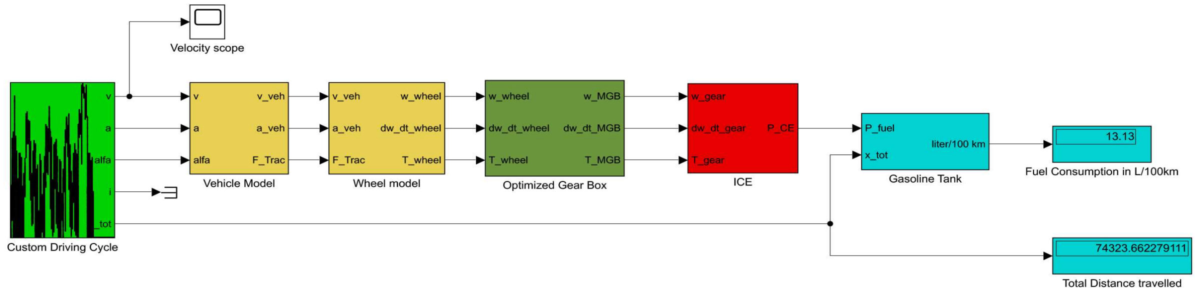

Figure 7 Conventional ICE based powertrain configuration.

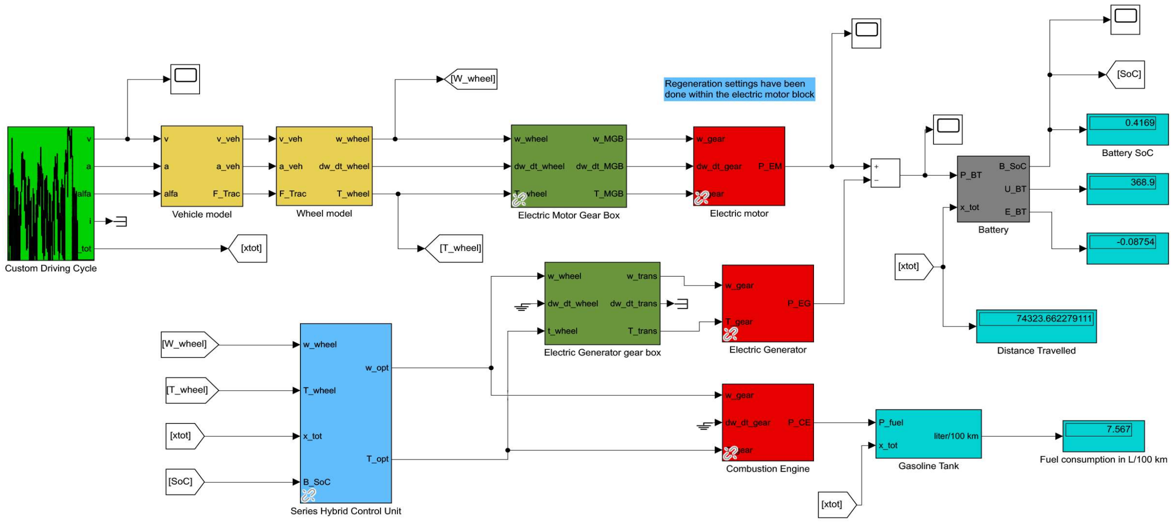

Figure 8 Series hybrid powertrain configuration.

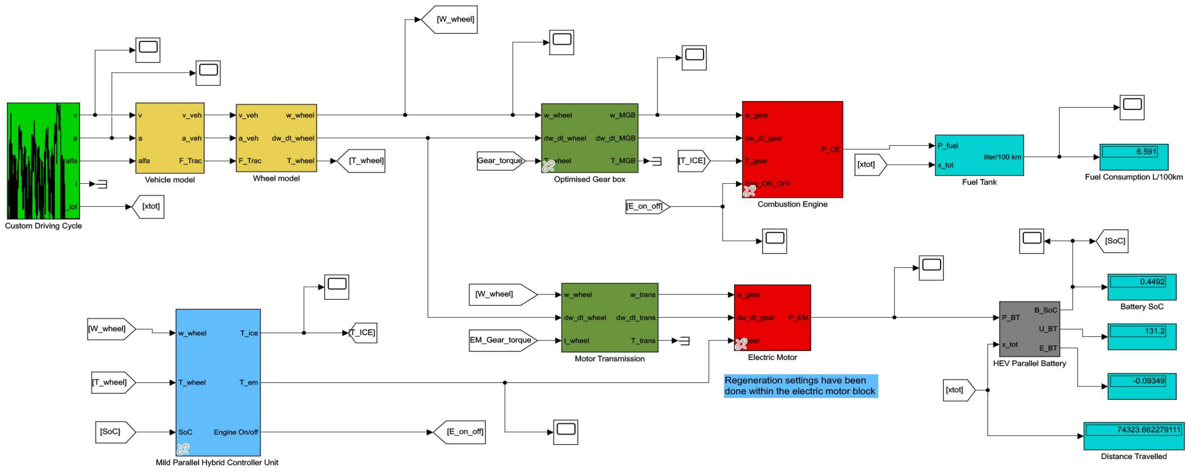

Figure 9 Parallel hybrid powertrain configuration.

References

[1] "Dynamometer Drive Schedules | Vehicle and Fuel Emissions Testing | US EPA." [Online]. Available: https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules. [Accessed: 11-Mar-2021].