CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Optimizing vehicle fuel consumption using a mild-hybrid powertrain

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Declaration of authorship

I hereby declare that this master's thesis has been written by me in person. All information derived from other works has been acknowledged in the text and the list of references.

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Abstract

This master's thesis is intended for hybridisation of conventional internal combustion engine-powered vehicle into a mild hybrid vehicle and optimises it for fuel savings. This research is done using a specific vehicle and a specific test track with gradient data. The vehicle used as the test car is Skoda Octavia 1.4 TSI. MATLAB Simulink and Stateflow environments have been used to model and run the simulations for this mild-hybrid vehicle. The goal is to improve fuel efficiency by utilising the energy recuperation potential. Appropriate electric motor/generator has been selected based on the energy requirements. Hybrid controller algorithm required to moderate ICE and EM is designed to retain a similar level of state of charge by the end of the trip. In conclusion, obtained simulation results of mild-hybrid vehicle model have been compared to ICE vehicle and optimised for better efficiency.

Keywords: Mild hybrid optimisation, MATLAB Simulink, SOC optimisation,
fuel efficiency Improvement, hybrid vehicle control logic

Abstrakt

Tato diplomová práce se zabývá přeměnou klasického vozidla poháněného spalovacím motorem na mild hybrid a optimalizace spotřeby paliva. Výzkum je prováděn za použití gradientních dat získaných na dané testovací trase a jako testovací vozidlo byla použita Škoda Octavia 1.4 TSI.K vytvoření modelu mild-hybridního vozidla a provedení simulací byl použit software MATLAB Simulink. Cílem práce je zlepšit spotřebu paliva za využití systému rekuperace. Na základě energetických požadavků byl vybrán vhodný elektromotor. Ovladač, který reguluje činnost spalovacího motoru a elektromotoru, je navržen tak, aby byl stav nabití baterie ke konci jízdy přibližně stejný jako na začátku. Získané výsledky ze simulací prokazují, že hybridní vozidlo má nižší spotřebu paliva.

Klíčová slova: Mild- hybridní optimalizace, MATLAB Simulink
Zlepšení palivové účinnost

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Contents

1 INTRODUCTION

1.1 BASIC TERMS

The word Hybrid means something such as a vehicle, plant or electronic circuit that has two different components but performing essentially the same function (Anon., n.d.).In the automotive world, a hybrid vehicle is one which uses two distinct power sources in its powertrain layout. Most of the vehicles on road today use the combination of Internal Combustion engine ICE (petrol/diesel) with Electric Motor /Generator EM in multiple different layouts to suit the requirements (Anon., n.d.). The vehicle with a powertrain combination of ICE and EM is called Hybrid Electric Vehicles or HEV’s. Electric Motor / Generator uses an additional battery as energy accumulators. Ultra-capacitors and flywheels (howard, n.d.)are alternative choices when a high burst of energy is needed in a short span of time. There are two ways to classify a hybrid vehicle. First one is based on the structure of powertrain which is Serial, parallel and Series -parallel architectures. The second one is based on the size of electric motor and battery capacity. These are further classified to different subgroups based on the level of hybridization. Which are (xengineer, 2018)

1. Micro-Hybrid
2. Mild Hybrid (MHEV)
3. Full Hybrid (HEV)
4. Plug-in Hybrid (PHEV)
5. Range Extender (BREV)

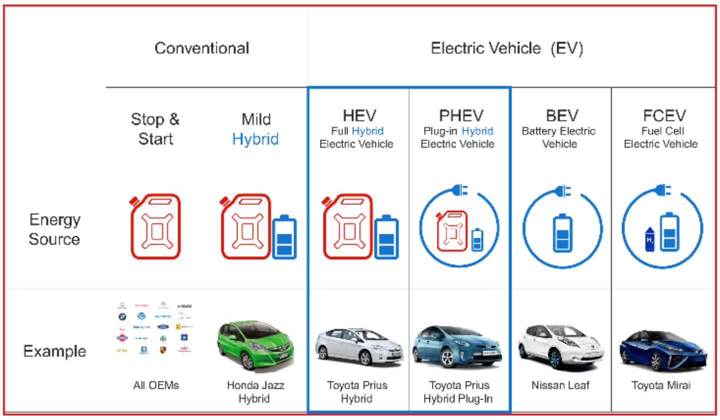


Figure 1-1Types of hybrid Vehicles (Launch, 2019)

This research is focused on the optimisation of mild hybrid vehicles.

1.2 GOAL

The goal of the thesis is to design and test a mild hybrid architecture on a designated track. The required data for the track is collected by the test vehicle with OBD and GPS. Our aim is to test the hybrid architecture for fuel savings.

P2 architecture that is being used for this study has the best offering in terms of cost of hybridization, development time and ease of integration.

To minimise the cost of development, companies and researchers take advantage of the model-based design software which will rapidly cut down the research time with the ability to test different powertrain configurations. For this research, we have used MATLAB/SIMULINK environment to build the mathematical models of the car with the conventional powertrain and also for the development of the model with the hybrid powertrain

1.3 MOTIVATION

Hybrid vehicles have been in mass production for two decades. It has changed the global perspective of future mobility. In recent years, increased concern about climate change has led to the introduction of stringent emission norms which paved the way for further development of hybrid electric vehicles as they offer significant advantages over conventional automobiles.

1. Energy recuperation during braking
2. Start-stop system for better efficiency
3. Full electric driving possibility in low speed
4. Torque boost
5. Ability to operate ICE (Internal Combustion Engine) in its efficient region

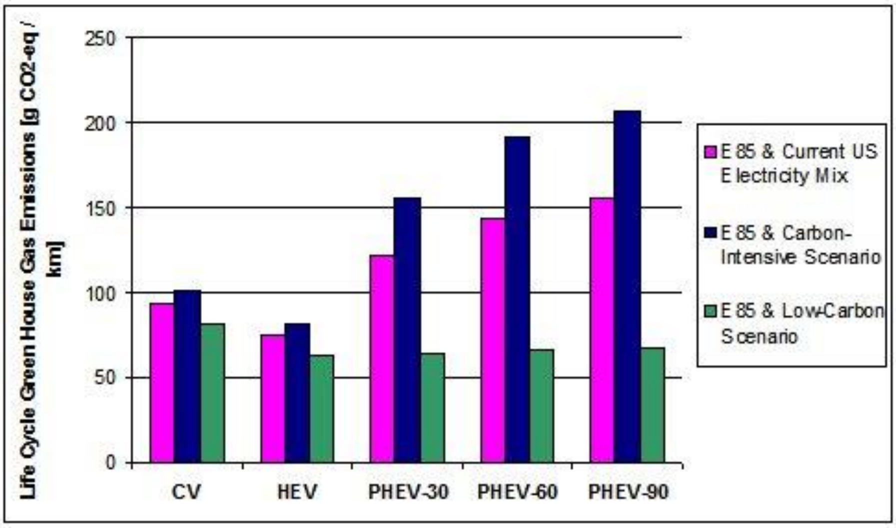


Figure 1-2 CO2 Emissions based on vehicle classification (XIE, 2008)

Hybrid vehicles provide better efficiency in On-road conditions in terms of CO2 whilst they are almost equal to conventional cars in Well to Road CO2 emissions. In this research, the concentration was on Mild Hybrid architecture as they provide the best balance for hybridisation of existing vehicles for industries with minimum development cost. Hybrid vehicles allow the engine downsizing which in turn results in better fuel consumption and emissions (Network, 2016)

1.4 MILD HYBRID ELECTRIC VEHICLE -MHEV

Mild hybrids are also known as power-assist hybrids. A mild hybrid electric vehicle consists of two sources to provide torque where the Internal Combustion Engine acts as the main source of torque, Electric Motor (EM) is usually in the size of 12-20KW of power. The energy required for the electric motor is drawn from additional High voltage (HV) battery which is solely used for this motor, energy flow in HV battery is bidirectional, so it is also used to store energy during regeneration. During the regeneration phase, the electric motor operates as a generator. There are multiple scenarios in which EM operates as a generator which affect the efficiency of the architecture. Mild hybrids operate in a parallel configuration in most of the vehicles. (Hussain, 2003)

- The electric motor acts as Kinetic Energy Recovery System (KERS) and recuperates the braking energy which is otherwise lost in a conventional vehicle. The generated negative torque is converted to reusable energy and stored in the battery. Depending on the rate of deceleration it shares the braking torque with friction brakes.
- ICE is operated in an optimal efficiency region to minimise fuel consumption. These operating points are decided based on engine RPM, torque and brake specific fuel consumption (BSFC) data. In this state electric motor assists with either negative or positive torque based on torque required. Because of this MHEV will have better efficiency and reduced emissions.

1.4.1 MHEV Classification

Hybrid vehicles are initially classified based on the power of the electric machine and battery capacity. Mild hybrids are further classified based on the position of electric motor and the type of connection to the drivetrain. This will critically influence the range of functions that can be used in MHEV.it impacts the whole vehicle in terms of fuel efficiency, cost of integration and dynamic performance.

1.4.1.1 P0 – Belt Integrated Starter Generator

P0 system is based on a 48V based architecture which allows a higher recuperating power when compared to the 12V system. The electric motor is attached to the engine through an accessory belt. It will also increase the comfort of the passengers with additional functionality like stationary air-conditioning by engaging a switchable pulley decoupler, the cost of integration for this mode of the hybrid system is lower than any other type.

1.4.1.2 P1 –Electric Motor/Generator Mounted on Crankshaft side

In the P1 system, the electric motor/generator is attached directly to the crankshaft. This will eliminate the 12v starter as the electric motor can efficiently perform engine start/stop function. P1 architecture is more advantageous for the regeneration than P0 but engine acts as a parasitic force as it can’t be decoupled from the motor. The clutch is present between the electric motor and transmission.it will have better torque boosting capacity which is advantageous during high torque demand states. (Schröder, 2018)

1.4.1.3 P2- Electric Motor/Generator Mounted on the Transmission side

P2 hybrid machines have the electric motor/generator attached on the transmission side of the powertrain. It has better flow efficiency because of the position of the electric machine minimising torque losses during the recuperation. This architecture also gives the possibility for full-electric driving and standing recharging capability of the battery. The electric machine can be directly placed in between the transmission and crank or it can be connected through a gear mesh based on the packaging requirement.

For P3 type hybrid vehicle the electric motor connected to the output shaft of the transmission which will give enhanced capabilities of P2. Whereas in P4 the electric motor is placed on the rear axle of the vehicle which will give the maximum regeneration potential.

1.5 P2 MILD HYBRID ARCHITECTURE

P2 architecture is the main topic of this thesis. As it has much more potential than P0 in terms of recuperation potential and ability of electric driving. The size of the electric motor is usually from 10 to 20KW.the cost of integration of this system is high. Depending on the capacity of the electric machine this system has high torque boosting capability and engine can be disconnected completely during braking which results in better regeneration only losses during this phase are due to the transmission. There are a range of functions which can be used with this system (E.Fuhs, 2009)

- Engine start/stop –(*Figure 1.8*)
- Cold engine cranking
- Stop in motion (sailing or coasting)
- Engine load point shift for optimal efficiency
- Torque fill during acceleration
- Torque Boost for overall performance-(*Figure 1.9)*
- Standstill charging-(*Figure 1.7*)
- Energy recuperation (overrun phase)
- Braking Energy Regeneration (*Figure 1.6*)
- Electric Driving (creep)-(*Figure 1.4)*
- Stand still air conditioning (cool welcome) -(*figure 1.3)*

The two types of P2 are On-axis and Off-axis electric machine, In the first one, the electric motor is directly on-axis to the crankshaft which requires additional space and increases packaging difficulty whereas Off-Axis machine is relatively easy to integrate and can mesh by using direct gear or a chain which will have negligible transmission losses. For this research, we have used Borg Warner P2 Off-Axis Module (Warner, 2018) as a reference. This module is an off-axis module; therefore, it is placed externally with a chain mesh. It’s compact length benefits from minimal axial length requirement which makes it a suitable choice for the hybridization of the existing line-up of cars. The ratio between the motor and the axle is tuned on required torque capacity and RPM range of the vehicle.

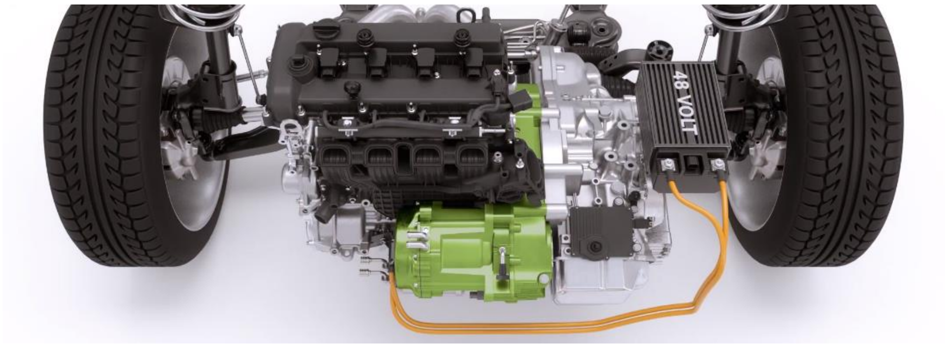


Figure 1-3 Borg Warner P2 Off-Axis Hybrid Module (Warner, 2018)

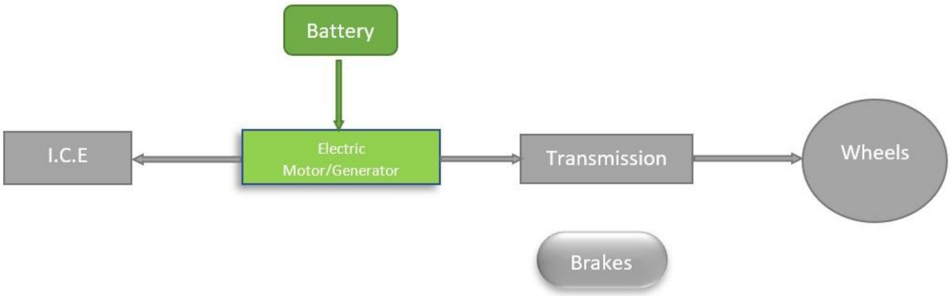


Figure 1-4 Standstill Air conditioning mode

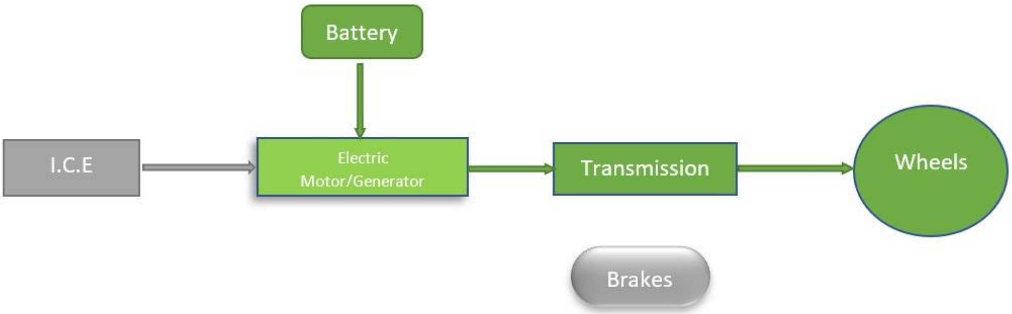


Figure 1-5 Electric Driving mode

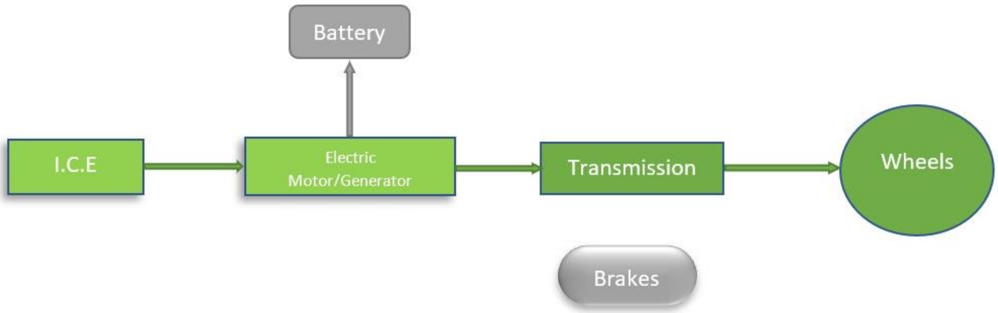


Figure 1-6 Normal ICE operation mode (passive electric motor)

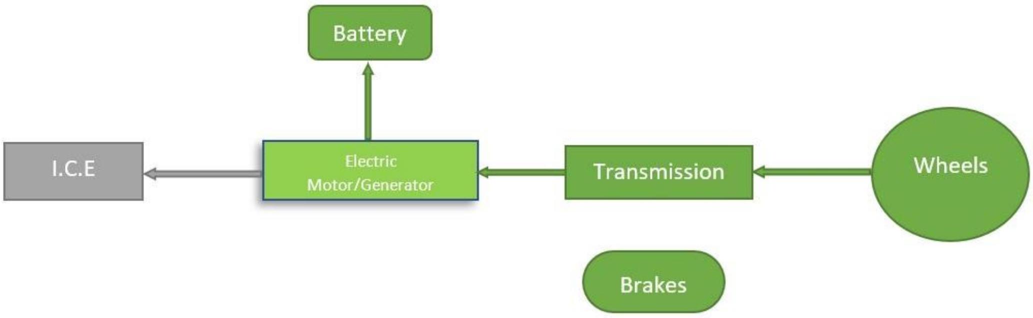


Figure 1-7 Regenerative Braking

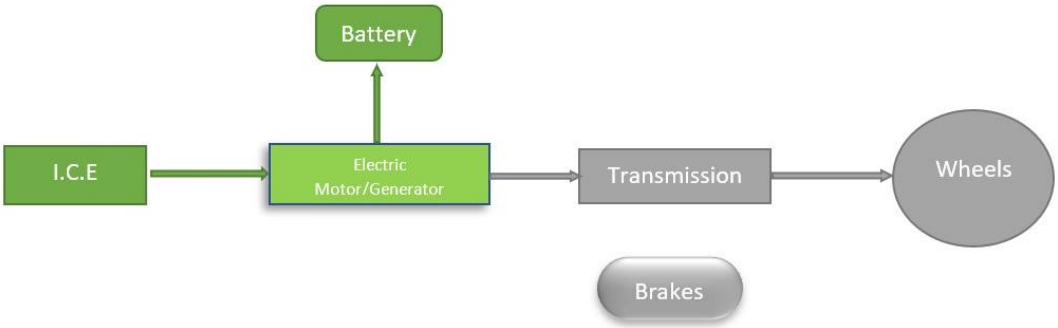


Figure 1-8 Standstill Battery Charging mode

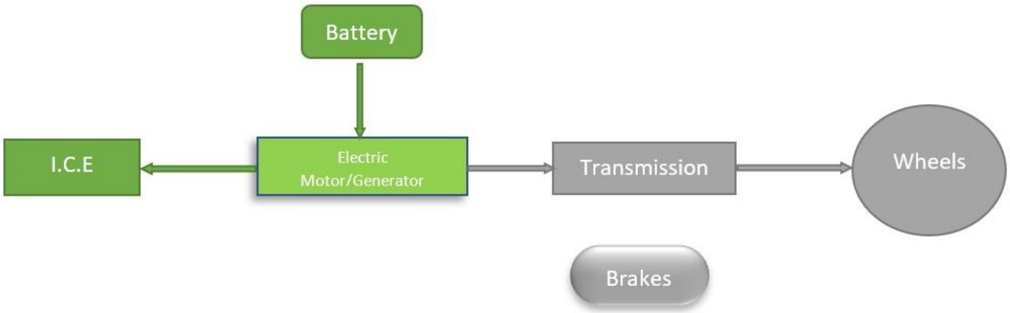


Figure 1-9 Engine Start /Stop

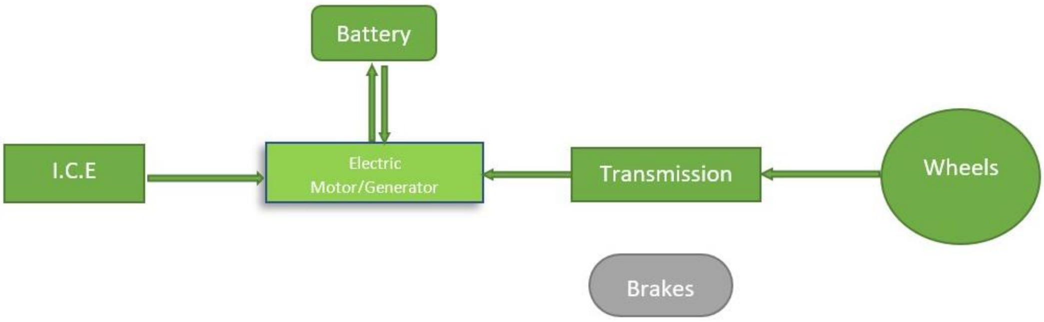


Figure 1-10 Torque assist

2 INITIAL APPROACH

2.1 DATA COLLECTION

Our goal is to test the mild-hybrid system in the specific track that was used to collect the data. The runs were made four different routes with Škoda Octavia Combi 1.4 TSI.

The tracks are 1. Neratovice to Celakovice 2. Celakovice to Neratovice 3. Kostelec to Prague 4. Prague to Kostelec.

As the models are modular to the type of the track in which we run, we proceeded by selecting Praha to Kostelec track out of the available routes. The data received consists of OBD data, fuel data and GPS data. The OBD data includes time, vehicle speed, engine speed. GPS data also includes the data necessary to find the gradient at every time step. Unlike the Driving cycles which were used for vehicle testing, this track test is also going to include gradient which will yield better results for a hybrid vehicle with the ability to calculate the recuperation energy during braking. In test cycles gradient is not considered as it makes the standardization of the test more difficult. In real life running of the vehicle, it is very likely to encounter gradients from time to time. In the case of hybrid vehicles, the design principle is also based on regenerative braking which can be tested to its full potential with gradient data.

2.2 RESISTANCES ON THE CAR

For a vehicle to move in a straight line it must overcome resistance forces acting on it. Its characteristics are completely determined by all the forces that are acting on it in this direction. These forces are key to determine the tractive effort required by vehicle for acceleration, top speed, climbing ability. Etc. Figure 2.0 shows the forces acting on the car which is going uphill, the tractive force, $F_{traction}$, is the force in between the tires of driven wheels and road surface that propels the vehicle forward.

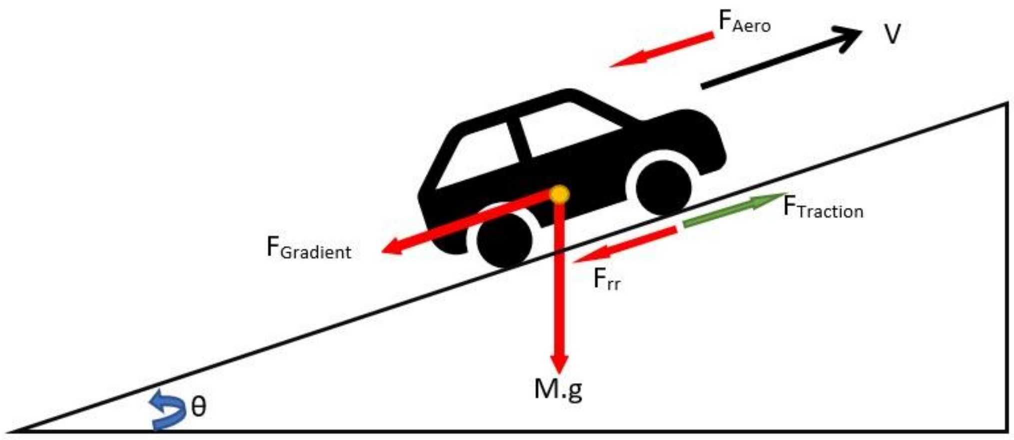


Figure 2.0 *Forces acting on the vehicle*

The resistance forces are

1. Acceleration Resistance
2. Gradient Resistance
3. Rolling Resistance
4. Aerodynamic Resistance

The tractive force must overcome all the resistive forces in order to propel the vehicle forward.

2.2.1 Acceleration Resistance

The inertial forces act on the vehicle during acceleration or braking due to rotating parts in the car mainly consists of transmission elements and rotating parts in the engine. Newton's second law of motion can be expressed in equation form as (Hussain, 2003)

$$F_{acceleration} \quad = M_t\, a$$

Where

$F_{acceleration}$ =Resistance force due to acceleration(N)

M_{total} =Total mass of the vehicle (Kg)

a =Acceleration of the vehicle (m/s^2)

M_{total} includes both the rotational mass components and non-rotating components as well.

M_{total} = $((M_{kerb} * K) + M_{load})$

M_{kerb} =kerb weight of the vehicle

M_{load} =Load in the vehicle

K =Rotational inertia Coefficient

Vehicle load consists of Driver and onboard passengers and luggage. For the test vehicles on board measuring equipment is also taken into consideration. K denotes the proportion of mass that is rotary.

2.2.2 Gradient Resistance

When a vehicle is going either uphill or downhill, its weight produces a component that is always directed in the downward direction. This component either opposes the forward motion (climbing) or helps the forward motion (descent). This gradient force is usually called as gradient resistance.

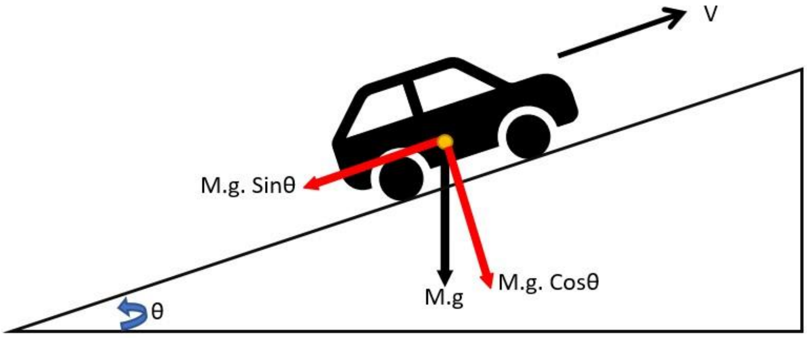


Figure 2.1 *Gradient Resistance*

F_{Grad} = M_{total} g Sinθ (Haralad Naunheimer, 2011)

For smaller angles, θ can be used instead of Sinθ

Where

M_{total} = Total mass of the vehicle (Kg)

g =Acceleration due to gravity (m/s^2)

θ =Gradient

2.2.3 Rolling Resistance

Rolling resistance is primarily comprised of resistance from tire deformation, penetration and surface compression. It is caused by the hysteresis in the tire materials. The pressure in the contact area between tire and ground is distributed symmetrically to the centreline Hysteresis causes an asymmetric distribution of the ground reaction forces the pressure in the leading half of the contact area is larger than the trailing half. This results in ground reaction force shifting forward, with the normal load acting at the centre causes a negative moment which opposes rolling of the wheel. The rolling resistance is more prominent in the soft road conditions as they tend to deform more than the hard-tarmac roads.

$$F_{Roll} = M_{total}\, g\, f_r \qquad \text{(Haralad Naunheimer, 2011)}$$

Where,

f_r is the Rolling Resistance coefficient,

The rolling resistance coefficient is a function of tire material, tire structure, tire temperature, tire inflation pressure, tire geometry, road roughness, road material, presence or absence of liquids on the road. In order to save fuel on passenger cars, low resistance tires have been developed.

2.2.4 Aerodynamic Resistance

The vehicle travelling at a speed will experience the resistance force due to aerodynamic forces this is referred to as aerodynamic drag. It is mainly caused by the aerodynamic shape of the vehicle and skin friction. This resistance increases with increasing speed. Aerodynamic resistance is a function of speed, frontal area, the shape of the body and air density.

$$F_{aero} = \frac{1}{2} * \rho * S * Cd * V^2 \text{ (Haralad Naunheimer, 2011)}$$

ρ = Air density

S = Frontal Area(m^2)

C_d = Coefficient of drag

V = Velocity of the vehicle(m/s)

The frontal area of the vehicle pushes the air in front of it. However, air cannot move out of the way instantly. It is necessary to make the shape as aerodynamically fluid as possible to reduce to improve the flow around the body. In the same way, a boxy shape at the back of the vehicle creates the drag, a low-pressure zone which pulls the car back. This drag is called shape drag which completely determined by the shape of the vehicle. Since velocity is the function of the square, aero forces are very high during high speeds. coefficient of drag and frontal area of car can be optimized to increase aero efficiency.

The vehicle velocity data we have is measured by onboard measuring devices, there is a possibility of errors in the data. To eliminate that and to get more accurate results for the aerodynamic resistance we have changed the velocity component in the formula. we took the average velocity as velocity component using the velocity of the previous time step.

$$V^2_{avg} \quad = \quad V_{n-1}^2+V_n^2$$

Therefore, the equation can be rewritten with the average velocity component

$$F_{aero} \quad = \quad \frac{1}{2} * \rho * S * Cd * V^2_{avg}$$

2.3 TOTAL RESISTANCE

Total resistance forces at the wheel are the sum of all the individual forces acting on the vehicle. It is the Tractive effort of the vehicle. This is the effective force that is required to propel the vehicle.

$F_{tr} \quad = \quad F_{acceleration}+F_{Grad}+F_{Roll}+F_{aer}$ (Haralad Naunheimer, 2011)

F_{tr} = Tractive force of the vehicle (Nm)

2.4 POWER AT THE WHEELS

Power available at the wheels can be conveniently calculated using the available tractive force and instantaneous vehicle speed.

$P_{wheels} \quad = \quad F_{tr}*V$ (Haralad Naunheimer, 2011)

Pwheels= Power at the wheels (Nm/s)

2.5 TORQUE AT THE WHEELS

Torque is the rotational force acting on the wheel acting at the contact patch of the tire. Automotive tires are designed to have flex in them because of this the radius of the tire changes slightly in the dynamic conditions. Dynamic Wheel radius gives the distance travelled per revolution of the wheel, rolling without slip

$$T_{wheels}= F_{tr} * r_{dyn} \qquad \text{(Haralad Naunheimer, 2011)}$$

r_{dyn}=Dynamic wheel radius (m)

2.6 WHEEL RPM

The velocity of the vehicle is the longitudinal speed of the body. The rotational speed of the wheels is obtained from the tangential and rotational velocity equation

$$\text{Velocity}= \text{Radius} *\text{Rotational velocity } (\omega_{rad}) \qquad \text{(Hussain, 2003)}$$

$$V = r_{dyn} *\omega(\text{rad/s})$$

$$V = (r_{dyn} *\omega_{rpm}*60)/2\pi$$

$$\omega_{rpm} = \frac{V*2\pi}{\text{rdyn}*60}$$

ω_{rpm} gives the instantaneous wheel RPM which can be used to calculate the wheel energy

2.7 ENERGY ON WHEELS

A moving car possesses both translational and rotational energy. Each wheel has rotational energy, so the final energy includes translational energy of the car and rotational energy of all the four wheels.

$$\text{Energy} = \text{Kinetic Energy (Translational +Rotational)}$$

$$=\frac{1}{2}*M_{tot}*V^2+4(\frac{1}{2}*I*\omega^2_{rpm})$$

3 ICE VEHICLE SIMULINK MODEL

To compare results to the hybrid vehicle it is also necessary to develop the MATLAB/SIMULINK model of the original vehicle. The Simulink model developed for this model is based on the equation-based modelling approach based on the model from the MathWorks Racing Lounge (MathWorks Student Competitions Team, 2018). Equation based modelling approach necessary provides initial results which are important to know the direction of the development process, also speeds up the development process whilst cutting the costs down.

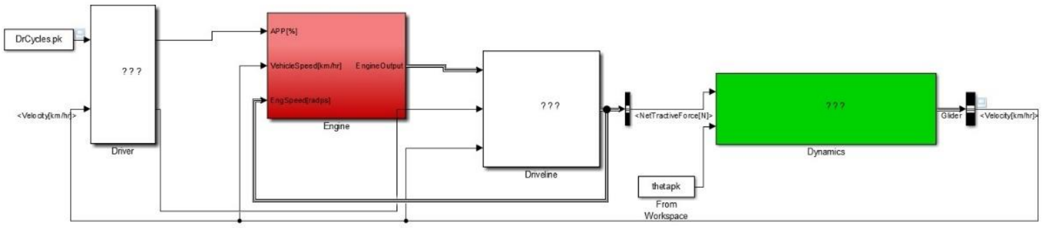


Figure 3-1 ICE vehicle overview

3.1 TRACK

The goal of this research is to test the capability of a hybrid vehicle in a specified route instead of using the standardized test cycles. Out of the available four routes for this research we have selected the route from Prague to Kostelec nad Labem, a central Bohemian town in the Czech Republic. The track is about 26km 2 which also includes highspeed zones and frequent stops. The cycle runs for 3151 seconds longer than the standardized test cycles. This data is collected in real-time using onboard equipment, though the vehicle speed might vary based on driver, traffic and weather conditions this would be the closest resemblance for the majority of drivers and cars.

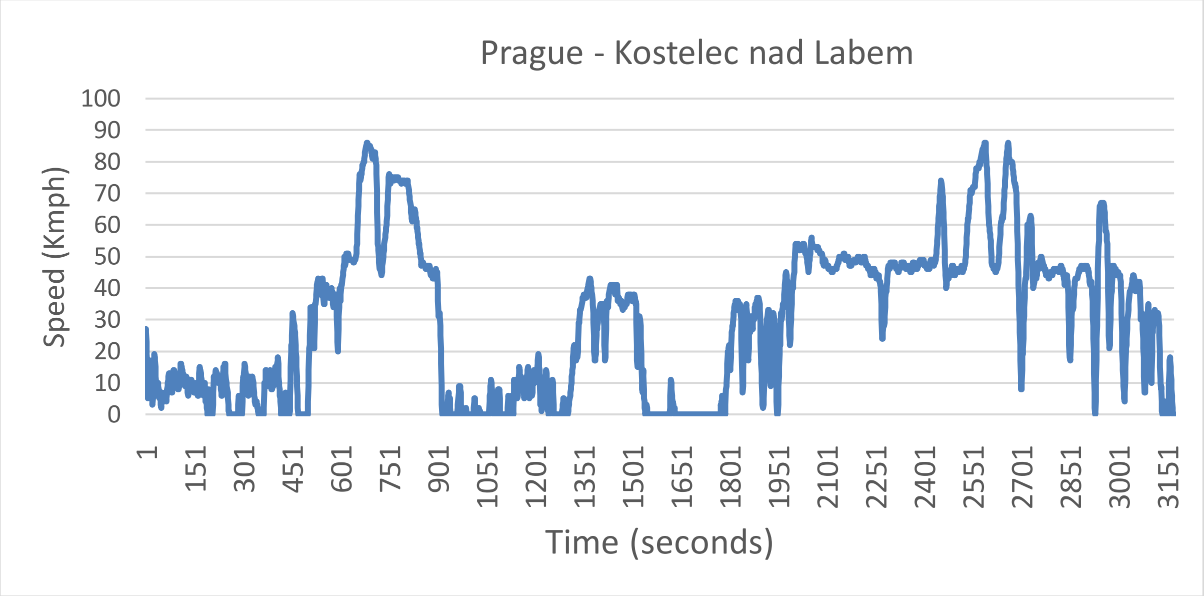


Figure 3-2Prague – Kostelec nad Labem Velocity Time profile

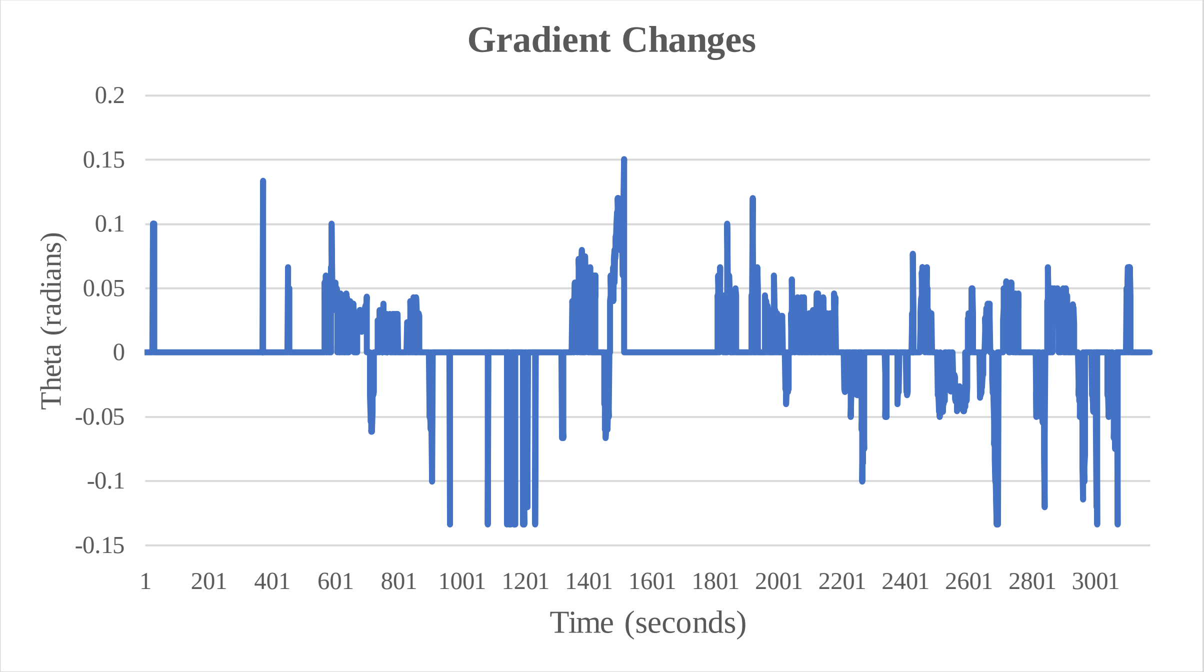


Figure 3-3 Gradient Time profile

The gradient changes along the track are illustrated in Figure 3-3 shows that there are significant changes in the altitude changes, which would impact the vehicle energy consumption. The energy recovery system in a hybrid car takes advantage of downhill to harvest energy to the battery which can be used to assist the vehicle during torque boost. this gradient data is given as input to the model in synchronization to drive cycle

3.2 DRIVER

The target of this SIMULINK model is to make a responsive model to which will be able to reproduce the vehicle behaviour based on the available vehicle information on the selected route. In order to do that we used a PID controller as an automated driver. based on the required speed, the driver module will be able to give the output signal to the accelerator pedal to speed up or signal to the brake pedal to slow down the vehicle. The signal ranges from 0 to 100 % which represents the range of pedal input. 100% indicates fully depressed pedal and 0% indicates that pedal is in untouched position. Figure 3-4 Automated Driver Controller shows the simple controller which functions as a driver based on cycle speed and current vehicle speed inputs.

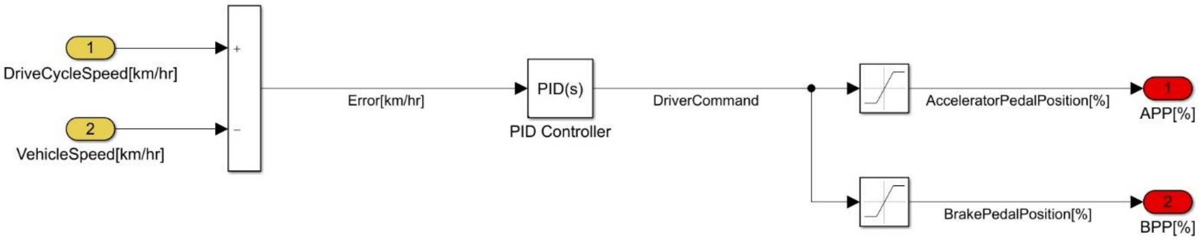


Figure 3-4 Automated Driver Controller

3.3 VEHICLE RESISTANCE

As shown in section 15` it is necessary to calculate resistance forces acting on the vehicle to determine the tractive effort that the vehicle needs at every step. In the Simulink environment, it can be used to calculate the current vehicle speed by manipulating the equations. The output from transmission block is the input for vehicle dynamics block as the tractive force.

Tractive force relation with aerodynamic resistance, rolling resistance and gradient resistance is used to determine the acceleration of the vehicle

$$F_{traction} - F_{aero} - F_{rolling\ resistance} - F_{gradient} = F_{acceleration}$$

Equation 3-1

$$F_{aero} = \frac{1}{2} * \rho * S * Cd * V^2$$

$$F_{Roll} = M_{total}\, g\, f_r$$

$$F_{Grad} = M_{total}\, g\, \text{Sin}\theta$$

$$F_{acceleration} = M_t\, a$$

Integrating the acceleration gives the velocity of the vehicle, which is the current speed of the vehicle. Integrating the velocity value will give the position of the vehicle. This can be used to find the distance travelled by car. The implementation of these equations can be seen in Figure 3-5 Vehicle Resistance.

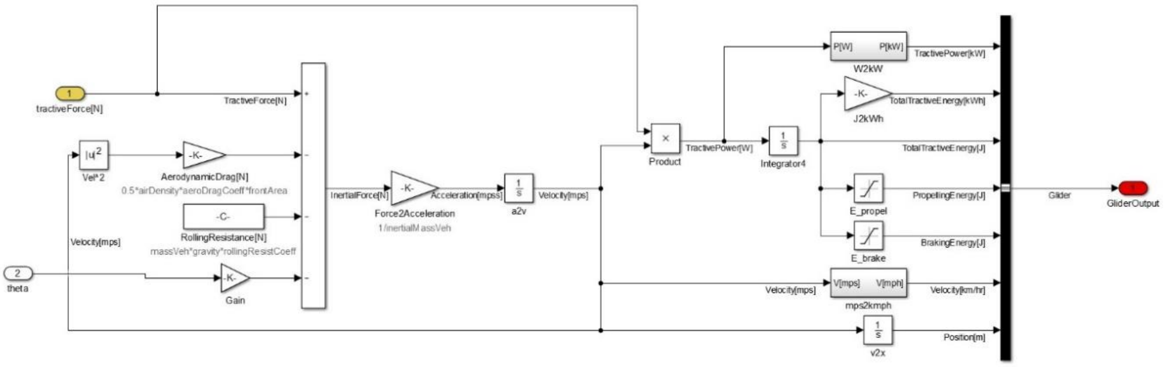


Figure 3-5 Vehicle Resistance

3.4 ENGINE

The engine model block is an equation-based model which calculates power output based on the accelerator pedal position (APP%). The engine speed and vehicle speed are also used to determine the relative power and torque output. The detailed overview of the model can be seen in Figure 3-6 Engine Model. It has subsystems to calculate fuel consumption of the car and power output. The maximum engine torque is relevant to engine speed, the subsystem engine torque limiter calculates the maximum engine torque that is available for that rpm. This is done in Simulink using 1D lookup table which has rpm on X-axis and Torque on Y-axis. By using the linear interpolation, we get the estimated maximum torque for the specific engine speed. *Figure 3-7 Maximum Engine Torque* shows the torque curve for specific to the engine used for this research.

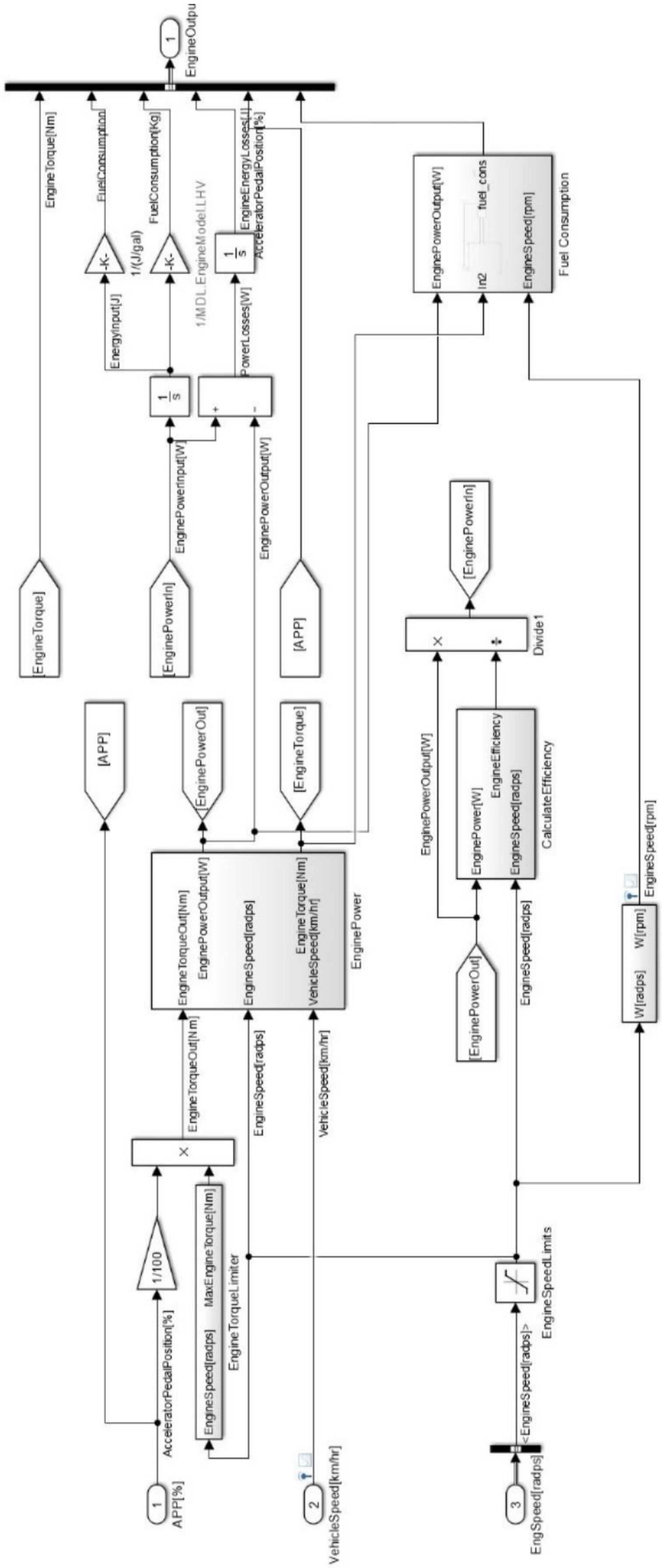


Figure 3-6 Engine Model

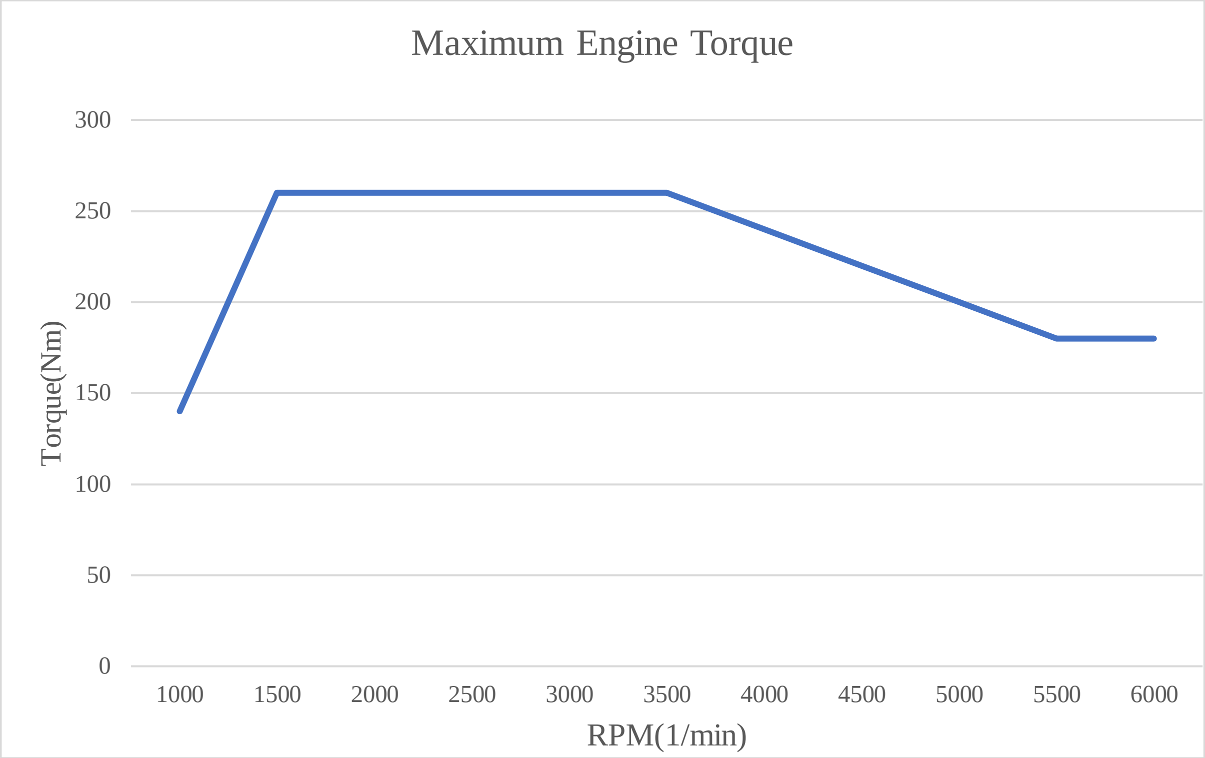


Figure 3-7 Maximum Engine Torque

The maximum available engine torque extracted from the torque limiter subsystem is then sent to engine power controller as an input signal.

Engine speed limits control the maximum possible rpm of the engine. It sets the redline of the engine and limits the maximum speed to set value. The minimum value is set to the idle speed of the engine.

3.5 ENGINE POWER CONTROLLER

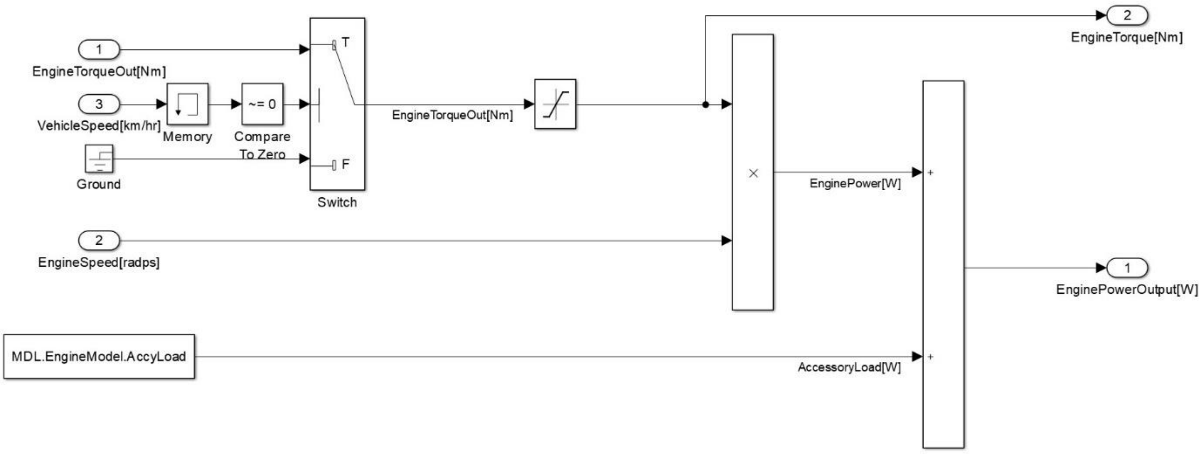
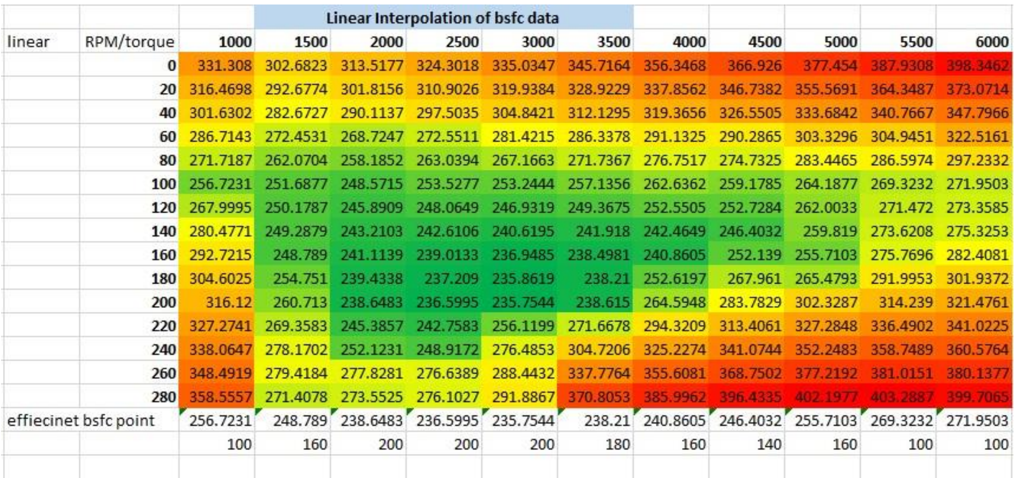


Figure 3-8 Engine Power Controller

The engine power block is the simplest way to current engine power of the vehicle. As we know that power is the product of engine torque and engine speed, it takes those two as inputs to generate instantaneous power. The accessory load is a parasitic load that draws power from the engine to power auxiliary systems. After including the additional loads on the engine, we will be able to get the actual engine power.

3.6 FUEL CONSUMPTION

This research has been done with a specific testing car, the engine used is a Skoda 1.4 TSI, Figure 3-9 BSFC (g/(kW.h)) table provides the fuel consumption of engine with respect to torque and engine speed. It can be seen from the colour coded BSFC map that the most efficient regions are represented in the green colour in the rpm region of 1500 to 3500 and a torque range of 100 to 200NM. This table is generated from the raw data using the linear interpolation method to find fuel consumption across the range of operating points. This map is used to determine the most efficient operating points of the engine across the working range. Optimal engine torque and engine rpm data are used in the engine controller to determine the load shifting operating points to switch between the engine and electric motor and to make them work together. This way it is possible to eliminate the undesirable working regions of the engine.



			Linear Interpolation of bsfc data									
linear	RPM/torque	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**
	0	331.308	302.6823	313.5177	324.3018	335.0347	345.7164	356.3468	366.926	377.454	387.9308	398.3462
	20	316.4698	292.6774	301.8156	310.9026	319.9384	328.9229	337.8562	346.7382	355.5691	364.3487	373.0714
	40	301.6302	282.6727	290.1137	297.5035	304.8421	312.1295	319.3656	326.5505	333.6842	340.7667	347.7966
	60	286.7143	272.4531	268.7247	272.5511	281.4215	286.3378	291.1325	290.2865	303.3296	304.9451	322.5161
	80	271.7187	262.0704	258.1852	263.0394	267.1663	271.7367	276.7517	274.7325	283.4465	286.5974	297.2332
	100	256.7231	251.6877	248.5715	253.5277	253.2444	257.1356	262.6362	259.1785	264.1877	269.3232	271.9503
	120	267.9995	250.1787	245.8909	248.0649	246.9319	249.3675	252.5505	252.7284	262.0033	271.472	273.3585
	140	280.4771	249.2879	243.2103	242.6106	240.6195	241.918	242.4649	246.4032	259.819	273.6208	275.3253
	160	292.7215	248.789	241.1139	239.0133	236.9485	238.4981	240.8605	252.139	255.7103	275.7696	282.4081
	180	304.6025	254.751	239.4338	237.209	235.8619	238.21	252.6197	267.961	265.4793	291.9953	301.9372
	200	316.12	260.713	238.6483	236.5995	235.7544	238.615	264.5948	283.7829	302.3287	314.239	321.4761
	220	327.2741	269.3583	245.3857	242.7583	256.1199	271.6678	294.3209	313.4061	327.2848	336.4902	341.0225
	240	338.0647	278.1702	252.1231	248.9172	276.4853	304.7206	325.2274	341.0744	352.2483	358.7489	360.5764
	260	348.4919	279.4184	277.8281	276.6389	288.4432	337.7764	355.6081	368.7502	377.2192	381.0151	380.1377
	280	358.5557	271.4078	273.5525	276.1027	291.8867	370.8053	385.9962	396.4335	402.1977	403.2887	399.7065
effiecinet bsfc point		256.7231	248.789	238.6483	236.5995	235.7544	238.21	240.8605	246.4032	255.7103	269.3232	271.9503
		100	160	200	200	200	180	160	140	160	100	100

Figure 3-9 BSFC (g/(kW.h)) table

The above-mentioned table is used in SIMULINK as a lookup table to find out the instantaneous fuel consumption.it uses engine torque and speed as input signals to find the exact fuel consumption value. This value is multiplied to the instantaneous engine power and integrated over the cycle to find out the total amount of fuel that is consumed. This subsystem has been used in both Hybrid model and the conventional model to determine and compare fuel consumption. The goal of this research is to find the efficiency of the mild-hybrid over the conventional car with an IC engine. This subsystem is an instrumental way to directly compare the two vehicles.

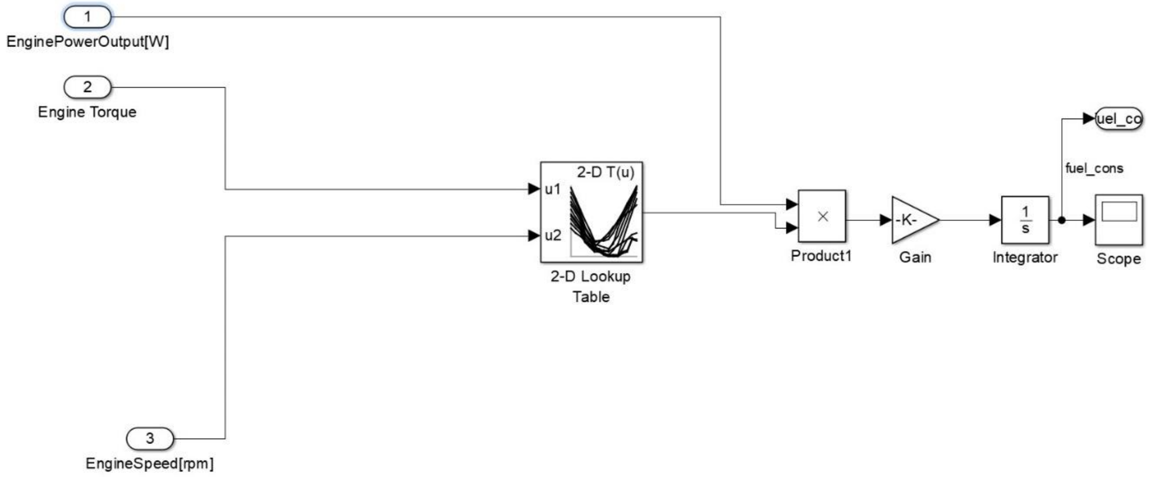


Figure 3-10 Fuel Consumption Estimation

3.7 TRANSMISSION

The driveline of this model serves the purpose of torque multiplication of gearbox and differential. This has been executed in a basic way to find the torque output to the wheels. The input signals for this system are vehicle speed, engine torque and accelerator pedal position percentage. The important part of the gearbox is to select the appropriate gear ratio based on the accelerator pedal position and speed of the vehicle. We have used Stateflow to select the gear ratio. The gear selector uses upshift and downshifts threshold rpm to keep the gear shifting the desired range. The selected gear ratio is then multiplied to a fixed final drive to get the output torque to the wheels. The vehicle speed and gear ratio along with the dynamic wheel radius are used to find the accurate engine speed.

$$\text{Engine Speed (rad/s)} = \frac{\text{Vehicle Speed} * \text{Gear Ratio} * \text{Final drive ratio}}{\text{Dynamic wheel radius}}$$

The torque output to wheels is used to calculate the net tractive force that is sent to wheels.

$$\text{Net Tractive Force(N)} = \text{Driveline Torque Output (Nm)} / \text{ Dynamic Wheel radius(m)}$$

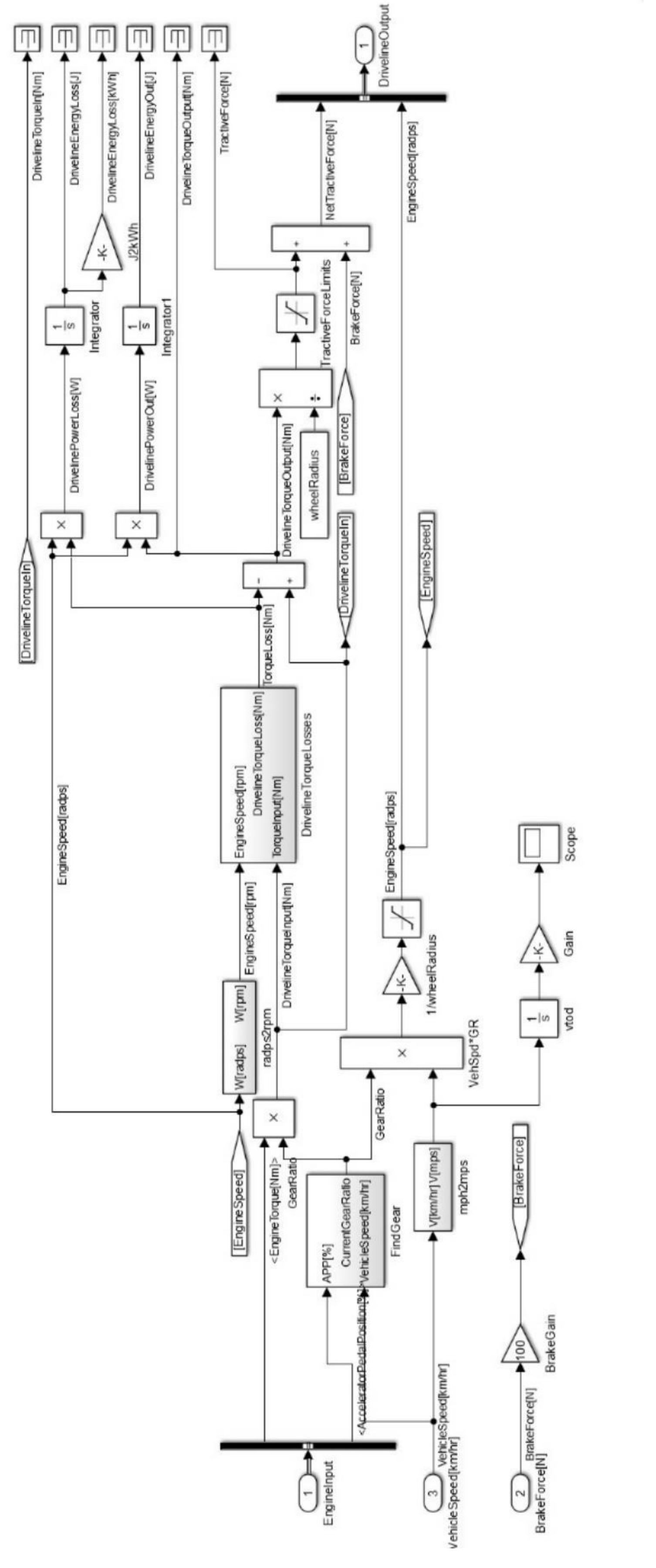


Figure 3-11 Transmission subsystem

4 HYBRID VEHICLE SIMULINK MODEL

The hybrid model is based on the existing model with the addition of an electric motor, battery and 2 simple clutch models. The important part of any hybrid vehicle is the controller, it controls all the available functionalities from the available combustion engine and electric motor. The complicated algorithms required to take advantage of all the hybrid modes is beyond the scope of this research. We have used Stateflow to implement the logic algorithms to make the ICE and EM to interact with each other collectively. (amir khajepour, 2014)

4.1 ELECTRIC MOTOR

The electric motor used in this mild hybrid is a 15kW permanent magnet synchronous motor (PMSM), this small capacity is the motor is suitable for the necessary functionality requirements. As this model is equation-based, it has been executed using the equations instead of using complex PMSM model. The input signals for the system are accelerator pedal position percentage and Motor Speed. The layout of this Mild hybrid architecture is a single shaft arrangement. It means that the motor and engine crankshaft is always rotating at the same speed when engaged. The engine speed is controlled by the driver with respect to accelerator pedal position and selected gear ratio. Therefore, the ICE dictates the motor speed. The input signal for the motor speed is synchronised with the engine speed in this subsystem. The motor speed control subsystem receives a signal from the control unit, it will switch on or switch off the motor based on the signal from the control unit. The motor torque limiter subsystem controls the torque output of the motor based on the engine speed. The braking system of the vehicle has its total regenerative force split between friction brakes and regeneration capacity of the motor.

In the motor torque limiter, the regeneration braking torque limit is set to -0.5 of max torque. So, the braking torque is split evenly between the generator and friction brakes evenly. This ratio can be changed to suit the requirements. It can be set to a more aggressive number to boost the regeneration potential. In extreme cases if the necessary braking torque is under maximum torque of the generator, entire braking can be done just by using the generator. In that case, driver doesn’t have to use the brake pedal, taking the foot off the accelerator pedal will trigger the braking. In the majority of situations, it is undesirable, therefore the braking torque ratio is split between the friction brakes and generator.

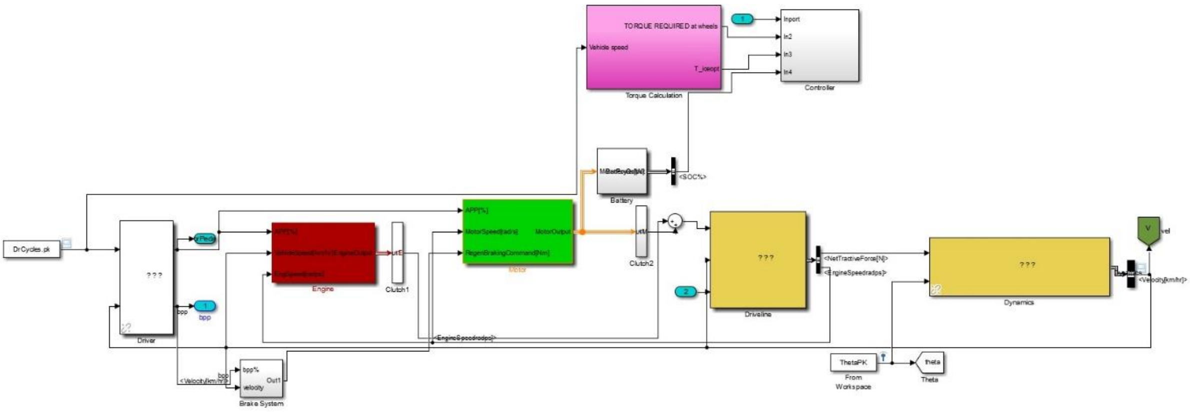


Figure 4-1 MHEV model overview

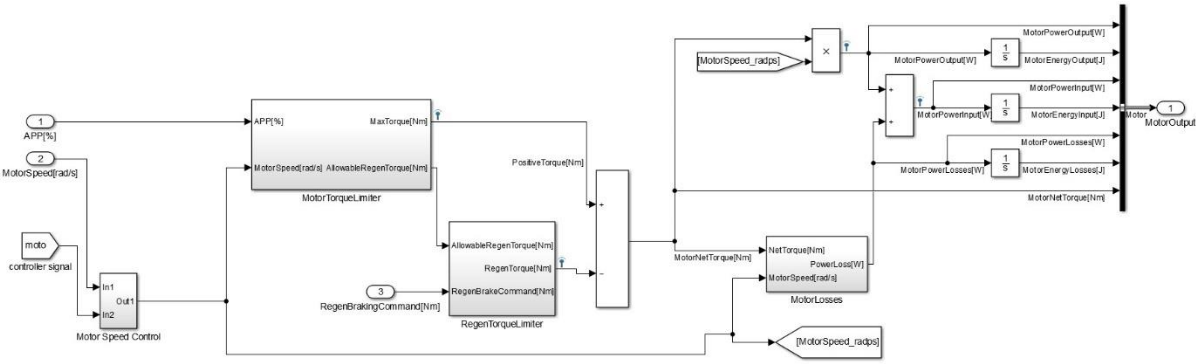


Figure 4-2 Electric motor subsystem

4.2 REGENERATION TORQUE LIMITER

Allowable regeneration torque command is the input signal received from the motor torque limiter, that is the maximum possible regeneration potential. The second input signal is the regeneration braking command which is received from the brakes subsystem. a is a dynamic signal which is dependent on the brake pedal position. As long as the received command from the brakes is in between the maximum possible regeneration potential and zero the absolute value is passed on as the regeneration torque. If it exceeds the maximum value, allowable regeneration torque is given as output to regeneration torque. This can be observed in the below-mentioned *Figure 4-3 Regeneration Torque limiter subsystem*.

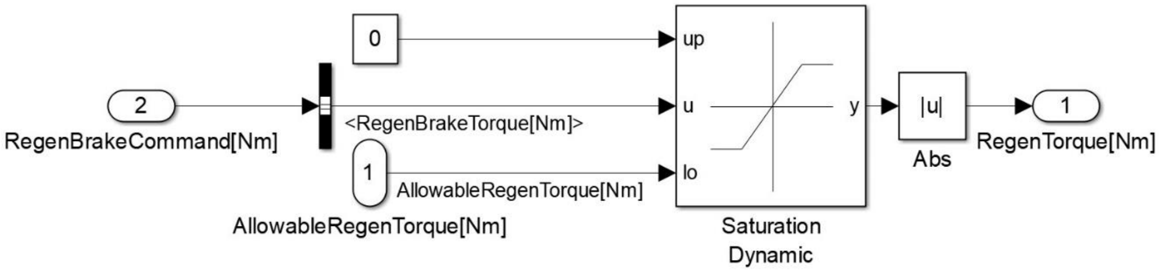


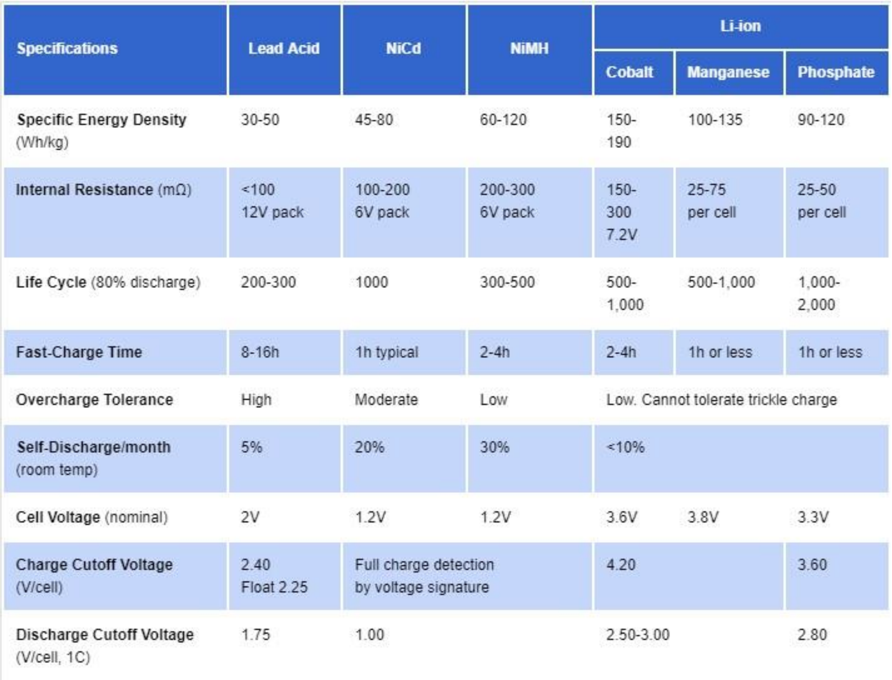
Figure 4-3 Regeneration Torque limiter subsystem

Final subsystem calculates the motor losses to estimates the net torque output that is being used by the system. This data is used to calculate the energy that is being used by the motor, the signal is passed to the driveline through the clutch C2 and to the battery to calculate the power that is drawn from the battery.

4.3 BATTERY

The battery plays a critical role in the mild hybrid electric vehicle development process. The functional ability of the vehicle depends on the capacity of the battery. As there is no external way to charge the battery for mild hybrid vehicles it is necessary to find the optimal capacity required for the vehicle. More than the required capacity would increase the weight of the battery, which would affect fuel efficiency significantly. A smaller capacity battery will save whilst compromising on the functionality. (E.Fuhs, 2009)

There are several types of batteries that available for the mild hybrid car, the energy density and cost of the battery are important for the selection



Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific Energy Density (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal Resistance (mΩ)	<100 12V pack	100-200 6V pack	200-300 6V pack	150-300 7.2V	25-75 per cell	25-50 per cell
Life Cycle (80% discharge)	200-300	1000	300-500	500-1,000	500-1,000	1,000-2,000
Fast-Charge Time	8-16h	1h typical	2-4h	2-4h	1h or less	1h or less
Overcharge Tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-Discharge/month (room temp)	5%	20%	30%	<10%		
Cell Voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge Cutoff Voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20		3.60
Discharge Cutoff Voltage (V/cell, 1C)	1.75	1.00		2.50-3.00		2.80

Table 1 Different Types of Batteries (Anon., 2019)

Li-ion batteries offer the best energy density 150-190 Wh/kg and cycle life of up to 1000 for 80% discharge from **Error! Reference source not found.** (Anon., 2019). With efficient thermal management, the operational temperature range can be increased to make the vehicle suitable to be used in regions with sub-zero temperatures. Based on these factors Li-ion batteries are used for this research. Battery technology is rapidly developing where advanced research is conducted to improve its performance characteristics. The main disadvantages of the Li-ion battery are cost, durability and safety. Li-ion batteries are less durable than Ni-Cd or NiMH. (E.Fuhs, 2009)

Use of nanostructures in batteries greatly increases surface area and effective electrode area, Internal resistance is lower, battery current, I(A), can be increased.

I = JA (E.Fuhs, 2009)

Where

J is the current density (A/m2)

A is the area (m^2)

Current density is almost fixed by cell voltage, electrolyte conductivity, electrode spacing. Hence, more surface area increases cell current.

P = IV = Power(W)

Where

V is the cell voltage(V)

This analytical model is designed to monitor the state of charge of the battery. It uses battery current and open-circuit voltage of the battery to determine internal that is being drawn from the battery. The initial battery state of charge value is set and every time the motor draws energy from the battery the state of charge will drop. In the same way, every time the generator operates the state of charge of the battery will increase recovering the energy from the generator.

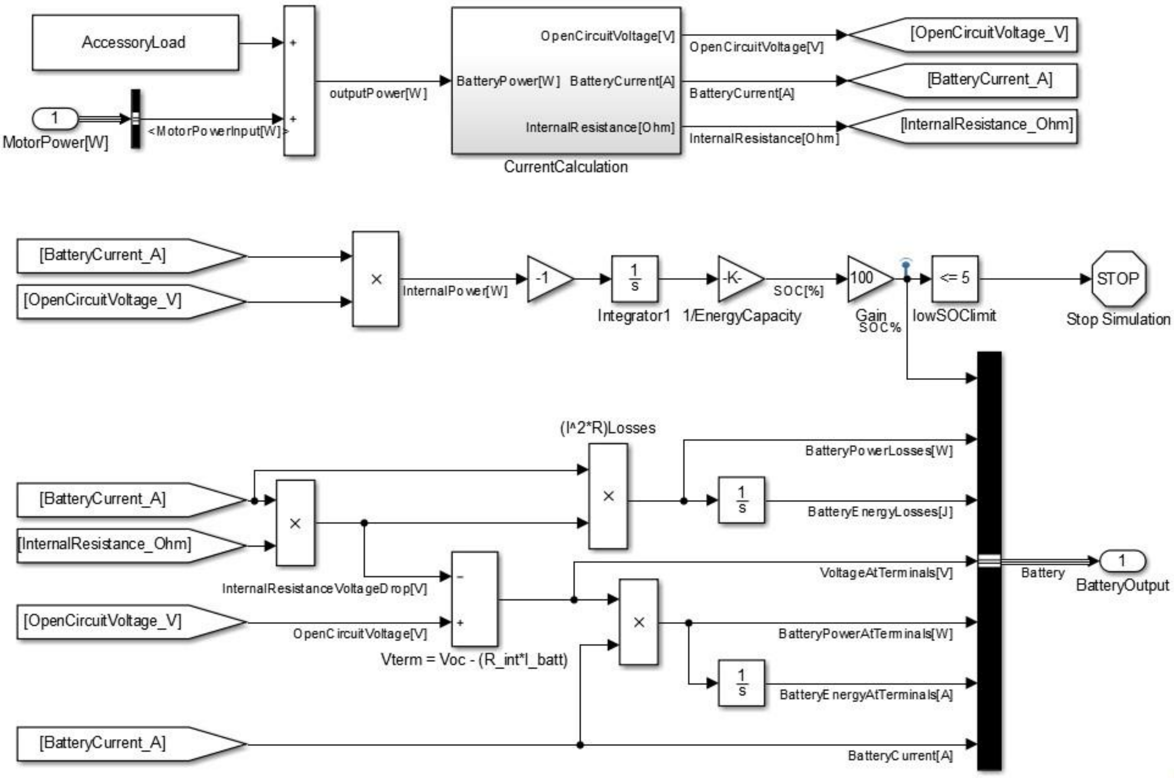


Figure 4-4 Battery Model

4.4 CURRENT CALCULATION

This subsystem is dedicated to calculating the battery current.it uses the open-circuit voltage and battery current values. Both the resistance and open-circuit voltage are constant, the battery power is the dynamic input signal used in the equation to generate instantaneous battery current. This generated signal is sent to main battery mode to calculate SOC during the cycle.

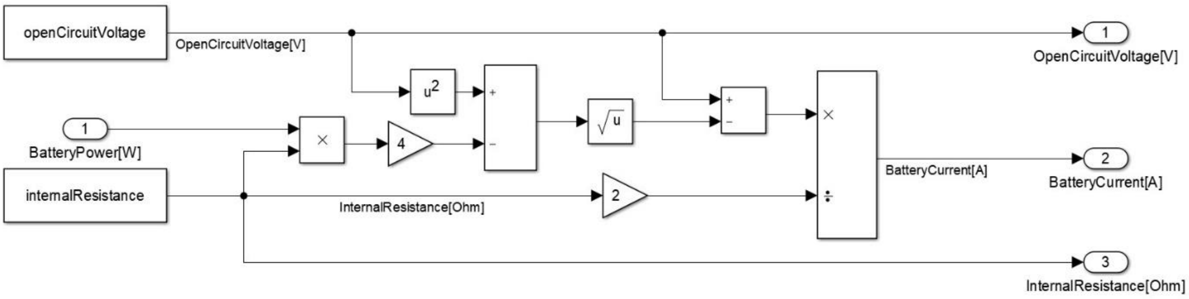


Figure 4-5 Battery Current Calculation

4.5 CLUTCH

The parallel architecture single shaft mild-hybrid contains two clutch units to provide all the necessary functionalities. The first clutch is placed between the crankshaft and electric motor when disengaged ICE will be isolated from the powertrain. This is used during the full electric mode and kinetic energy recovery phase. The second clutch is placed in between the electric motor/generator and the input shaft of the gearbox. This clutch is disengaged during standstill charging mode of the battery or during the stand-alone operation of the air conditioning system.

The clutch model has been designed to transmit the torque in the closed operating position, upon receiving the signal from the controller clutch will switch to open mode and transmit zero torque as the output signal.

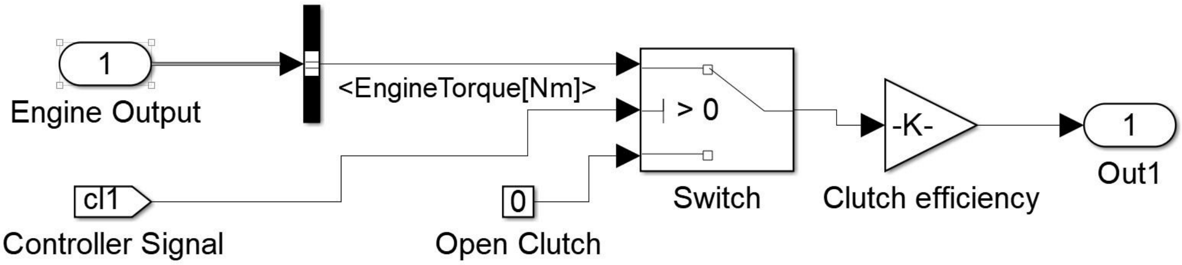


Figure 4-6 Clutch Model

4.6 CONTROLLER

The hybrid controller is the key component of the mild-hybrid vehicle which manages combustion engine, electric motor and the two clutches based on the torque requirements. Figure 4-7 Hybrid Controller shows the control module designed in Stateflow to switch between different driving modes based on the torque requirements.

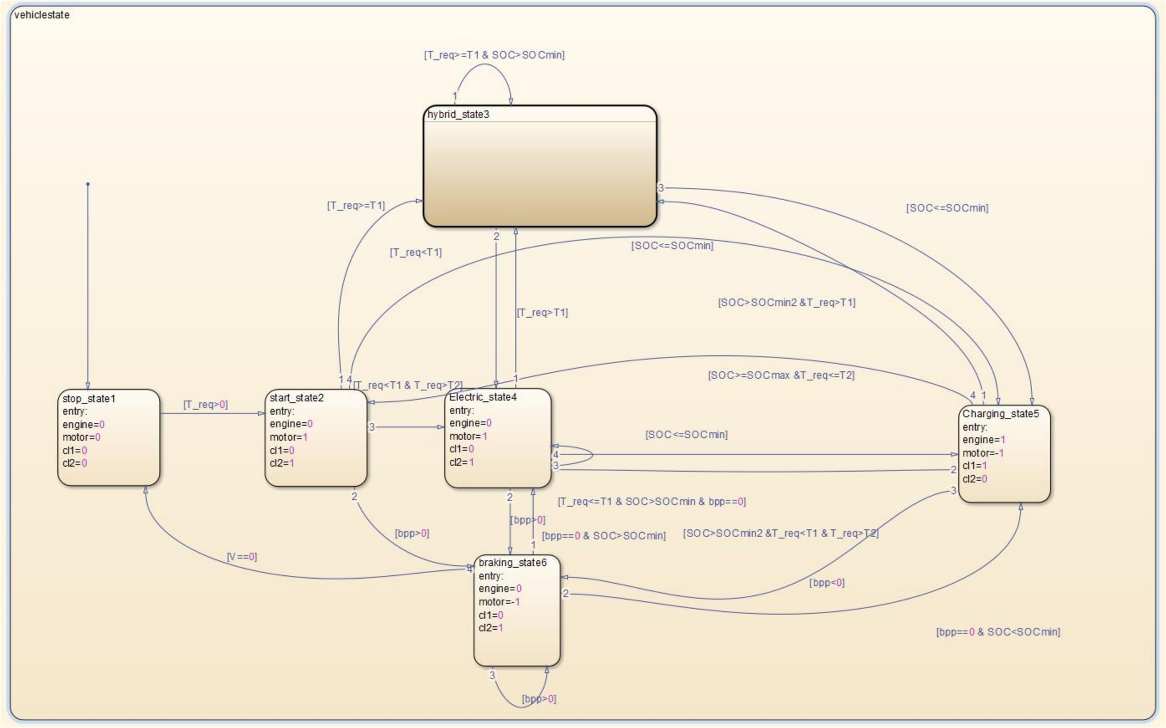


Figure 4-7 Hybrid Controller

The chart starts in the engine stop state where all the systems are off where the control signal to all the components is zero. (miletic, 2018)

- When the driver uses the accelerator pedal the torque required is greater than zero which makes the controller switch to start state where the electric motor is engaged initially to provide the output power. If the torque required is greater than the torque that the electric motor can provide the controller will switch to hybrid mode.

  T1 – Maximum continuous torque of the electric motor (Nm)
  T2 – Minimum torque required to move the vehicle (Nm)
- Electric state: The vehicle continues in electric mode if the SOC is above the SOC minimum and torque requirement is under the maximum continuous torque of the electric motor.

- Braking state: Whenever the vehicle enters braking situation the engine is disengaged, and the motor is set to generator phase. The clutch 1 which connects the ICE and electric motor are opened. Because of this, the negative inertial load on the generator decreases, boosting the energy regeneration potential.

- Charging state: If the state of charge level falls below the minimum, the vehicle operates in charging mode which makes the ICE to produce additional torque to supply to EM for recharging the battery.

- Hybrid state: The hybrid state works to keep the engine operating in its most efficient region. When the vehicle is running in hybrid mode the controller will check the torque required against the Optimal torque required for fuel efficiency. (E.Fuhs, 2009)

  If the optimal torque is greater than the requested torque and SOC < SOCmax (maximum state of charge) the engine will operate at the higher load condition, transferring the additional torque to the generator and charging the battery.

  If the optimal torque is lower than the requested torque, SOC > SOCmin (minimum state of charge) and torque difference is less than maximum EM torque, the engine will operate in the optimal region and deficit torque will be supplied by the EM utilising the battery charge.

In the hybrid mode, the vehicle operates in ICE centric efficiency mode, making the engine operate in its most efficient region throughout the rpm range. It is also possible to consider the efficiency of the electric motor during the hybrid mode which is beyond the scope of this project.

Figure 4.7 shows the optimal torque data derived from the BSFC map of the engine. the controller uses this information from the lookup table to either supply additional torque with EM or charges the battery using excess torque. (E.Fuhs, 2009)

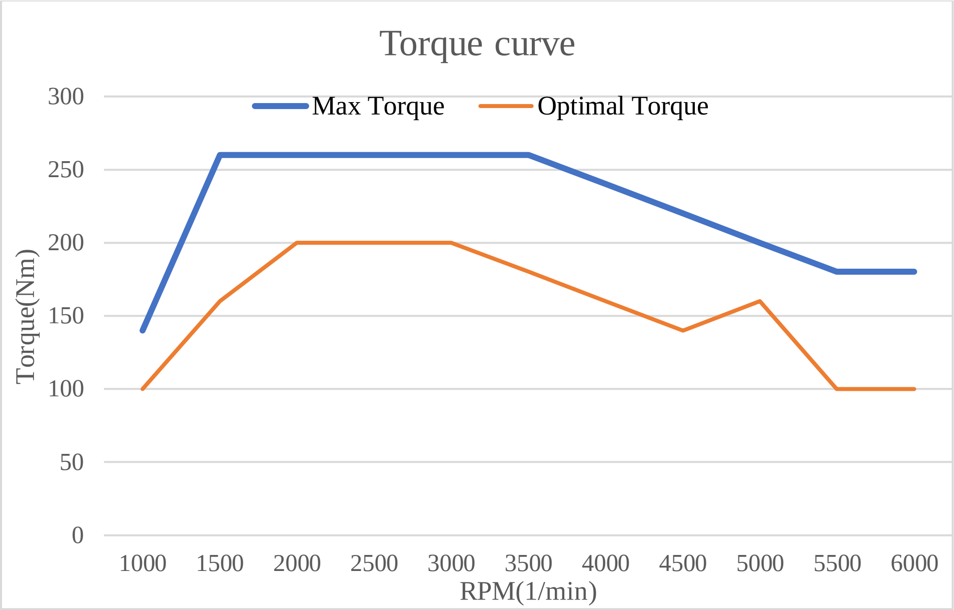


Figure 4-8 Optimal Engine Torque vs Max Engine Torque

5 SIMULATION RESULTS

5.1 ICE VEHICLE

The first set of simulations were run on the combustion engine vehicle configuration to reproduce the on-road vehicle speed and fuel consumption results as identically as possible. The first model has the vehicle velocity vs time and gradient vs time as inputs.

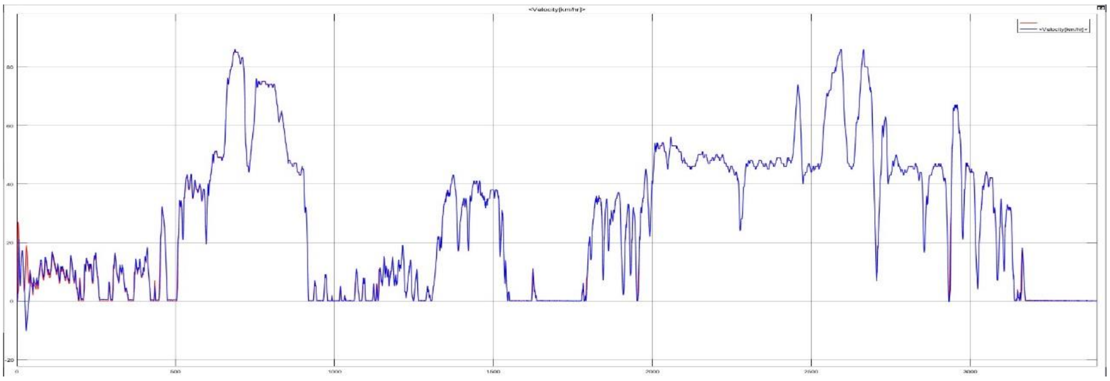


Figure 5-1 Combustion Engine vehicle speed vs time profile

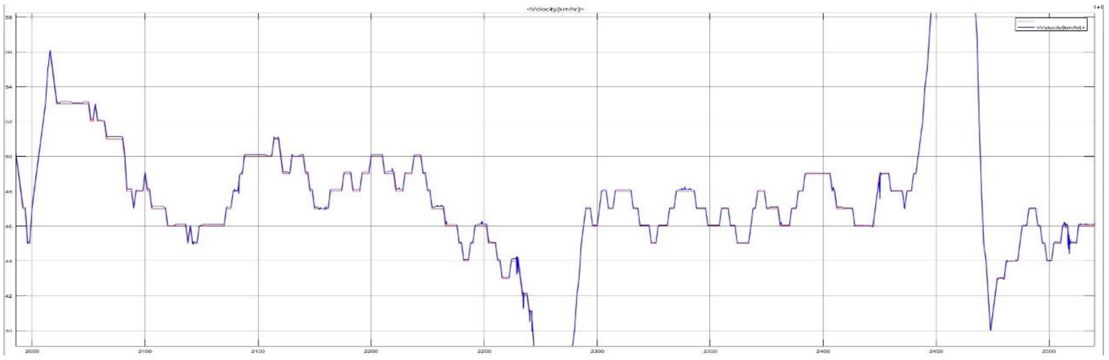


Figure 5-2 Magnified section of the vehicle speed profile

It can be seen that the ICE vehicle model is able to reproduce the velocity of the vehicle closely matched to the actual data collected during the test. Figure 5-2 shows the magnified section of the profile where the vehicle speed closely matched with the target speed with a slight margin. The Automated driver controller (PID controller) gives the required signal either APP or BPP to control the speed of the vehicle. PID controller has to be tuned to get the desired response time and precision. The simulations have been conducted with the following gain values.

Kp= 28, Kd = 0, Ki = 1

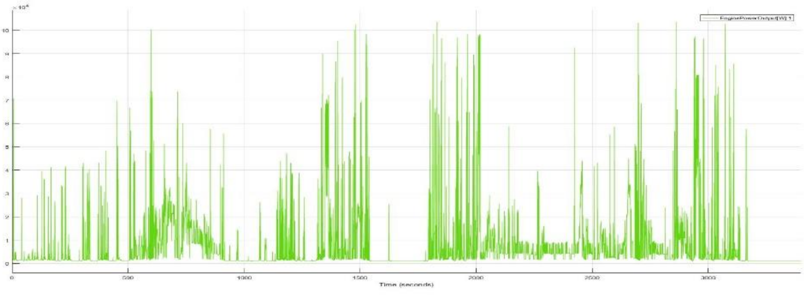


Figure 5-3 Engine Power

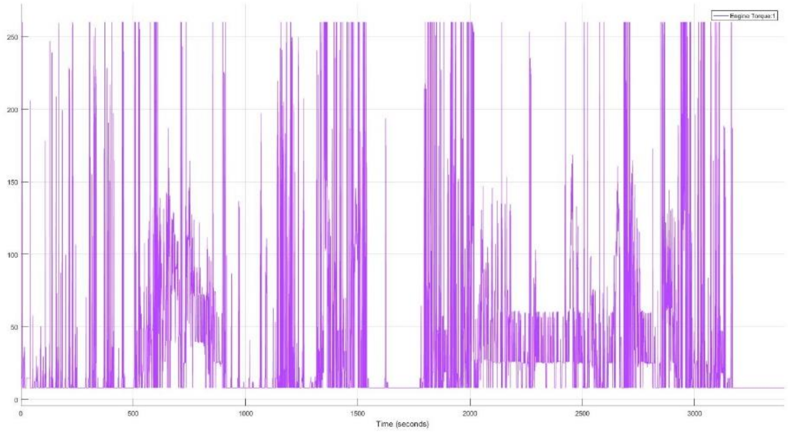


Figure 5-4 Engine Torque

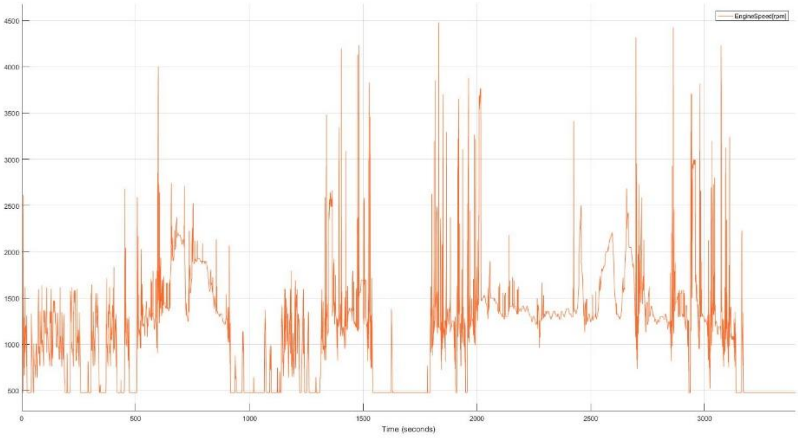


Figure 5-5 Engine RPM

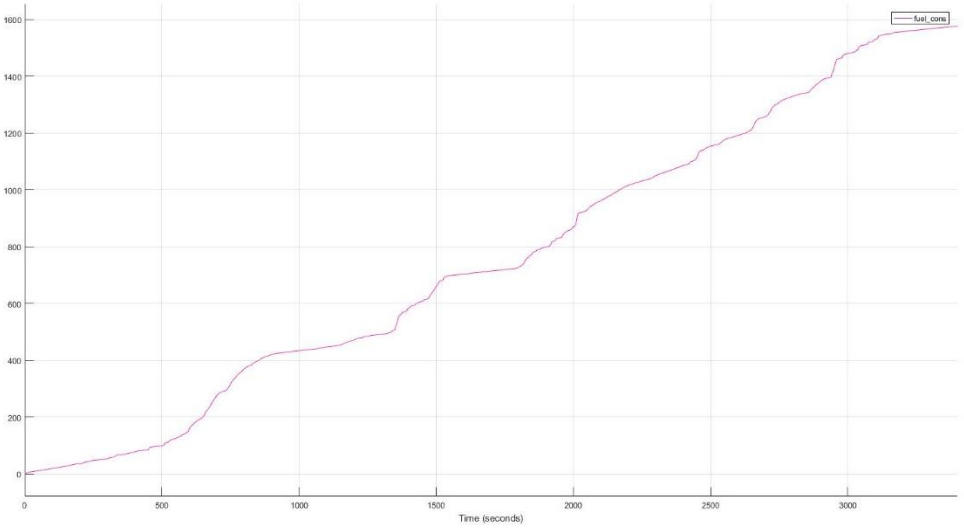


Figure 5-6 Fuel Consumption of ICE Vehicle

The vehicle fuel consumption is calculated using the Engine torque (Figure 5-4) and Engine RPM (Figure 5-5) values to interpret the BSFC map of the engine. The instantaneous consumption values are integrated for the entire course to calculate total fuel consumption. The simulation yielded the total fuel consumption value of 1577g for the Prague -Kostelec course. This value is used to compare the final results from MHEV simulations.

5.2 MILD HYBRID VEHICLE SIMULATION RESULTS

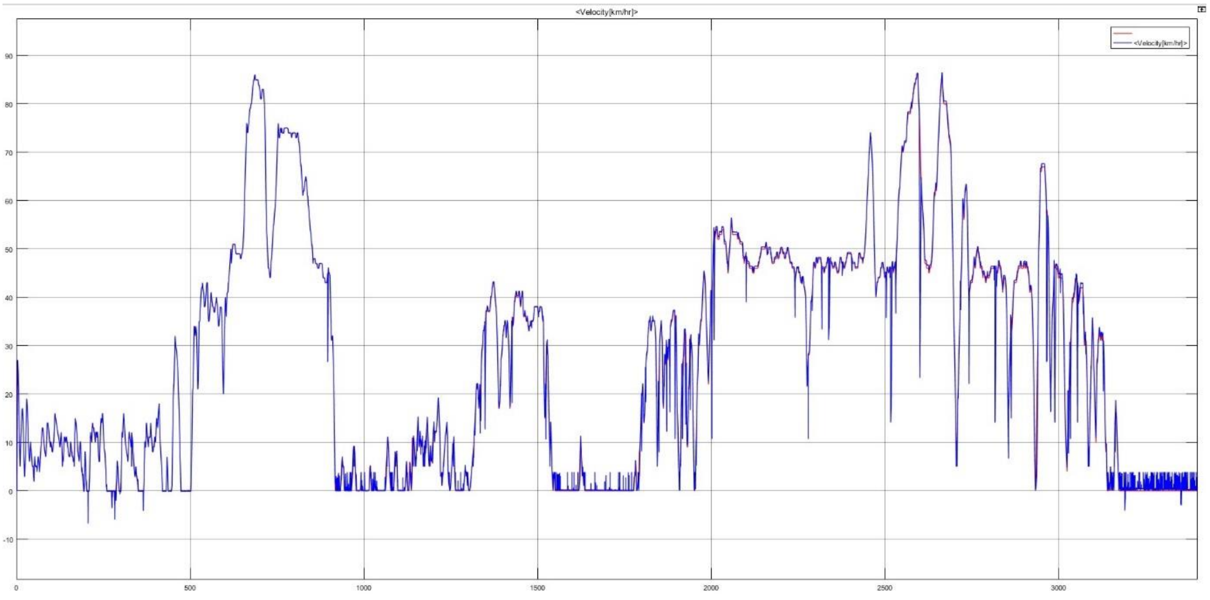


Figure 5-7 MHEV speed vs time profile

Figure 5-7 displays the velocity profile of the vehicle with the mild-hybrid powertrain. The speed of the vehicle closely matched the target speed during acceleration and deceleration but it can be seen that there are a considerable amount of low amplitude steady-state oscillations. The steady state oscillations can be solved by tuning the Driver controller, but we chose to keep the gain values exactly similar to the driver controller values of the ICE vehicle as it will give rise to the straight forward comparison of fuel consumption between the two vehicles.

The resultant fuel consumption value of the mild-hybrid vehicle is 1391.9 g which shows 11.73 % of fuel savings compared to its predecessor. This savings in fuel consumption are insignificant if the SOC is far from the initial state of charge. Figure 5-9 shows that the initial and final values of state of charge of battery are at a similar level. The drop in the charge is during its torque boosting and electric driving phase and once the charge goes to set minimum level it would prioritise the charging of the battery so that for the next run the battery won't have to start at its minimum level. The initial simulations were done with a maximum battery capacity of 4kWh, repeated simulations were done with decreasing battery capacity to find the optimal and minimal possible battery capacity based on energy consumption.

Figure 5-9 shows the SOC of the battery after the entire cycle, the 1.5 kWh battery has been used for that particular simulation run. this battery was able to withstand electric driving and torque assistance and still retained a similar level of SOC by the end of the track.

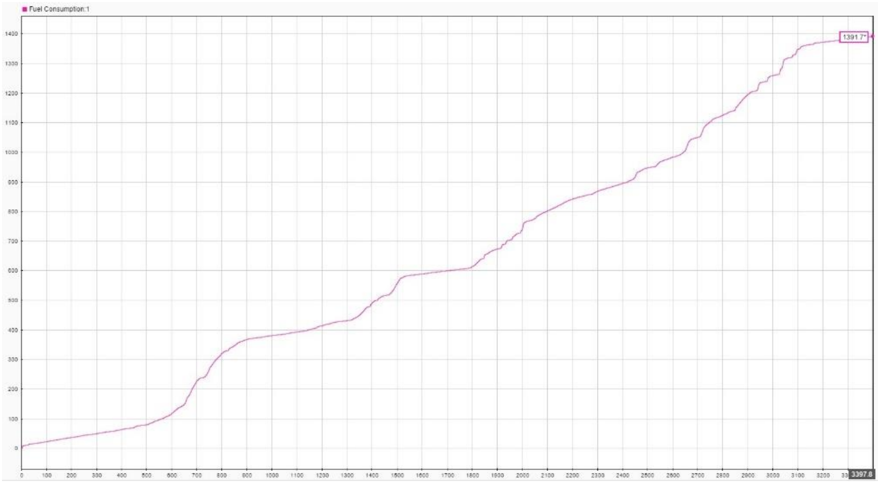


Figure 5-8 MHEV Fuel Consumption

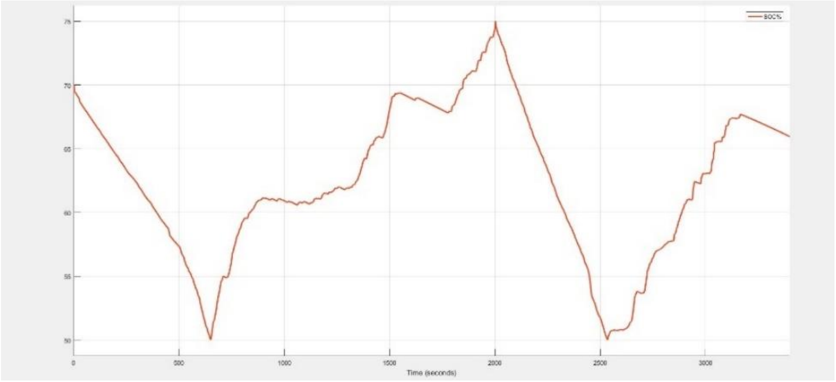


Figure 5-9 MHEV *SOC*

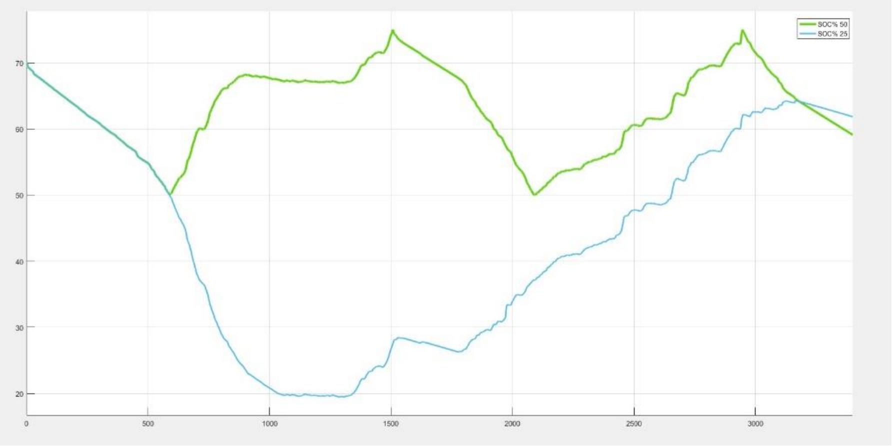


Figure 5-10 SOC with SOCminimum 50% and SOC minimum 20%

6 CONCLUSION

This project describes the development of mild-hybrid powertrain to optimise fuel consumption by adding additional elements to a conventional vehicle.

The data collected through the test vehicle has been analysed to remove unrealistic data points. The gradient values have been calculated using the GPS altitude data and distance. The road gradient is an important factor for this project as it differentiates it from the standardised test cycle. With this available information, we were able to calculate more accurate energy levels at the wheels.

The Simulink model is based on the racing lounge of MathWorks (MathWorks Student Competitions Team, 2018). Two Simulink models have been used, the first one with conventional powertrain and the second one with the proposed mild-hybrid powertrain. The mild-hybrid model is developed to incorporate controller signals, electric motor/generator and battery. The electric motor characteristics were chosen to be close to the Borg-Warner P2 Off-axis hybrid module. (Warner, 2018). A controller using Stateflow has been developed to manage the (Adel, 2010) internal combustion engine, electric motor and battery along with two clutches placed between the crankshaft and electric motor and between electric motor and input shaft of the gearbox.

The models were using the speed profile and gradient (theta) as input signals. We used the BSFC map to calculate fuel consumption. Optimal torque for maximum efficiency for the rpm range has been derived using the BSFC map. This was critical in implementing the hybrid controller to shift the load point. The battery capacity has been determined based on the multiple simulations to retain a similar level of state of charge by the end of the cycle.

The results were satisfactory in terms of the functionality of the model and controller. A working model close to the proposed model has been achieved. The results obtained from the different runs of the simulations show that the mild-hybrid vehicles are clearly efficient in terms of fuel savings. The percentage of fuel savings varied slightly from each run with the modulation of electric motor characteristics, controller algorithm and Tuning of PID controller which was used as an automated driver It has to be noted that out of many available hybrid modes, we have used only engine centric load point shifting method to obtain the positive results.

7 AREAS OF FURTHER RESEARCH

The research can be further optimised in several ways. The controller algorithm used for this project focuses on load point shifting, other strategies can be added to improve the complexity of the controller and to get further advanced results. A strategy with the balance between the efficiency points of both electric motor and combustion engine can be developed to save more energy. The regenerative braking can be further optimised to capture more energy. A constant regenerative braking distribution factor has been used in this project to split the braking force between generator and friction brakes. Variable braking distribution factor can be used to capture more energy during braking.

The other areas that can be further improved are the battery and electric motor modelling. More complex 3phase PMSM models, power converters can be used to generate more accurate results for the optimisation of energy utilization and fuel consumption. These components also add various non-linear effects which were beyond the scope of this project.

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9 LIST OF FIGURES

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11 APPENDIX

A

Vehicle Parameters

Type of Car	Škoda Octavia Combi 1,4 TSI
Type of Engine	Turbocharged gasoline with direct injection
Engine Displacement (cm^3)	1395
Number of Cylinders	4
Fuel	Benzín BA 95
Engine Power (kW)	110
Gearbox	6-speed manual
Vehicle curb weight (kg)	1277
Vehicle Load	380
Coefficient of rolling resistance (f)	0.015
Dynamic radius, r_{Dyn} (m)	0.295
Tyre inertia	1.25
Drag coefficient C_d	0.304
Frontal Area (m2)	2.2
Gear ratio 1	3.78
Gear ratio 2	2.12
Gear ratio 3	1.36
Gear ratio 4	1.03
Gear ratio 5	0.86
Gear ratio 6	0.73
Final drive ratio	3.647
Air Density	1.2
Accessory Load (W)	600

B

Simulink workspace variables

The energy capacity of Battery (kWh)	1.5
Initial State of Charge	70%
Internal Resistance (ohm)	0.05
Open Circuit Voltage(V)	48
Electric motor Max torque (Nm)	90
Electric motor Max Power (kW)	20
SOC minimum	20%
SOC maximum	95 %
T1 (maximum continuous torque for electric driving) Nm	50
T2 (moving Torque) Nm	5