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Modelling and Simulating a Hybrid Electric Vehicle

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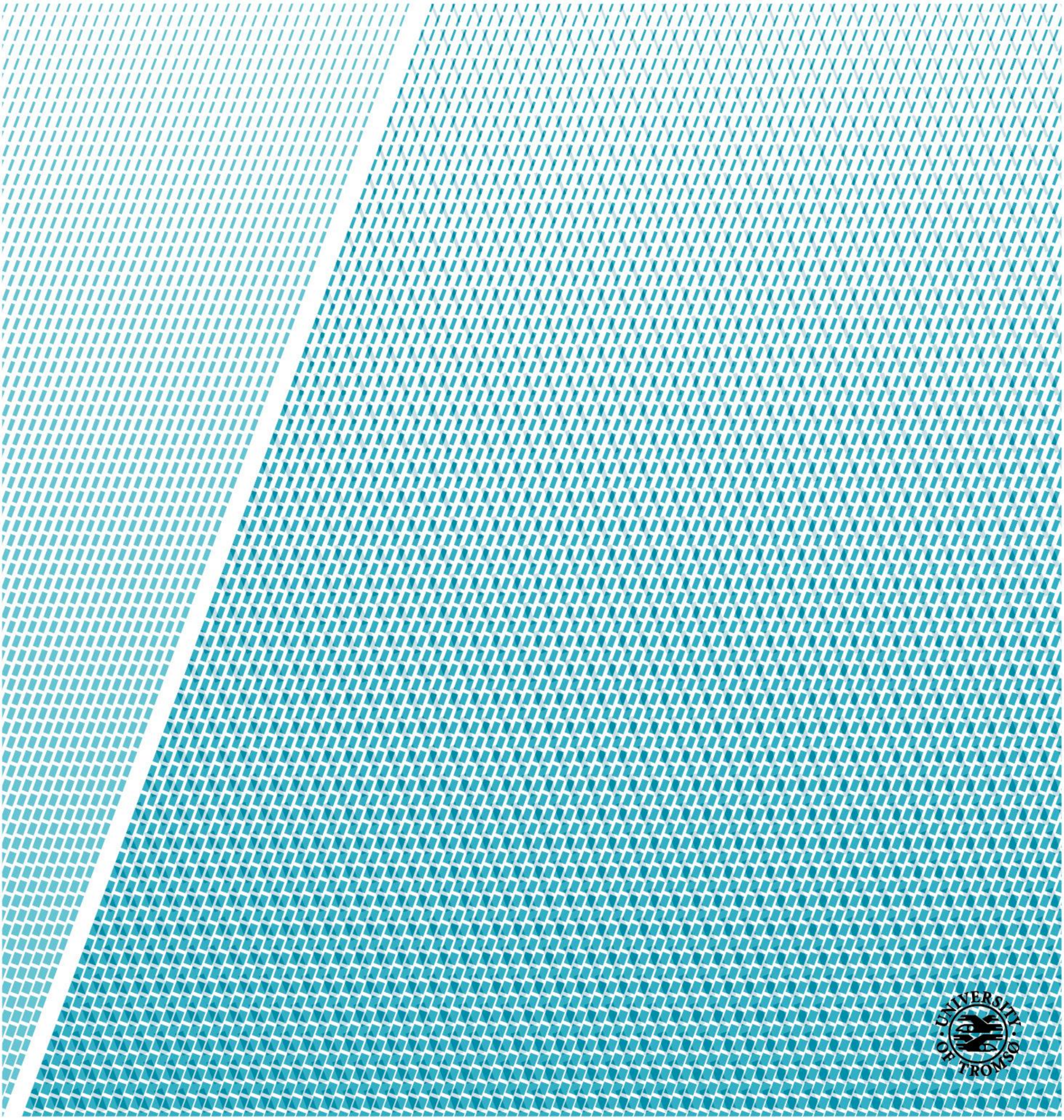

Abstract

This thesis presents an overview of the different types of hybrid electric vehicle structures and basic guidelines regarding choice of components. The simulation model of a hybrid electric vehicle was created for this thesis to investigate the impact on fuel efficiency in relation to rolling resistance coefficient and vehicle weight. Although the model is not designed for optimal engine operation, the results indicate that lower rolling resistance coefficient and lower vehicle weight leads to reduced fuel consumption. Proposed improvements to the simulation design are presented in the report.

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Abbreviations

AC	Alternating Current
BSFC	Brake Specific Fuel Consumption
DC	Direct Current
ECVT	Electric Continuous Variable Transmission
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HSD	Hybrid Synergy Drive
IGBT	Insulated-Gate Bipolar Transistor
ISG	Integrated Starter/Generator
KPH	Kilometer Per Hour
MG	Motor/Generator
MPH	Miles Per Hour
PHEV	Plug-in Hybrid Electric Vehicle
PMSM	Permanent Magnet Synchronous Machine
RPM	Revolutions Per Minute
SOC	State Of Charge

1 Introduction

1.1 History

The hybrid electric vehicle may seem like a new invention as Toyota popularized the concept with the Prius in 1997, although it was actually invented in 1900 by Ferdinand Porsche [1]. The Lohner-Porsche Semper Vivus was an upgraded version of the purely electric Lohner-Porsche featuring two 3.5 horsepower engines each connected to a generator to produce electric power. Due to poor battery technology at that time, the range of a purely electric vehicle was limited and the batteries were huge and heavy. The solution to this problem was to reduce the size of the battery and implement a gasoline-powered generator. However, the gasoline-electric hybrid concept was not a commercial success until Toyota introduced the Prius. Today Toyota Motor Corporation has a cumulated sale of over 7 million units of their various hybrid models [2].

1.2 Motivation

On the road to zero-emission vehicles for improved air quality in densely populated areas and slow down global warming, the hybrid electric vehicle is an intermediate stage in the transition away from the conventional fossil-fueled vehicle technology. Since the infrastructure is not yet facilitated for large amounts of full-electric vehicles, the hybrid electric vehicle can utilize the existing infrastructure of gas stations to refuel. As the petroleum resources are diminishing, there will be an inevitable shift in energy sources for the transportation sector eventually. To buy some time in order to prepare for the large-scale entry of full-electric vehicles, the use of petroleum is optimized through hybrid technology.

Hybrid electric vehicles combine the use of the internal combustion engine with an electric machine to optimize the operation of the engine. The design to a powertrain is to isolate the engine from the vehicle operating conditions, allowing the engine to operate more efficiently. Because of the increased efficiency, the engine can be downsized to further reduce fuel consumption and still provide sufficient power.

An important feature of the hybrid vehicle is the regenerative braking. Rather than wasting the kinetic energy of the vehicle as heat dissipation through the brakes, the electric machine captures the energy and stores it in the battery, resulting in increased mileage and less wear of the brakes [3].

1.3 Original project description

The purpose is to create a (Simulink) simulation model to simulate the performance of a hybrid electrical vehicle. Provide with some guidelines regarding choice of components and settings predicted to increase the fuel efficiency of hybrid car. Interesting information could be how the fuel efficiency is affected by; size of internal combustion engine, choice of gear ratio, vehicle weight, rolling resistance coefficient, having a separate starter motor or using the generator as starter motor.

2 Literature review

2.1 Levels of hybridization

Hybrid electric vehicles are categorized into different levels of hybridization: micro, mild, full, and plug-in. Most mild, full, and plug-in hybrids have the function of regenerative braking in addition to assist in vehicle propulsion, whereas the micro hybrid does not support these features. Micro hybrids only support a start/stop function where the engine shuts down when the vehicle stops and restarts when the brake pedal is released. Some micro hybrids utilize an integrated starter/generator (ISG) that has the combined function of a starter and an alternator. By having both functions combined into one unit, the overall vehicle weight is slightly reduced. Although the ISG does not contribute in propelling the vehicle, the fuel efficiency can increase up to 10% compared to a non-hybrid. The mild hybrid can achieve an increased fuel efficiency of 20-25% by the incorporation of an electric motor to assist in vehicle propulsion. The full and plug-in hybrid have even more powerful components, which can be used for purely electric operation. The differences between full and plug-in hybrids are the size and power capability of the engine and electrical system. Since the plug-in hybrid can connect to the power grid to recharge, the electrical system is bigger and more powerful, and it can utilize a smaller engine. The fuel efficiency of the plug-in hybrid is similar to that of the non-plug-in hybrid, around 40-45%, whereas the fuel economy is better as it can rely more on electrical power [4].

2.2 Powertrain structures

2.2.1 Series Hybrid

The series structure is similar to an electric vehicle with the addition of an engine to power a generator that provides electrical power to the battery and/or to the electric motor to extend the range of the vehicle. Since the engine is not mechanically coupled to the drive shaft, the engine speed and power can be adjusted to operate at optimal efficiency when running. However, since all of the engine output is converted to electric energy, the series hybrid suffers from conversion losses.

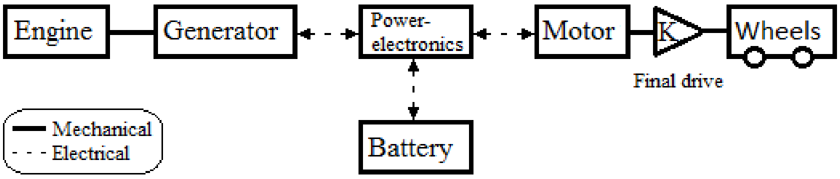

Figure 1 Schematic of a series hybrid structure

The control system of the power management in the hybrid series is simple, compared to the other hybrid vehicles types, since the motor power demand is independent of the engine output. There are no clutches in need for control either. The series hybrid powertrain is widely used for medium to heavy urban vehicles such as delivery trucks and buses, whereas for commercial vehicles, it is not that popular [5].

2.2.2 Parallel Hybrid

The parallel structure looks more like a conventional powertrain with the engine mechanically coupled to the driveshaft through a transmission. In addition to the conventional powertrain, there is an electric motor coupled to the crankshaft or driveshaft using a belt, chain, or a clutch system. All three alternatives support combined and engine-only operation, whereas the clutch system additionally enables the possibility of disengaging the engine from the drivetrain to provide the option for purely electric operation.

Compared to the other hybrid vehicles types, which have at least two electrical machines, the parallel normally only have one motor/generator unit (MG). The operation and contribution of the MG depends on its size. A relatively small MG can be used for starting the engine, some regenerative features, and limited contribution in propelling the vehicle. A larger MG can have greater involvement in regenerative operation, and may be used to propel the vehicle by itself.

The MG does not only contribute to extended range as a secondary power source. It can also help the engine in achieving higher fuel efficiency by shifting operating points of the engine. Since the engine speed is depended on the vehicle speed, the optimal operation point of the engine cannot be achieved in the same manner as the series hybrid. The improved efficiency comes from adjusting the load of the engine by engaging the MG. If the power demand of the engine is low, it acts as a generator to increase the load, and if the power demand is high, it acts as a motor to the decrease the load. This is proven to be effective in city driving when there are a lot of starts and stops as the motor assists in accelerating the vehicle from rest, which is a point of low fuel efficiency of a conventional powertrain. The operation of the power assistance must however be controlled with care in order to avoid depletion of the battery.

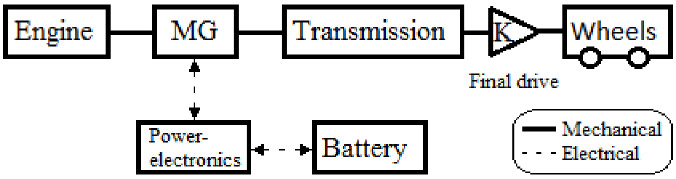

Figure 2 Schematic of a parallel hybrid structure with MG connected to crankshaft

An advantage of the parallel hybrid system is that the implementation to a conventional powertrain requires only minor modifications whereas the other structures are specially designed to a vehicle. The Renault Scénic is an example of this hybrid upgrade. A small 48V electric motor of 10kW is connected to the crankshaft of the existing powertrain, converting it into mild hybrid system [6].

2.2.3 Power-Split Hybrid

There are three main configurations of the power-split structure: input-split, output-split, and compound split, where the input-split is the most common [7]. A typical power-split hybrid uses two MGs, connected to the engine and the driveshaft through one or multiple planetary gears sets [8] [9]. The engine and MG1 connects to the carrier and sun gear (Figure 3), respectively, of the planetary gear. MG2 is connected to the driveshaft through a different planetary gear. The secondary planetary gear serves the purpose of acting as a speed reducer.

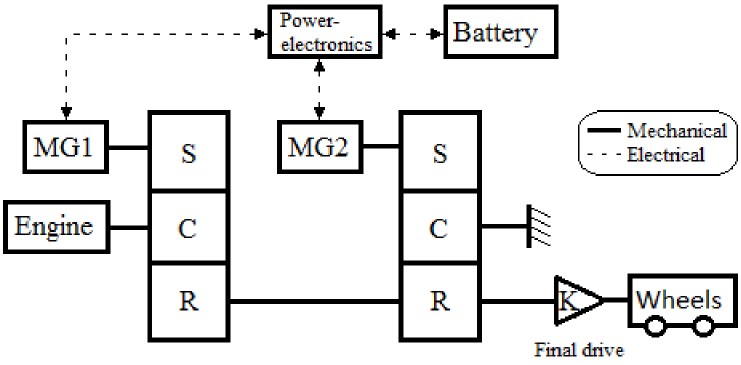

Figure 3 Schematic of Toyota Prius 2010 power-split structure

The power-split combine attributes of the series and parallel configuration. MG1 is used to control the engine speed while MG2 is used to provide the remainder of the power required to meet the driver demand. With the connection of the engine and MG1 to the planetary gear, the engine speed can be controlled independent of the vehicle speed. This function is known as Electric Continuous Variable Transmission (ECVT) and it allows the most efficient engine operation regardless of the vehicle speed. The ECVT eliminate the need for a fixed gear transmission, which reduce the number of moving parts. Due to fewer moving parts, this type of transmission is more reliable than a conventional transmission [10].

The power-split hybrids are efficient in city driving due to the ECVT function. However, since the two MGs and engine connects directly to the planetary gear, that is to say without any clutches or locking mechanisms in between, at least two of these components are turning when driving. Because of this, when operating in electric mode, MG1 needs to compensate for the speed of MG2 in order for the engine to remain stationary. The power-split also suffers from conversion losses due to the lack of locking mechanisms. When the engine runs, MG1 needs to operate as a generator, acting as a lock or brake on the planetary gear, in order to direct the power from the engine to the wheels. This results in a portion of the engine output circulating through MG1 and MG2 before reaching the final drive.

2.2.4 Multi-Mode Power Split Hybrid

The power-split structure discussed in the previous section is referred to as a single-mode power-split hybrid. A multi-mode power split hybrid is similar to the single-mode with the addition of clutches to lock gears or disengage the engine or MGs from the drivetrain. This enables the possibility for the vehicle to operate as a series, parallel, power-split, or as a conventional vehicle. With this freedom of choice to choose between different operating modes, it can achieve even better fuel efficiency than the other types. However, the control of the multi-mode is more complex compared to the other structures.

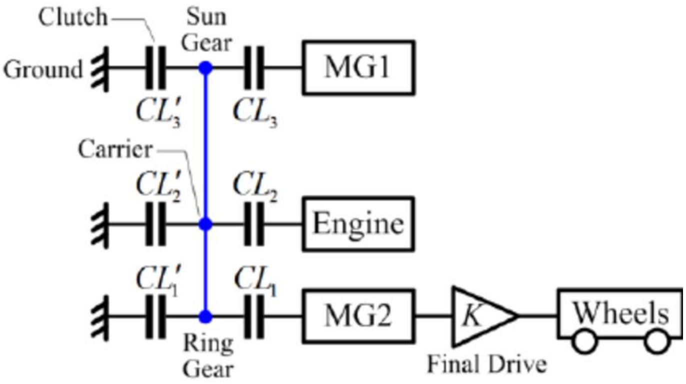

Figure 4 All possible clutch locations for an input-split configuration [11]

The number of operating modes depends on the number of clutches used and the placement of the clutches decide the functions of the operating modes. Figure 4 shows all possible clutch locations for an input-split configuration. The six clutches are grouped into three pairs. When a clutch in a pair is closed, the other clutch is open, and if the second closes, the first one needs to open. This gives the possibility of eight different modes. However, only four of the modes are useful. These four modes can be realized with the use of just three of the clutches. In Figure 5 a) the vehicle is propelled by MG2 alone and in b) MG1 is assisting MG2 in the purely electric operation. The state of the clutches in c) and d) shows series and power-split operation respectively.

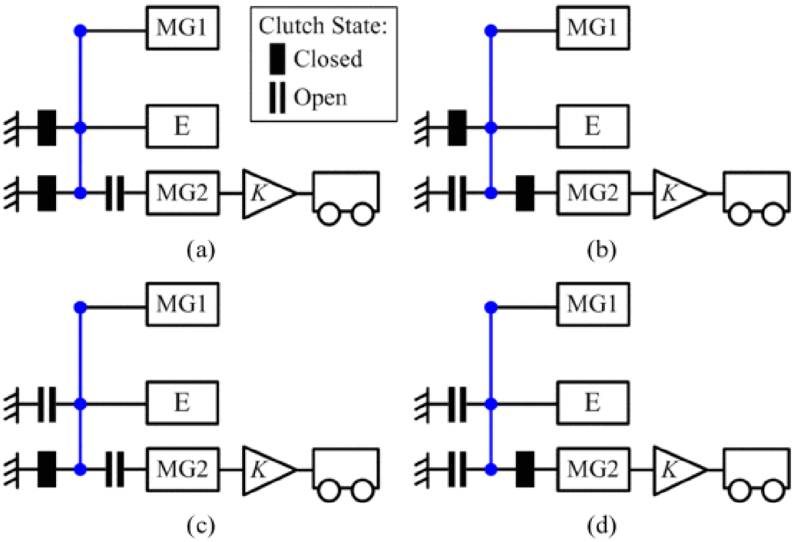

Figure 5 Useful operating modes for the input-split with three clutches [11]

There are endless numbers of different variations to the multi-mode design. As an example, by introducing a secondary planetary gear and limit the design to three clutches and one permanent connection, the number of possible designs is given by the equation:

$$N_{design} = C^3_{N_{clutch}} * C^1_{N_{clutch}} * P^4_6 = 2{,}620{,}800 \tag{1}$$

where $C^3_{N_{clutch}}$ is the number of possible clutches pairs, $C^1_{N_{clutch}-3}$ is the number of possible selected permanent connection, and P^4_6 is the number of possible locations to connect the engine, MG1, MG2, and the final drive [11]. Some multi-mode hybrids incorporate a fixed gear transmission in the design in addition to the ECVT function.

2.3 Powertrain components

This section presents the different components of a hybrid electric powertrain.

2.3.1 Engine

The majority of HEVs incorporate some type of internal-combustion engine in their design. The gasoline engine is the most common type used together with the electric machine in commercial HEV powertrains [12]. Compared to the other fossil-fueled engine, the diesel engine, the gasoline engine has higher power-to-weight ratio and a wider range of operation in terms of rotational speed. The gasoline engine is less efficient than the diesel engine, consuming more fuel and emitting more carbon dioxide (CO_2). Although the diesel is more efficient, it emits considerable higher amounts of nitrogen oxides (NO_X) and particulates, which are harmful to humans and animals [13] [14]. As the majority of vehicles in urban areas are passenger vehicles, vans, and light trucks, the use of diesel engine should be avoided in order to reduce emission of harmful pollution.

The fuel cell is a promising alternative to combustion engines as they produce energy from electrochemical potential to generate electric energy [15]. Rather than converting fuel to mechanical motion through a combustion process, the fuel cell combine its fuel, hydrogen, with the oxygen from the air through a membrane. Because the process involves the combination of hydrogen and oxygen without any combustion, the only products are electric energy and water. Internal combustion engines generally have low efficiency due to heat and friction losses, whereas the fuel cell has relatively high efficiency, does not rely on a combustion process, and consist of stationary components. As it is today, due to cost and the existing infrastructure, gasoline engines are cheaper and more convenient to utilize compared to fuel cells.

The selection of the engine in an HEV powertrain depends on the drivability requirements and the level of hybridization. Since micro and mild hybrids offers no or little assistance from the electrical machine to the propulsion of the vehicle, the engine must have similar specifications to that of an equivalent conventional vehicle in order to meet the same performance in terms of drivability. Full hybrids have greater involvement of electric power so the engine can be smaller. In the non-plug-in version, the engine is still the main source of energy, requiring the engine to produce sufficient amount power to avoid depletion of the batteries under normal driving conditions. For the case of the plug-in version, the choice of engine depends on the settings regarding the engine/electric operation and the capacity and performance of the electrical system. A PHEV designed for operation similar to a non-plug-in may utilize a similar engine, whereas a PHEV designed to operate mainly as an electric vehicle may manage with a relatively small engine.

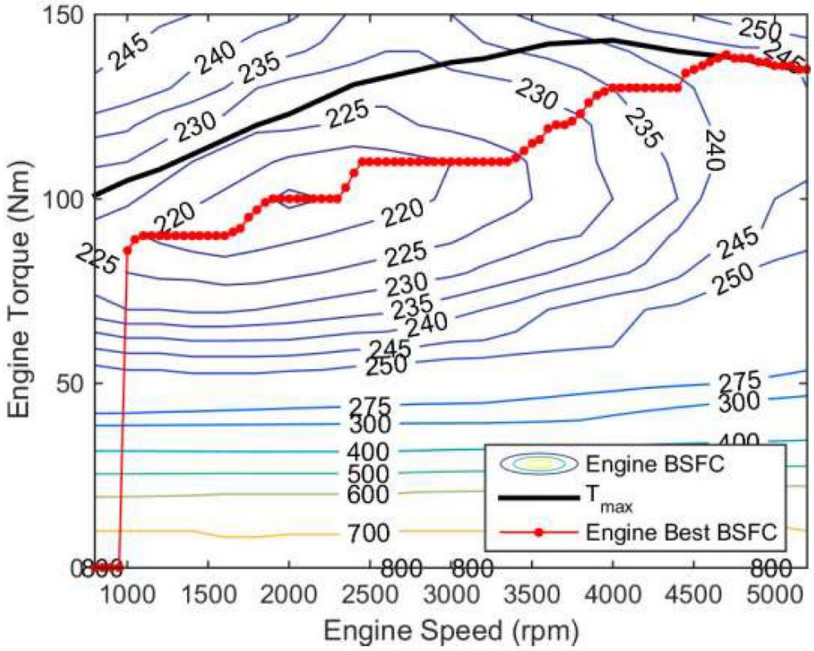

Figure 6 BSFC map of the Toyota Prius 2010 2RZ-FXE Engine [16]

Figure 6 shows the brake specific fuel consumption (BSFC) map of the gasoline engine used in Toyota Prius III. The red dotted line indicates the operating torque for best fuel efficiency to a specific engine speed. To achieve the best efficiency of the engine, the transmission system and MG shift the engine speed and compensate for the required torque. During cruising, the torque demand is lower than what is required for the best fuel efficiency. The MG applies a load to the engine and stores the generated power. When the battery has sufficient energy stored, the engine shuts down to save fuel and the vehicle operates in electric mode.

2.3.2 Electric machines

The permanent magnet synchronous machine (PMSM) is widely used in both HEV and EV applications. This type of machine has high power-to-weight ratio, provide high torque, and has high efficiency. As seen in Figure 7, the efficiency can reach up to 96%. Gasoline engines typically have an efficiency of 30% up to just below 40% [17] [18]. This makes the use of electric power in vehicles more desirable.

The maximum amount of torque is generated at low speeds. As the speed increases, the power increase to a maximum and the torque declines, as shown in Figure 8. These properties are well suited for vehicle propulsion as the highest torque demand is during acceleration and the torque needed to maintain a steady cruising speed is low. Because of these properties, there is no need for a transmission system in the application as a traction motor. By choosing a suitable gear ratio, the motor can operate at an efficient level at cruising speed still having sufficient torque available.

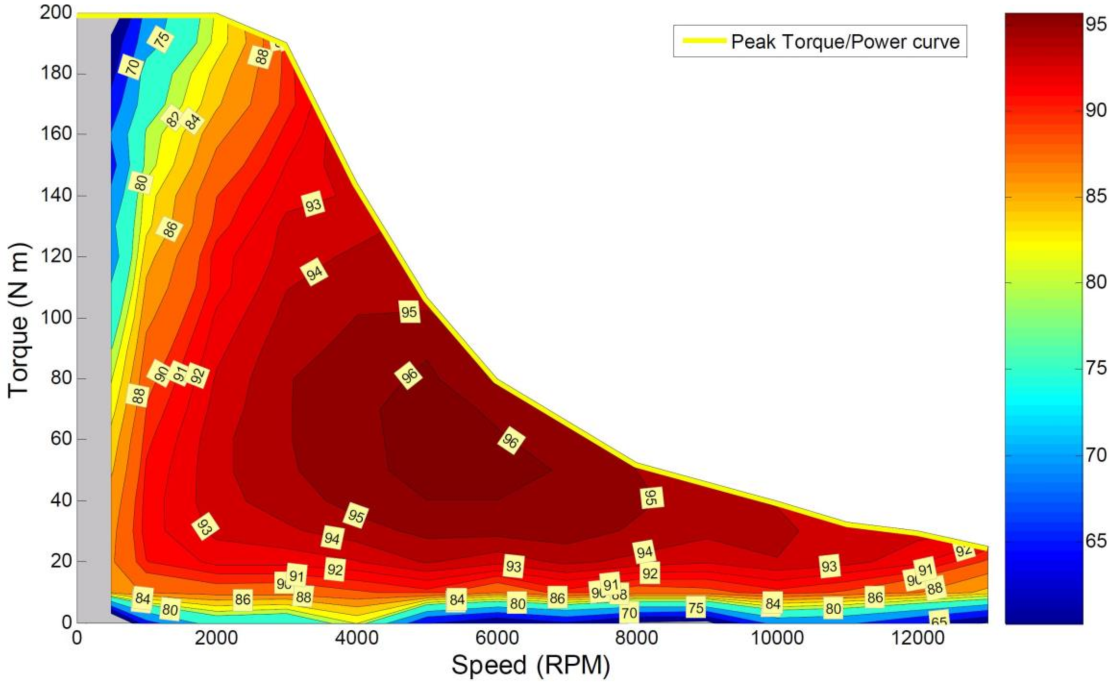

Figure 7 Toyota Prius 2010 MG2 efficiency contour [8]

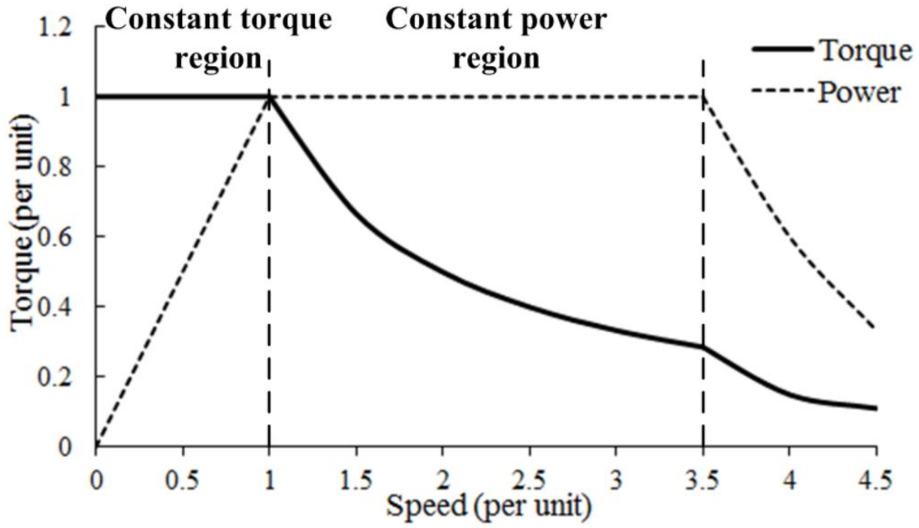

Figure 8 Torque and power curve [19]

2.3.3 Inverter

The inverter used in HEV and EV applications is a high power device that is important for the operation of controlling the electrical machine. It has bidirectional power flow, changing DC to AC during motor operation and AC to DC during generator operation. The inverter consists of six IGBTs controlled by a high frequency pulse width modulated signal to create AC waveforms[20]. To ensure optimal use of the electrical machine, the efficiency requirement for inverters in HEV applications is high [5].

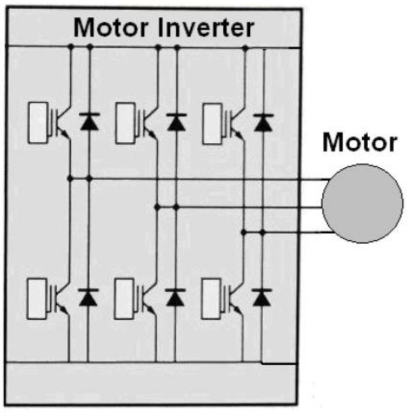

Figure 9 Inverter [8]

2.3.4 Battery pack

The battery pack is an important part of the hybrid system as it is the power source for the electric motor and stores the electrical energy recovered from the kinetic energy during regenerative braking. Micro hybrids, mild hybrids, and full hybrids operates at 12-42V, 60-200V, and >200V respectively where >60V is considered as high voltage [4]. The battery pack capacity is sized according to the manufacturer specifications depending to what the degree the vehicle will be operated in electric mode. Non-plug-in hybrids use the engine as the main propulsion source and the electric motor as supplementary. In order to keep the vehicle as light as possible, these have relatively small battery packs. The Toyota Prius III has a 42kg, 1.3 kWh NiMH battery pack. As plug-in hybrids can utilize the energy from renewable energy sources, they can rely more on electrical power to make them more environmentally friendly. The clean energy reduce the emissions, however, the added weight will result in higher energy consumption. The Toyota Prius III plug-in has a relatively small battery pack compared to other plug-in hybrids. Its Li-Ion battery pack has a capacity of 4.4kWh and weighs 80kg [21]. The Chevrolet Volt has a much bigger battery pack that has a usable capacity of 14kWh, which add 183kg to the vehicle [22].

The battery pack consists of multiple battery cells in series and parallel configuration to meet the desired voltage and capacity. In addition to the cells, there are other components and systems in the pack that includes voltage, current, and temperature measurement, a cell balancing circuit, and a cooling system [23]. This ensures that the battery operates at its optimum efficiency and within its limits to prevent damaging of the cells.

The most common types of batteries found in hybrid electric vehicle are the Nickel-Metal Hydride (NiMH) and the Lithium Ion (Li-Ion). These types of batteries has high power to weight ratio, high capacity, fast charging, and long lifecycle, which makes them suitable for automotive applications. Both types are recyclable and the NiMH contains no toxic materials [24]. An advantage of the NiMH is that it requires simple circuitry whereas the Li-Ion has the need for protection circuits to prevent over-charge and over-discharge [25] [26].

The operating range of a battery in terms of state of charge (SOC) is from 25% to 95% [27]. This gives a usable capacity of 70%. As the battery degrades over time, the capacity reduces to about 80% at the end of its life. To have sufficient usable capacity at the end of life, the battery pack should be oversized. As an example, in order to have at least 5kWh of available energy at the end of life, the initial capacity should be about 9kWh.

Table 1 Comparison of NiMH and Li-Ion batteries [24]

	NiMH	**Li-Ion**
Gravimetric energy density (Wh/kg)	60-120	110-160
Cycle life	300-500	500-1000
Fast charge time (h)	2-4	2-4
Cell voltage (nominal)	~1.25V	~3.6V
Self-discharge/month (%)	30	10
Cost (7.2V in $)	60	100
Maintenance requirement	2-3 months	Not required

The NiMH battery is a mature technology, meaning that there will not be any major advances in this type of battery. Li-Ion however, has not yet reached its peak and is already outperforming the NiMH in several areas. As the development of the Li-Ion continues and the price of production reduces, this will be the battery of choice for both in hybrid electric and purely electric vehicles.

2.3.5 DC-DC Converter

The bidirectional DC-DC converter in an HEV powertrain is used to link the voltage of the battery system to the higher voltage of the DC bus. For example, the nominal battery voltage of the Toyota Prius III is 201.6V and the operating voltage of the inverter and MGs are 650V. Instead of having more battery cells in series to increase the voltage, the DC-DC converter boosts the voltage to match the MG system. The converter operates in this boost mode when there is a power demand from the bus side. During regenerative braking, or whenever power flows to the battery, the converter operates in buck mode, stepping down the voltage to the battery side.

Due to battery dynamics and its internal impedance, the converter is also used to regulate the power flow and optimize the inverter performance [28]. When the battery delivers current, the internal impedance causes the voltage at the terminals to drop. The higher current, the more the voltage drops. To accommodate for a specific power demand, the current must increase to compensate for the voltage drop. The voltage of the battery also declines with the SOC, which means that the current has to compensate even more. Without a DC-DC converter, the inverter needs to be oversized to be able to handle the increased current. If not, the maximum amount of power the battery can deliver to the MG is heavily reduced. When delivering power to the battery, the opposite happens. The voltage increases and the current drops. Without the converter, these voltage fluctuations will make the operation of the MG and inverter less efficient and the control of the MG more difficult.

2.3.6 Transmission system

The function of the transmission system is to optimize the use of the engine by converting the output to meet the driver demand in terms of torque and speed. As seen in the presentation of the structures, the transmission system varies among the different configurations. The two types of transmission used in HEVs are the ECVT function of the planetary gear and the fixed gear transmission.

The ECVT consists of an MG unit and a planetary gear with the function of adjusting the engine speed independent of the vehicle speed. Instead of having the engine speed vary proportionally with the vehicle speed through a fixed gear ratio, the ECVT continuously adjust the engine speed to operate at a point of best fuel efficiency. The relation between the speeds and number of teeth for a planetary gear is given by:

$$(R+S)*\omega_c = R*\omega_r + S*\omega_s \tag{2}$$

where R and S are the number of teeth on the ring gear and sun gear respectively, and ω_c, ω_r, and ω_s are the angular speeds of the carrier, ring gear, and sun gear respectively.

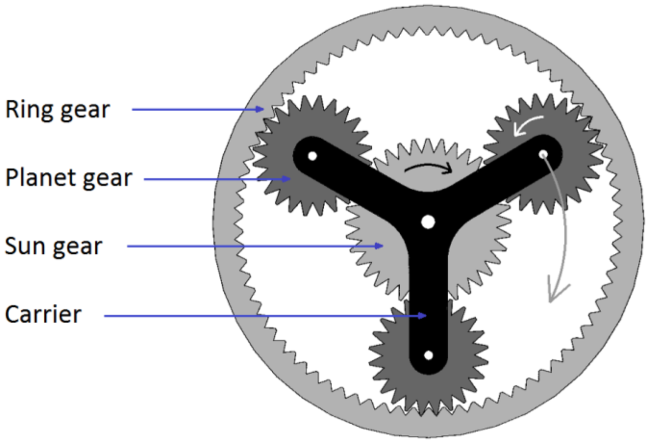

Figure 10 Planetary gear

The fixed gear transmission performs both speed and torque conversion whereas the ECVT only performs speed adjustment. As power is a product of torque and angular speed, the shift in torque is inversely proportional to the shift in speed when changing gear ratios. If the engine is required to provide a specific amount of power and operates in a region of poor fuel efficiency due to high speed and low torque generation, the transmission system can change to a higher gear ratio, having the engine operate at lower speed and higher torque generation, resulting in better fuel efficiency.

In the series hybrid, there is no need for a transmission system as the engine only connects to a MG unit. It may be necessary to use a single gear to have the output of the engine match the optimal operating speed of the generator. There is no need for a transmission system for the MG used for propulsion either, as discussed in 2.3.2.

3 Modelling

The base vehicle for the simulation model is the Toyota Prius 2010 HSD. This is a single-mode power split hybrid structure consisting of an engine, two MGs, and two planetary gears, as shown in Figure 3. The simulation model consists of predefined blocks and simplified systems to make it as computationally efficient as possible.

The electrical system consists of the battery, DC-DC converter, and the motor and generator. The DC-DC converter is modelled as a controlled voltage source providing the electrical machines with a constant voltage on the bus side. On the battery side, a controlled current source is used to regulate the flow of current to and from the battery. Rather than using an exact modelling of the electrical machines and drive system, these are modelled using servomotor blocks to emulate the operation and performance. All auxiliary loads to the electrical system are neglected in the model design.

The mechanical system consists of the engine, vehicle body, tires, and gears. The fuel consumption of the engine is calculated from a BSFC table derived from Figure 6 that can be found in Appendix. Since the properties of a tire varies very little during driving, the tires are modelled with a constant rolling coefficient. The rolling resistance force is defined as

$$F_r = C_r N \tag{3}$$

where C_r is the rolling resistance coefficient, and N is the normal force to the rolling surface. Typical rolling resistance coefficient is about 0.01-0.015 for ordinary tires on asphalt [29]. For the vehicle used in the simulation with a mass of 1380kg, the resulting losses due to rolling resistance coefficients of 0.01 and 0.015 are 135.4N and 203N respectively. With an increased mass of 300kg, the losses due to rolling resistance with the same coefficients are 164.8N and 247.2N. The increased mass will also have an impact of the fuel economy during acceleration, as it requires more energy to accelerate a heavier object.

The control system design consists of an outer loop for vehicle speed control and dedicated inner loops for the engine and each of the electrical machines. The input to the system is a vehicle reference speed. The speed controller uses a PI controller and converts the reference into separate speed references for the motor and engine. Both the engine and motor use a PI controller to regulate their speed to the reference speed. The generator also has its own control loop regulating the speed of the engine and adjusting the torque according to the charge demand, which is set at value equal to 20% of the available engine torque.

4 Simulation

The drive cycle used for the simulations is the IM240 inspection and maintenance driving schedule from the United States Environmental Protection Agency [30]. The vehicle travels 3.15 km (1.96 miles) in 240 seconds at an average speed of 47.27 kph (29.38 mph). The vehicle mass used for the simulation of the different rolling coefficients is 1380 kg and the rolling coefficient used for the simulation of the different vehicle masses is 0.012. The remaining parameters can be found in Attachment 2 and Attachment 3.

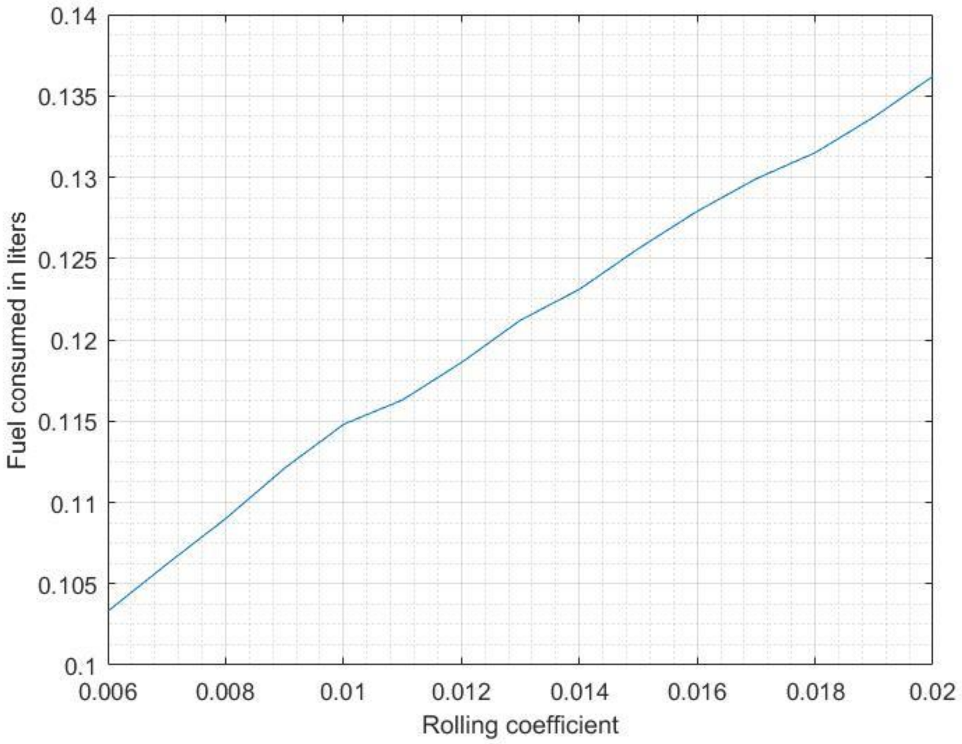

Figure 11 Fuel consumption for different rolling coefficients

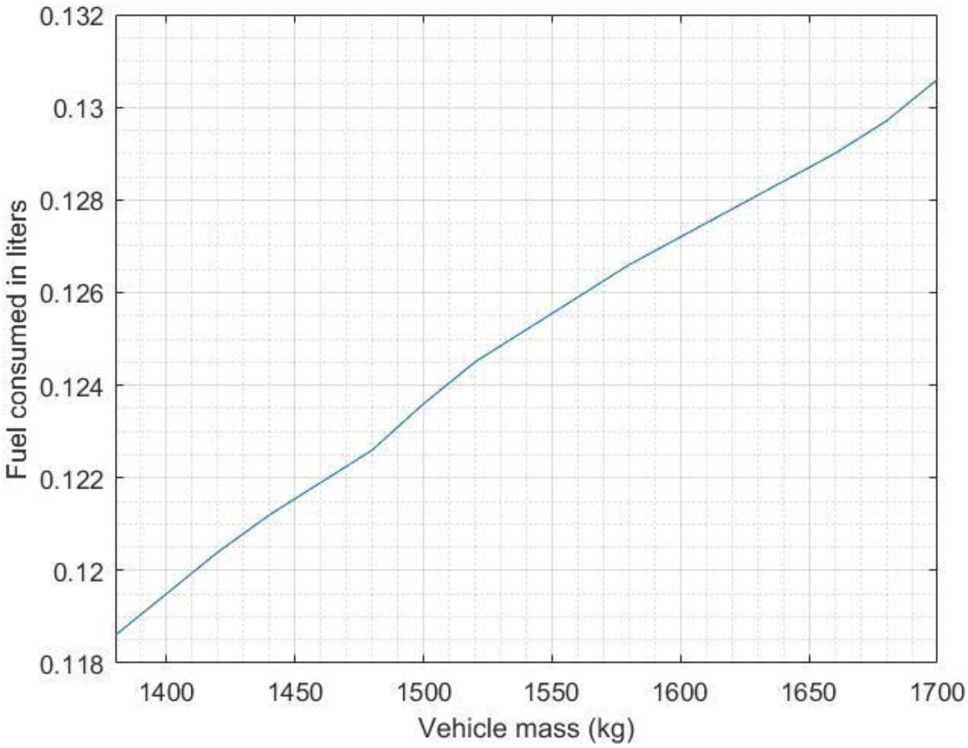

Figure 12 Fuel consumption for different vehicle masses

5 Conclusion

When designing an HEV, the choice of components need to be selected according to the type of structure and level of hybridization. The engine and electrical system must complement each other to achieve optimal performance. In addition, the need of a transmission, the number of MGs, and battery capacity must also be considered.

The simulations of the HEV show that the fuel consumption varies proportionally to the change of mass and rolling coefficient. Since simulation model is not optimized for best fuel efficiency, the results are not accurate. However, the results indicates that lower vehicle weight and reduce rolling resistance leads to improved fuel economy.

5.1 Future work

The engine operation in the simulation model should be optimized. By designing the control system to have the engine operating at the point of best fuel efficiency, as discussed in chapter 2.3.1, the model would provide a more accurate estimate of fuel consumption for different simulations. A part of this is to implement a variable charge controller to adjust the charge demand according to engine operating rather than using a constant percentage of the available torque. By comparing the measured output values of speed and torque of the engine to a lookup table, the electrical machines can adjust according to the deviation for best engine performance.

To avoid overcharging of the battery and poor engine operation, a mode selection can be implemented. Instead of having the engine running at lower efficiency when the battery is fully charged, the engine should be shut down and have the vehicle operate in purely electric mode.

A part of the original project description that is yet to be carried out is the investigation of fuel efficiency on relation to the size of the engine and choice of gear ratio. This should be done after the model is optimized as proposed above. The simulations conducted for this thesis should also be carried out again with an optimized simulation model. By investigating the results from these simulations, a more specific indication regarding the choice of components can be presented.

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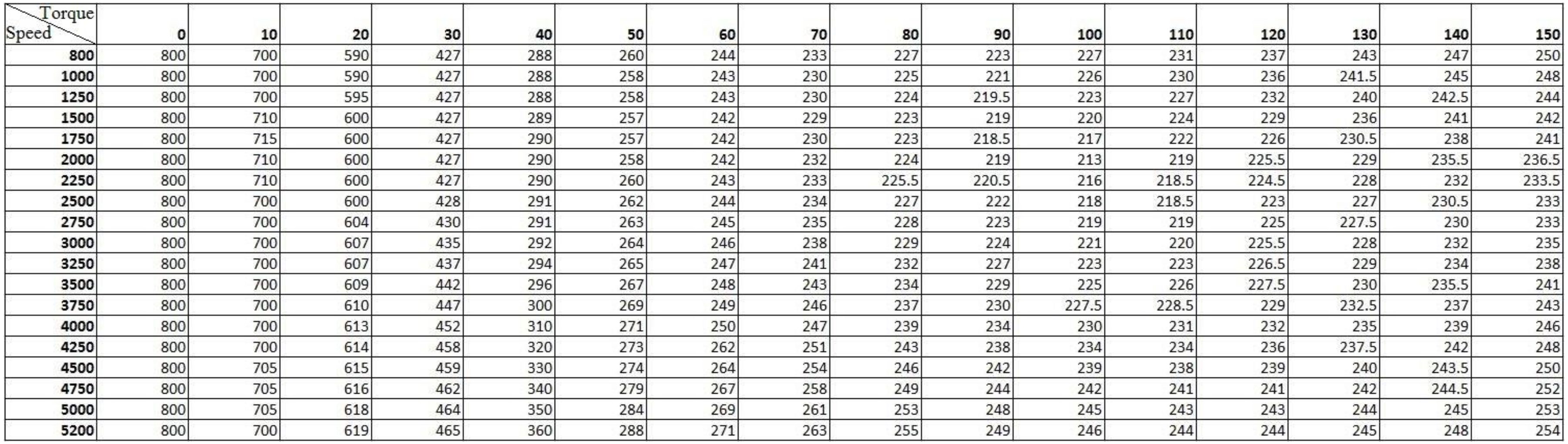
Appendix



Torque / Speed	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
800	800	700	590	427	288	260	244	233	227	223	227	231	237	243	247	250
1000	800	700	590	427	288	258	243	230	225	221	226	230	236	241.5	245	248
1250	800	700	595	427	288	258	243	230	224	219.5	223	227	232	240	242.5	244
1500	800	710	600	427	289	257	242	229	223	219	220	224	229	236	241	242
1750	800	715	600	427	290	257	242	230	223	218.5	217	222	226	230.5	238	241
2000	800	710	600	427	290	258	242	232	224	219	213	219	225.5	229	235.5	236.5
2250	800	710	600	427	290	260	243	233	225.5	220.5	216	218.5	224.5	228	232	233.5
2500	800	700	600	428	291	262	244	234	227	222	218	218.5	223	227	230.5	233
2750	800	700	604	430	291	263	245	235	228	223	219	219	225	227.5	230	233
3000	800	700	607	435	292	264	246	238	229	224	221	220	225.5	228	232	235
3250	800	700	607	437	294	265	247	241	232	227	223	223	226.5	229	234	238
3500	800	700	609	442	296	267	248	243	234	229	225	226	227.5	230	235.5	241
3750	800	700	610	447	300	269	249	246	237	230	227.5	228.5	229	232.5	237	243
4000	800	700	613	452	310	271	250	247	239	234	230	231	232	235	239	246
4250	800	700	614	458	320	273	262	251	243	238	234	234	236	237.5	242	248
4500	800	705	615	459	330	274	264	254	246	242	239	238	239	240	243.5	250
4750	800	705	616	462	340	279	267	258	249	244	242	241	241	242	244.5	252
5000	800	705	618	464	350	284	269	261	253	248	245	243	243	244	245	253
5200	800	700	619	465	360	288	271	263	255	249	246	244	244	245	248	254

Attachments

Attachment 1: HEV_Model

Attachment 2: HEV_Parameters_Script

Attachment 3: HEV_Parameters_Workspace