POLITECNICO DI TORINO

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Modelling and Design of systems and components for Hybrid Powertrains

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Abstract

The current carbon emission regulations have pushed the search for new systems and strategies to reduce these emissions. One such strategy which achieves lower emissions with a low cost is the ''mild hybrid electric vehicle''. This thesis focuses on modelling a mild hybrid electric vehicle's powertrain in Simulink/Simscape. Alongside the powertrain model a possible control solution is developed and tested on the developed model. The controller model is initially developed in Simulink and later converted in Stateflow format. After an adequate solution is found, code is generated from the model and the result is validated on a hardware in the loop HIL setup where the controller is transferred to an electronic control unit, while the powertrain model is loaded into a dedicated real-time processor. The final objective of this thesis is the preparation of the controller to be tested on a dynamometric test rig that includes part of the powertrain, and eventually testing the developed control strategy on an actual vehicle.

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Chapter 1

Introduction

1.1 State of the art

One of the greatest challenges facing car manufacturers today, if not the greatest challenge, is reducing the emissions of their vehicles and meeting the increasingly stricter criteria set by emission regulations. It is estimated that transport is responsible for nearly 30% of CO_2 emissions in the EU [1].

To meet those requirements, car manufacturers must reduce the fuel consumptions and use more efficient fuels. Different automotive technologies have been proposed to meet those requirements. In addition to improvements to the current traditional powertrain that relies on the Internal Combustion Engine (ICE) for power, alternative technologies have been proposed such as hydrogen fuel cells and battery powered electric vehicles BEV. However, while fuel cell technology won't be available for at least decades to come due to safety reasons, inefficiency in producing hydrogen and technological limitations [2], BEVs are still limited by the absence of adequate infrastructure and limited range. Therefore, hybrid electric vehicles are currently the only technologically viable option that's being evaluated by car makers.

1.2 Hybrid electric vehicles

Hybrid electric vehicles, or HEVs, are vehicles powered by a conventional internal combustion engine (ICE) and an electric motor. HEVs can offer different advantages when compared to their more traditional counterpart such as:

- Reduced fuel consumption
- Reduced carbon and toxic gas emissions
- Improvement of powertrain performance by increasing power and torque even at low speeds
- The introduction of electric motors can enhance the control of the vehicle

HEVs are classified in 4 main categories depending on their level of hybridization:

1. Micro hybrid
2. Mild hybrid
3. Full hybrid
4. Plug-in hybrid

1.2.1 Micro hybrid

Micro hybrids are usually powered with a 12V battery and have a maximum electric power capacity of 5 kW. Due to their limited power, their capabilities are limited to engine Start-Stop: when braking or idling the engine is turned-off and restarted again when needed, thus allowing to save fuel and reduce emission. Their main drawback of limited capacity and capability is compensated by their low price, ease of implementation and the simplicity of their control.

1.2.2 Mild hybrid

Mild hybrid vehicles have a battery ranging from 48V to 200V and are usually fitted with 5-20 kW electric propulsion power. Compared to micro hybrid their extended capacity allows them added capability. On top of the already explained above Start-Stop capability, the increased power of the electric machines allows them to assist the engine with additional torque during aggressive maneuvers and during transients, for example at low speeds where the engine efficiency is at its lowest. On top of that thanks to their higher torque and battery size, the electric motors can be used for braking: in conventional braking, the kinetic energy of the car gets converted and wasted as heat. By using the electric motors for braking by providing all the torque requested or by assisting the conventional brakes, part of the kinetic energy can be converted into electric energy to charge the battery. A more detailed description of the mild hybrid powertrain architecture will be provided in section 1.3.

1.2.3 Full hybrid

Full hybrid electric vehicles are equipped with a battery of at least 150 V and can power an electrical powertrain of at least 40 kW. In addition to the mild hybrid capabilities the full hybrid vehicles are also capable of driving the car on pure electric mode for short distances (around 4 kilometers). Thanks to the increased power, the full hybrid vehicle is able to recover and store even more kinematic energy during braking, thus allowing more fuel saving at the expense of an increased weight and price.

1.2.4 Plug-in hybrid

Just like a pure battery electric vehicle, a plug-in hybrid can recharge its battery by connecting to the alternating current AC grid. Plug-in hybrids are fitted with the most powerful electrical powertrain of all hybrids discussed so far, with a voltage up to 400 V and a power of around 80 to 150 kW. During normal operation, a plug-in hybrid runs on a pure electric mode for around 30 to 100 km depending on the size of the battery. After the battery is depleted to a certain level, the plug-in hybrid is propelled by the ICE and the electric motors continue to perform their regenerative braking.

What follows is a quick summary table of the capacity and capabilities of the hybrid categories that have been discussed.

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Table 1.1: The main capacities of various hybrid electric vehicles *[3]*

Type of hybrid	Capacity			
	Battery voltage [V]	Electric machine power [kW]	Pure electric mode range [km]	CO_2 estimated reduction benefit [%]
Micro Hybrid	12	2-3	0	5-6
Mild Hybrid	48-160	10-15	0	7-12
Full Hybrid	200-300	30-50	5-10	15-20
Plug-in Hybrid	300-400	60-80	<100	>20

Table 1.2: The main capabilities of various hybrid electric vehicles *[4]*

Type of hybrid	Capabilities			
	Start-Stop	Regenerative braking	Boost	Electric-only mode
Micro Hybrid	Yes	Possible	No	No
Mild Hybrid	Yes	Yes	Yes	No
Full Hybrid	Yes	Yes	Yes	Possible
Plug-in Hybrid	Yes	Yes	Yes	Yes

1.3 Architecture of parallel hybrid electric vehicle

In this section we will discuss the various possible mechanical architectures of hybrid parallel electric vehicles, with particular focus on the mild hybrid electric vehicle architecture.

1.3.1 P0 architecture

The P0 architecture or the belt starter generator architecture includes a 48V electric motor replacing the conventional starter. One of the main advantages of this configuration is the low cost of such implementation: to achieve this configuration all that is required is to replace the space occupied by the starter with a more powerful electric motor connected to the ICE via belt system, without much modification to the powertrain structure. However, this configuration presents some serious drawbacks. First, the electric motor can't be separated from the engine, which results in the constant presence of a parasitic torque from the engine whenever the electric motor is generating traction or recovering energy. Secondly, during cold starts of the engine, especially after a long period of inactivity, the torque required can be too big for the belt to handle; that's why a lot of vehicles with the P0 architecture still include the conventional starter for this function [5]. Alternatively, this problem can be circumvented by designing a more durable and robust belt system. A representation of the P0 configuration is shown in figure 1.1.

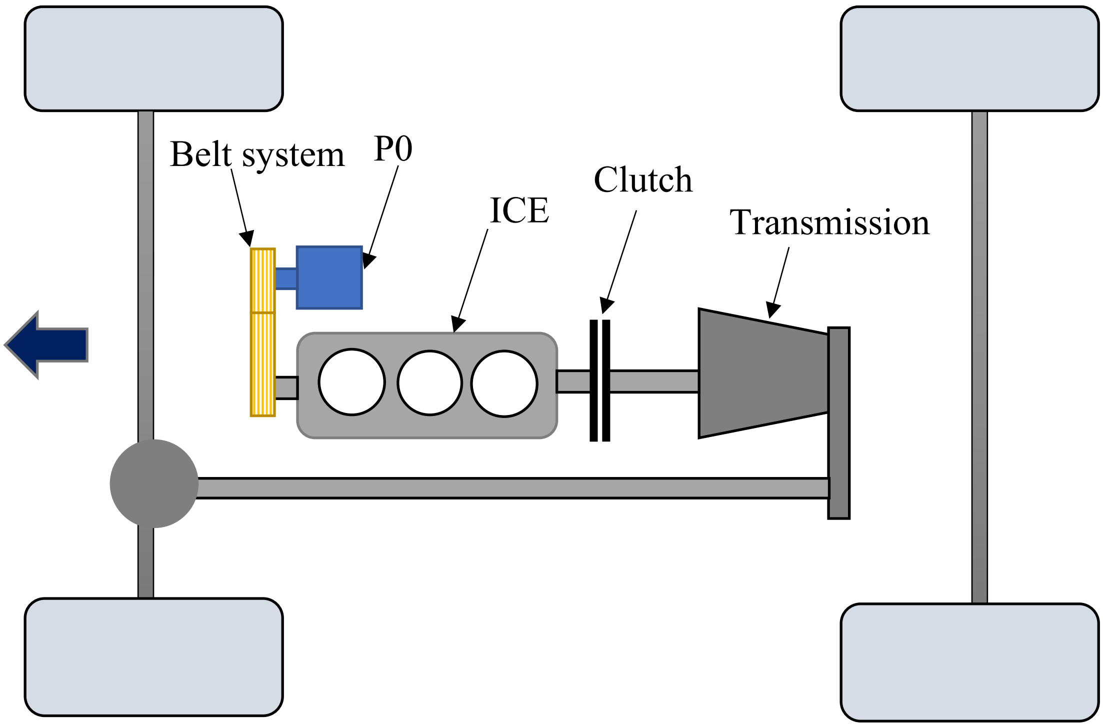

Figure 1.1: P0 layout

1.3.2 P1 architecture

In the P1 configuration the electric machine is placed directly in the crankshaft of the engine as shown in figure 1.2. Just like in the P0 configuration, the electric motor can replace the starter, however in this case the absence of the belt guarantees a greater efficiency since there are no coupling losses and eliminates the torque limitation previously imposed by the belt strength and slip. On the other hand, this configuration poses many disadvantages. First, the absence of a belt system or any coupling device means the absence of a transmission ratio, so the torque demand on the electric motor can be quite high. Second, the implementation is much more complicated and costly than the previous case since it can require the modification of the ICE structure. Thus, this configuration is no longer being researched and developed by car manufacturers.

Figure 1.2: Honda Insight Hybrid 2009 P1 layout *[5]*

1.3.3 P2 architecture

The main disadvantage of the P0 or P1 architecture is that the electric machine cannot be disconnected from the engine, so parasitic losses are always going to be present. To solve this problem the engine needs to be separated from the rest of the powertrain. This is usually achieved by using a clutch or a set of clutches depending on how the electrical motor is coupled with the power train. In the P2 configuration the electric motor is placed at the input shaft of the transmission. The Electric motor can be connected through gear mesh, belt drive, or directly placed on the input shaft and integrated into the transmission itself as shown in figure 1.3. Figure 1.4 shows a representation of the P2 configuration.

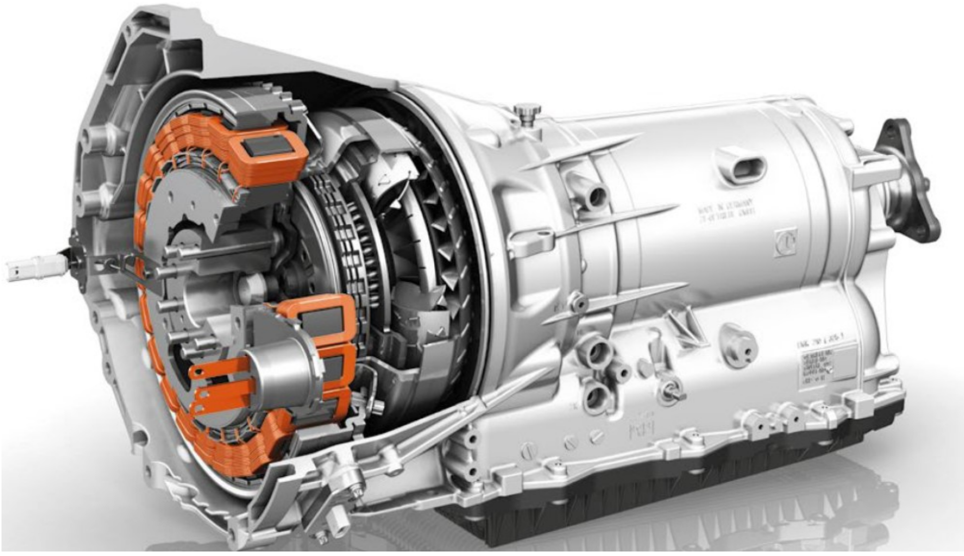

Figure 1.3: ZF integrated mild hybrid transmission [6]

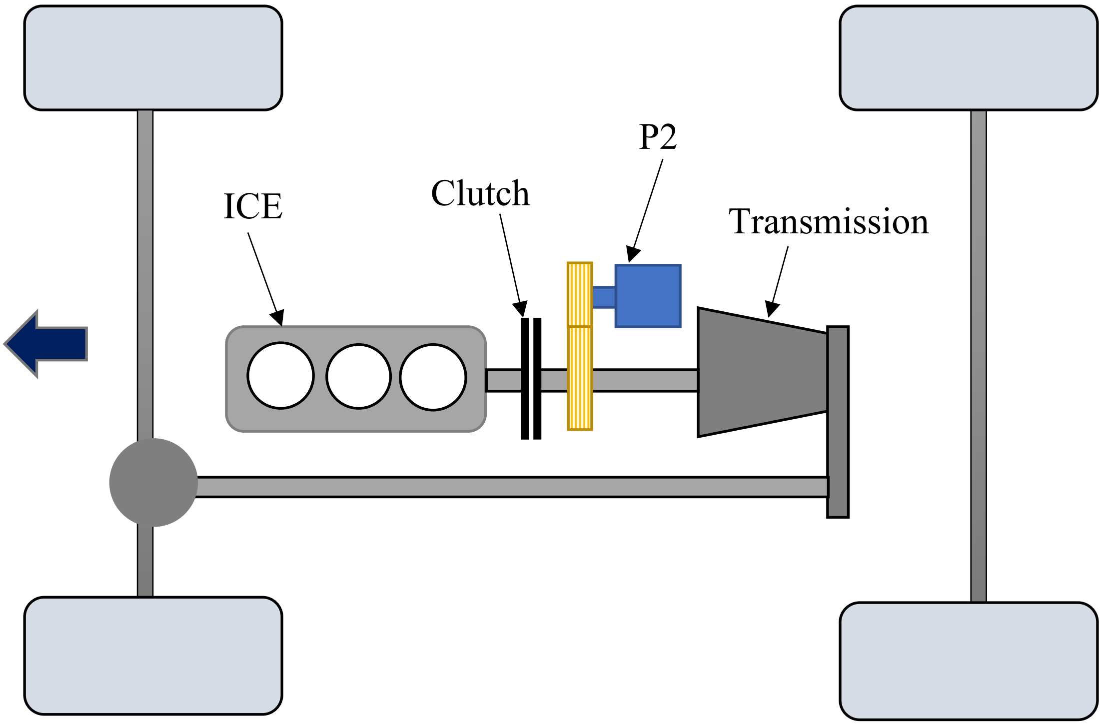

Figure 1.4: P2 layout

1.3.4 P3 and P4 architectures

In the P3 configuration the electric motor is located at the output shaft of the transmission or in the differential. This allows better torque output and better energy recuperation than in the case of the P2 layout since P3 isn't weighted down by the transmission losses.

P4 is the most efficient configuration, where the motor is inserted on the rear axle. If the ICE is connected to the front wheels this configuration could allow for four-wheel drive. This configuration is also called parallel-through-road, since the motor and the ICE are coupled through the road, this also means that P4 can only recharge when the engine is running.

It is to note that since P2, P3 and P4 are separated from the engine they require another electric motor (P0 or enhanced starter) on the engine side to perform Start-Stop. A representation of the P3 and P4 layout is shown in figure 1.5.

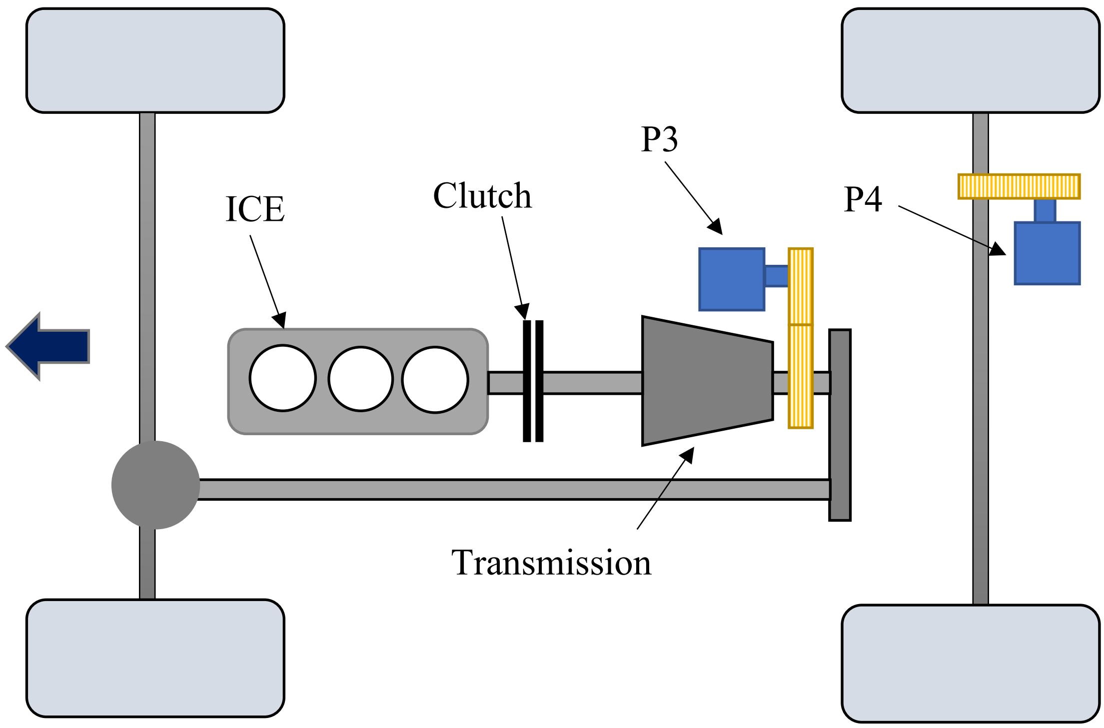

Figure 1.5: P3 and P4 layout

1.4 Series hybrid and series-parallel hybrid:

All the hybrid vehicle architectures discussed so far are considered parallel architecture, where the ICE is connected directly, mechanically coupled, to the wheels while the electric motors can work both as motors and generators. However other alternatives exist.

1.4.1 Series hybrid

In a series hybrid, the engine is decoupled from the wheels, and instead is directly connected to a generator, and so the main function of the ICE is replaced from driving the vehicle to generating electrical energy.

Depending on the current usage mode and battery state of charge, the generated electrical energy can be used partially to charge the battery or can flow entirely to the electric motor. In this case the electric motor is the only component responsible for creating traction.

Due to their simple design, series hybrids are generally easy to control, and are more efficient in urban and city driving conditions, while more powerful parallel hybrids are preferred in highway driving conditions. A representation of a series hybrid is shown in figure 1.6.

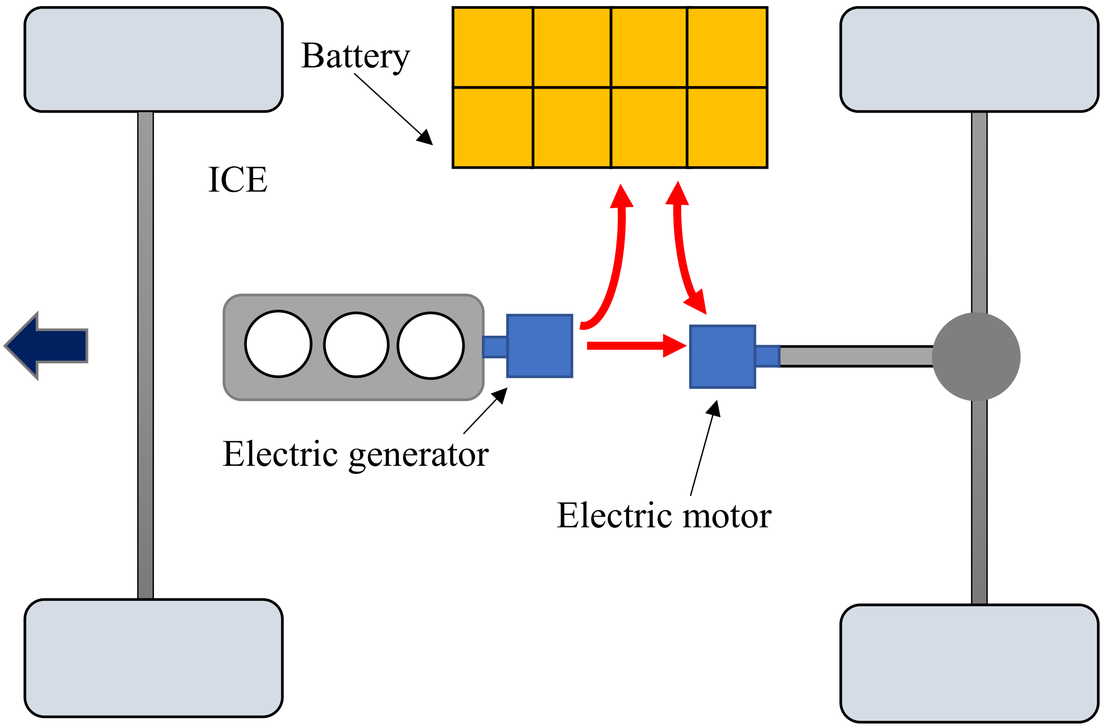

Figure 1.6: Series hybrid layout

1.4.2 Series-Parallel hybrid

A combination between the two architectures, parallel and series, is possible. By using a special device, a power split device, for example a planetary gear set, the ICE can be connected either through a series path or parallel path.

In the series path, the ICE takes care of providing the electrical energy for the battery and motor, while the motor propels the vehicle. In the parallel path, the ICE’s mechanical power is transmitted partially or completely to the wheels, and just like in the parallel configuration the electric motor can help with the boost function and providing extra torque.

Chapter 2

Model objectives

2.1 Problem description

This research activity aims to build a model for a specific architecture of hybrid parallel electric vehicle, and to develop a control strategy capable of running the model. The control strategy that will be developed is only a preliminary strategy that aims to check the model validity and integrity and is not to be considered the final strategy that will be adopted on the vehicle.

2.2 Vehicle architecture

The considered vehicle is a parallel hybrid vehicle with a combined P0P2 architecture. The motors are connected to the driveline via a belt drive system of 2.7 ratio. An 8-speed automatic transmission is used in the powertrain. A scheme of the vehicle is own in figure 2.1.

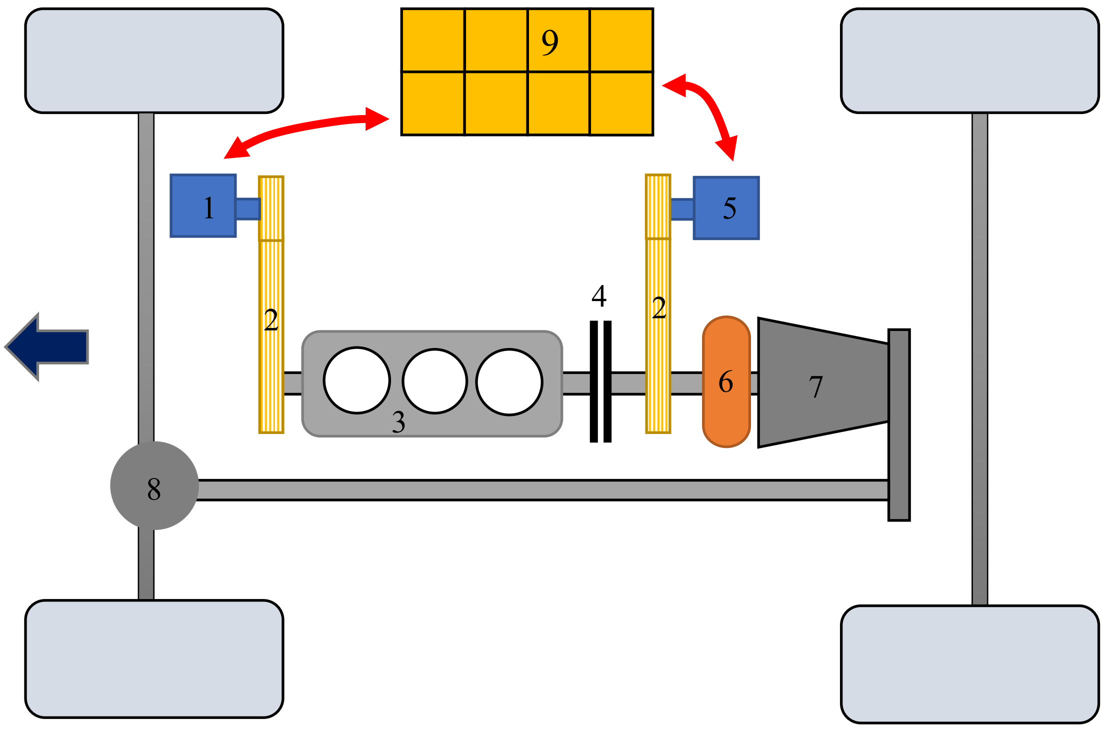

Figure 2.1: Vehicle architecture

2.2.1 List of components:

The vehicle is based on a light commercial vehicle with a gross weight of 3000 kg with the following list of main components:

- 1 and 5: the electric motors are placed in the P0 (1) and P2 (5) position. P0 is placed on the engine side, while P2 is placed on the input shaft of the transmission after the clutch K0 to separate it from the engine. Both motors are connected via a belt system. P0 and P2 are 48 V ,15 kW brushless DC motors with characteristics shown in the figures below. Figure 2.2 shows the power characteristic of the motors while figure 2.3 shows the torque and efficiency characteristic of the motors. Both figures show the traction (positive torque and power) and the generator (negative torque and power) characteristic.

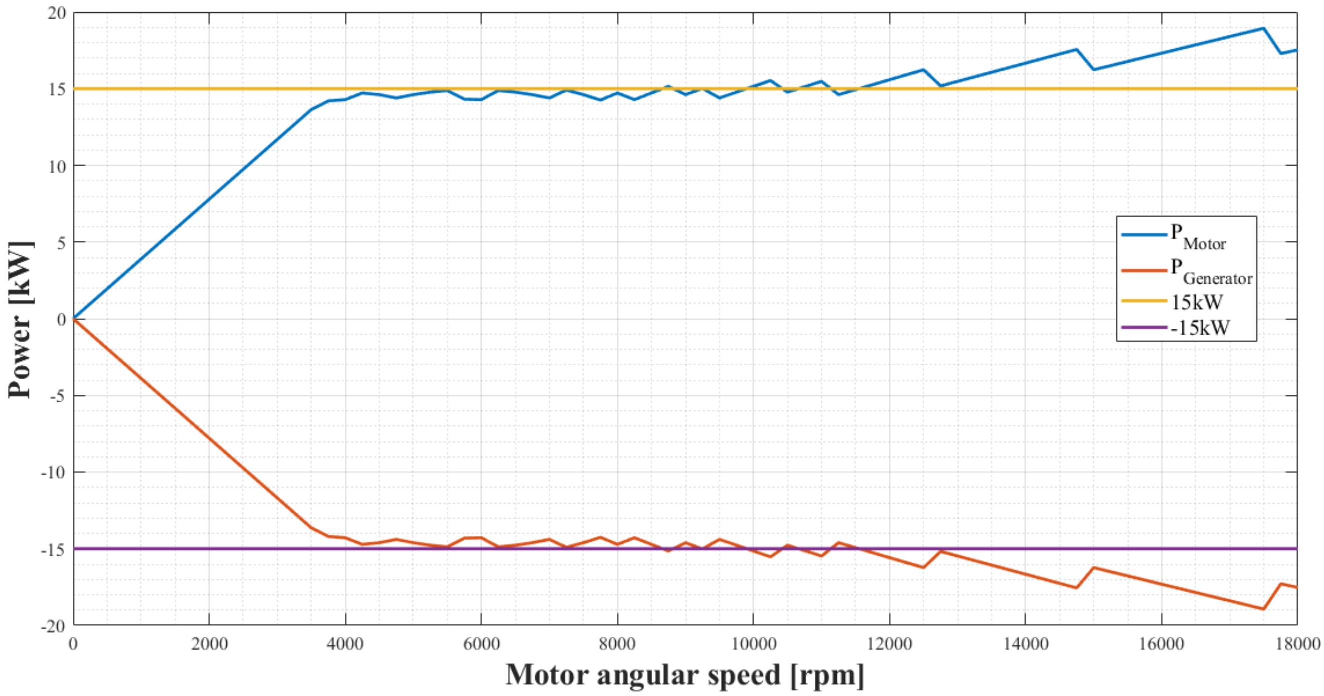

Figure 2.2: Electric motors power characteristic

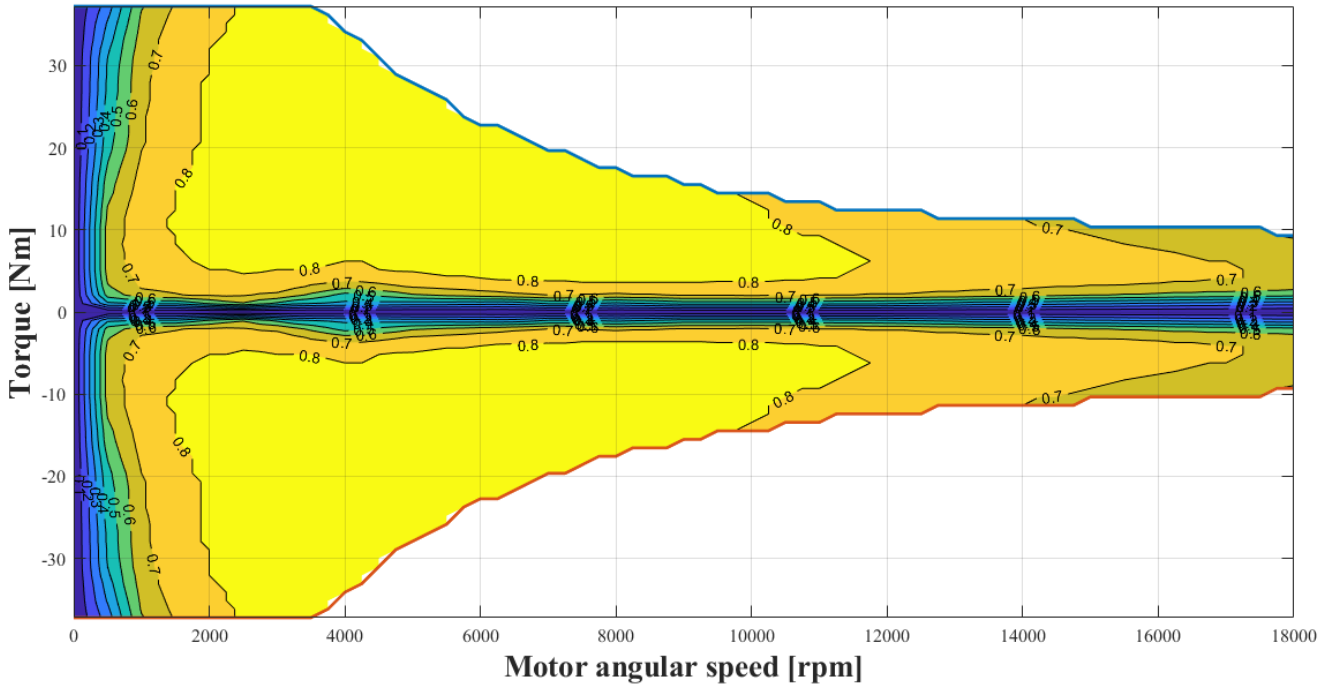

Figure 2.3: Electric motors torque and efficiency characteristic

- 2: Belt drive system with a transmission ratio of 2.7 and constant efficiency of 0.95. No further specifications are provided.
- 3: Internal combustion engine: for the engine the Iveco 2.3 liters F1A diesel engine has been used. The engine can provide a max torque of 350 Nm and a max power of 100 kW (136 hp). The torque of the engine as a function of angular speed and the fuel consumption map is shown in figure 2.4.

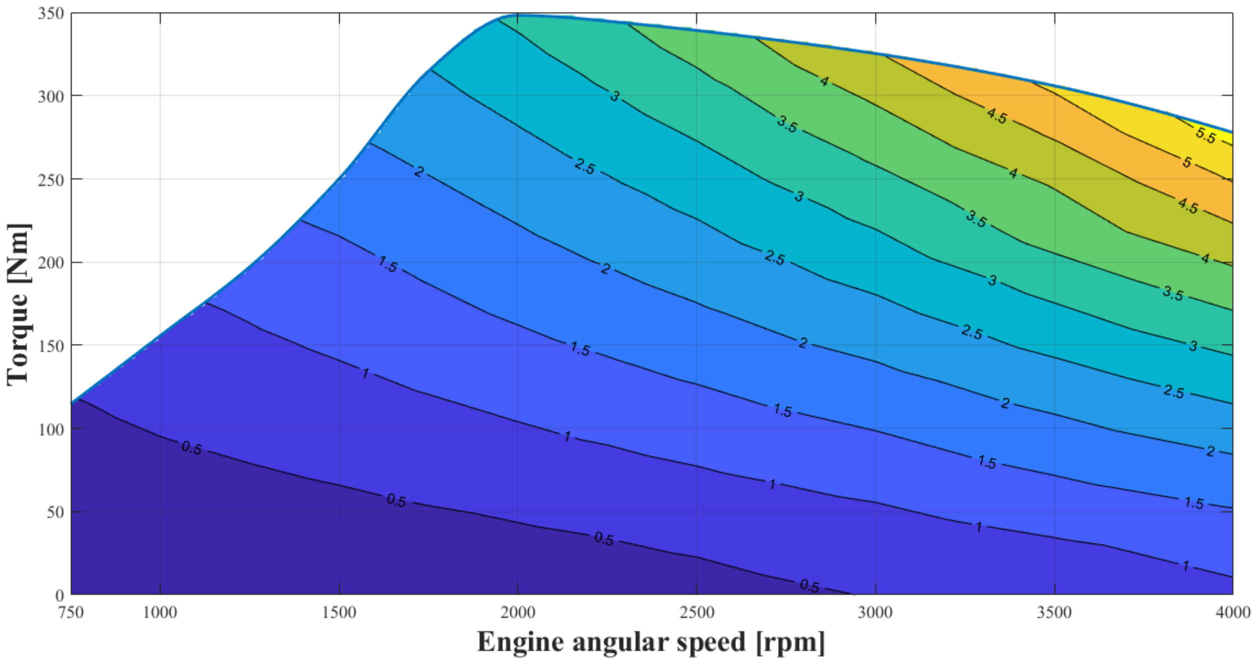

Figure 2.4: ICE torque characteristic and fuel consumption [g/s]

The above fuel consumption map can be transformed into a brake specific fuel consumption map or BSFC map. The BSFC is a parameter that reflects the efficiency of the ICE functioning at a certain point and it can be obtained by dividing the fuel consumption by the power produced at the output shaft of the engine:

$$BSFC = \frac{\dot{m}_f}{T.\omega}$$

Where:

- $\dot{m}_f$ is the fuel consumption [g/s]
- T is the torque [Nm]
- ω is the angular speed [rad/s]

Figure 2.5 shows the BSFC map of the engine expressed in [g/(kW.h)]

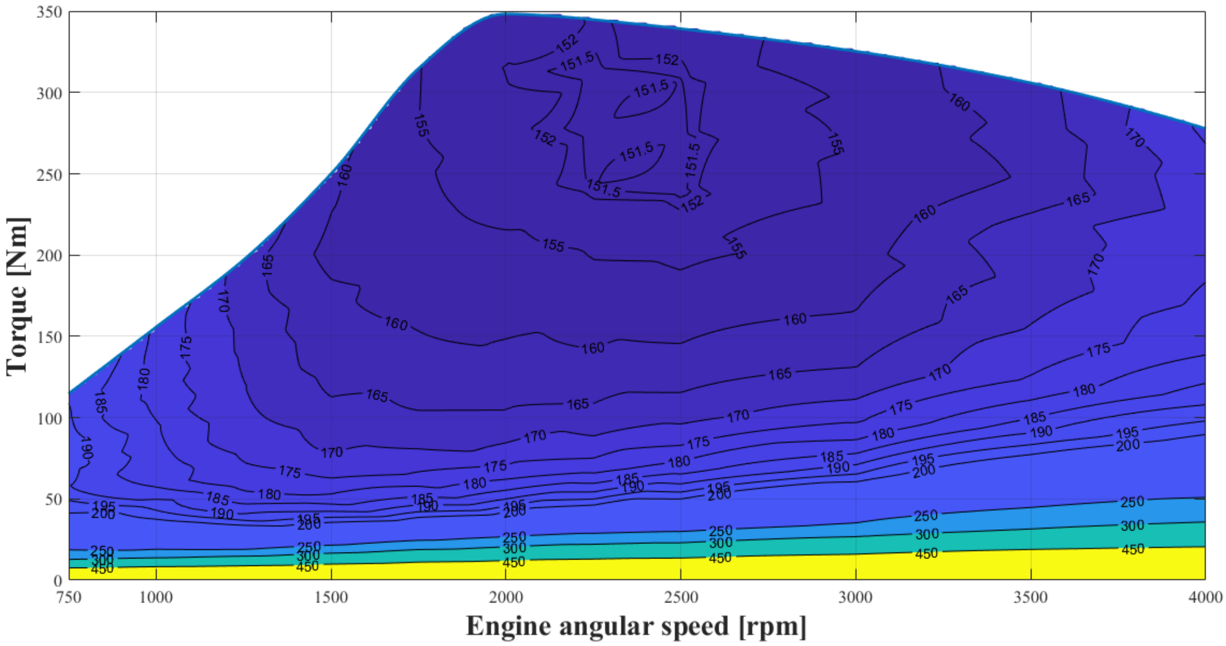

Figure 2.5: Engine torque characteristic and BSFC [g/kWh]

- 4: Clutch K0: the clutch has the function of separating the engine from the powertrain when the engine is not in use, thus removing the unnecessary resisting torque from the powertrain and improving the system's efficiency.
- 6: Torque converter: Placed before the automatic transmission has the function of avoiding stopping the engine when unwanted (during gear shifting, breaking or while standing stationary). The torque converter is also equipped with a lock up clutch with the function of reducing fluid losses and transmitting negative torque during regenerative breaking.
- 7: Transmission: The 3rd generation ZF-8HP automatic eight speed transmission is used for the vehicle transmission.
- 8: Differential: The differential connects the powertrain to the wheel axle. It has a final drive ratio of 3.62.
- 9: Battery Pack: The battery pack in charge of powering the electric motors and collecting the regenerated braking energy. A 48 V lithium ion battery pack with a capacity of 17.6 Ah is used.

2.3: Vehicle backward model

A backward model of the above-mentioned vehicle had been previously developed. In what follows a short description of the backward model and its workings will be given.

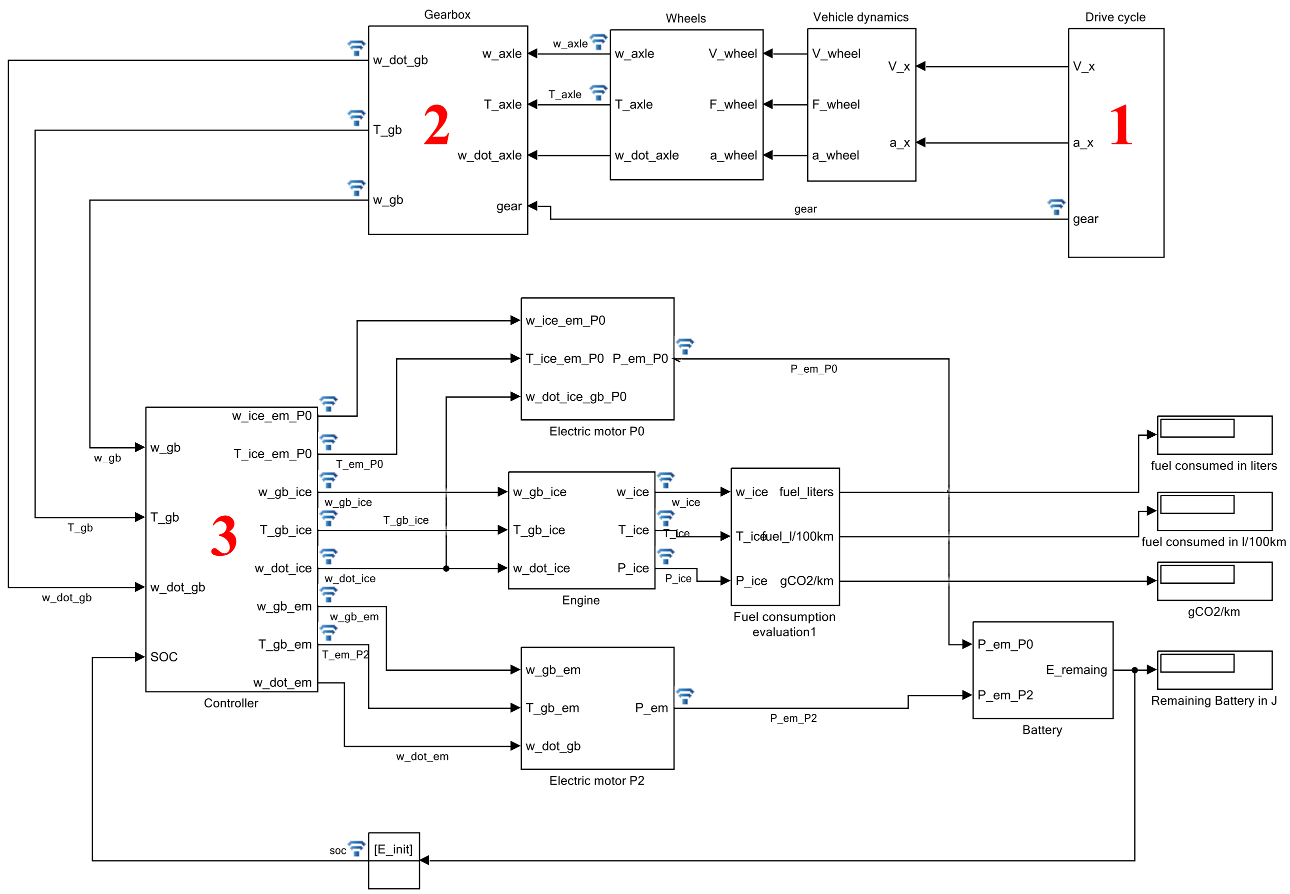

Figure 2.6: Vehicle's backward model

With reference to figure 2.6, in the backward model the drive cycle speed is considered as the vehicle speed and is taken as input (block 1). From the vehicle speed the air drag and acceleration are calculated, and therefore the required torque at the wheels or at the input shaft of the gearbox is obtained (block 2). In addition to air drag, rolling resistance and bearing losses are considered among the resisting forces that increase the required torque or limit the maximum recoverable energy.

The required torque then reaches the controller (block 3) which decides, according to a control strategy that will be explained in section 3, whether to employ the motors or engine.

The controller then sends the calculated torque request to the adequate block (engine or motors) each with its own efficiency map and inertia.

If a motor's block is used, then the energy depleted or generated is calculated and the energy included in the battery block is then decreased or increased. The battery then sends its state of charge to the controller who takes it into account in the next step.

If the engine block is used, then the fuel consumption is calculated instead and added to the overall fuel consumption of the entire cycle.

Chapter 3

Forward model

The problem with the above described backward model is that it can't take a driver's commands, and as such cannot be implemented in a hardware in the loop setup, where the vehicle model responds to commands coming from a controller, including the driver's command.

To solve this issue the model needs to be transformed into a forward model and be made closer to a real vehicle.

First, the control strategy adopted in both the forward and backward model will be discussed in section 3.1. In section 3.2 the implementation of said control strategy in the forward model will be discussed. And lastly, in section 3.3 a description of the plant forward model will be given.

3.1 Control strategy:

The control strategy is divided between traction modes and braking modes. The traction modes range from 1 to 3, while the braking mode range from -1 to -3. This is just a preliminary control strategy that serves only to check the plant model integrity. A more refined strategy that takes into account the efficiencies and emissions should be developed in the future.

3.1.1 Traction Mode 1:

Conditions:

- (Torque requested< Torque max available from P2)
- And (State of charge>=20%)

Actions:

- Torque P2 motor=Torque requested
- Clutch is open

Description: When P2 can provide all the torque requested by the driver, then only P2 provides traction power to the power train. In that mode the clutch is open as to not waste energy on the engine resisting torque, while the engine is running at idle speed of 800 rpm.

3.1.2 Traction mode 2:

Conditions:

- (Torque requested >= Torque max available P2)
- And (Torque requested < [Torque max available P2+Torque max available P0-Torque resisting ICE])
- And (State of charge>=20%)

Actions:

- Torque motor P2=alfa*(Torque requested + Torque resisting ICE)
- Torque motor P0=beta*(Torque requested+ Torque resisting ICE)
- Clutch K0 engaged

Description: When the maximum torque available from P2 alone is not able to satisfy the torque requested by the driver, but the sum of the maximum torques available from both P0 and P2 is enough to overcome the torque requested and the resistance posed by the engine, then P0 and P2 take care of providing the traction power needed by the car. Alfa and beta are two coefficients inferior to one, that determine the usage and power split between the two engines. This pure electric mode only activates if enough charge is present in the battery to sustain it. During this mode the clutch K0 is closed in order to transfer the torque from the motor P0. This means that some of the power is going to be wasted by the parasitic torque of the engine.

3.1.3 Traction mode 3:

Conditions:

- ([Torque requested + Torque resisting ICE] >= [Torque max available P2+Torque max available P0])
- Or (State of charge<20%)

Actions:

- Torque ICE = Torque requested
- Clutch K0 engaged
- Torque motor P2 = Torque motor P0 = 0

Description: When the motors are incapable of providing the requested torque or the battery is incapable of powering the motors (battery charge shouldn't go below a certain limit to avoid damage), then the engine provides the torque demand. During this mode the clutch K0 is obviously engaged to allow the engine to transmit its torque.

Figure 3.1 shows a representation of the various traction modes as a function of torque. The torques in the graph are made with reference to the input torque at the shaft.

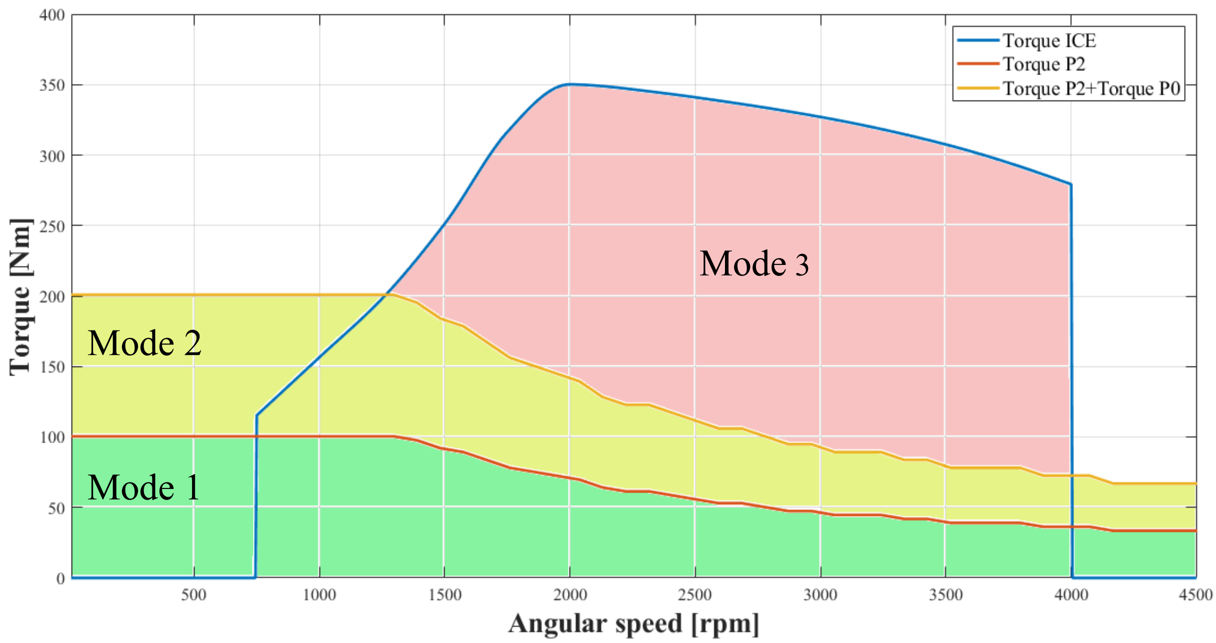

Figure 3.1: Traction modes in function of torque

3.1.4 Braking mode -1:

Conditions:

- ([Torque max generator P2+Torque resisting ICE]>Torque request braking)
- And (State of charge<=90%)
- And (Gear>1)

Actions:

- Torque generator P2=Torque request brake
- If (Torque request brake>Torque max generator P2) $\Longrightarrow$ (Torque brake = [Torque request brake-Torque max generator P2])
- Clutch K0 disengaged

Description: while braking, if the torque requested for braking is smaller than the maximum braking torque available from P2 plus the parasitic torque from the ICE, then brake using only P2. The reason why the ICE resisting torque is considered in the inequation is because the next mode includes closing the clutch, and therefore the resisting torque from the engine is going to be present. If P2 and the engine are enough to satisfy the torque request, then splitting the torque between P2 and P0, and by extension the engine, won't bring any benefit and won't increase the regeneration., since the torque at both motors will still be equal to the torque at P2 only before closing the clutch. In contrary, working each generator at lower torque might reduce the efficiency. That's why when P2 isn't enough to satisfy the torque but the request is still lower than the aforementioned sum, the brakes take care of filling the rest of the torque demand. Additionally, this mode can only activate if the battery is below a certain level of charge to avoid damaging it. Lastly the selected gear should be higher than the first gear, i.e. the speed of the vehicle should be above a certain threshold, that's because the only way to regenerate energy from the wheels of the vehicle is through locking up the clutch at the torque converter, which can only be done above a certain speed.

3.1.5 Braking mode -2:

Conditions:

- ([Torque max generator P2+Torque resisting ICE]>Torque request braking)
- And (State of charge<=90%)
- And (Gear>1)

Actions:

- Torque generator P2=alfa*(Torque request brake-Torque resisting ICE)
- Torque generator P0=beta*(Torque request brake-Torque resisting ICE)
- If (Torque request brake > [Torque max generator P2+ Torque max generator P0+Torque resisting ICE]) ⟹ (Torque brake = [Torque request brake-Torque max generator P2- Torque max generator P0- Torque resisting ICE])
- Clutch K0 engaged

Description: While braking, if the requested torque is greater than the sum of the maximum available generator torque at P2 and the resisting torque of the engine, then the clutch is closed and the torque demand is split between P0, P2 and the engine's resisting torque. If that's still not enough to satisfy the demand, then the conventional brakes are activated to fill the rest. Just like before, this mode only activates if the battery charge is below a certain threshold and the vehicle's speed is above a certain limit.

3.1.6 Braking mode -3:

Conditions:

- (State of charge>90%)
- Or (Gear<=1)

Actions:

- Torque brake = Torque request brake
- Clutch K0 disengaged

Description: while braking, when the state of charge of the battery is too high, or if the vehicle's speed is too low, then all the torque demand for braking is satisfied by the conventional brakes.

3.2 Control strategy implementation in forward model:

In the forward model, the control strategy was implemented in two stages:

1. First, it was implemented using Simulink blocks.
2. Second, the Simulink blocks implementation was replaced with a Stateflow chart.

A description of the controller for the forward model will be given, in the following section.

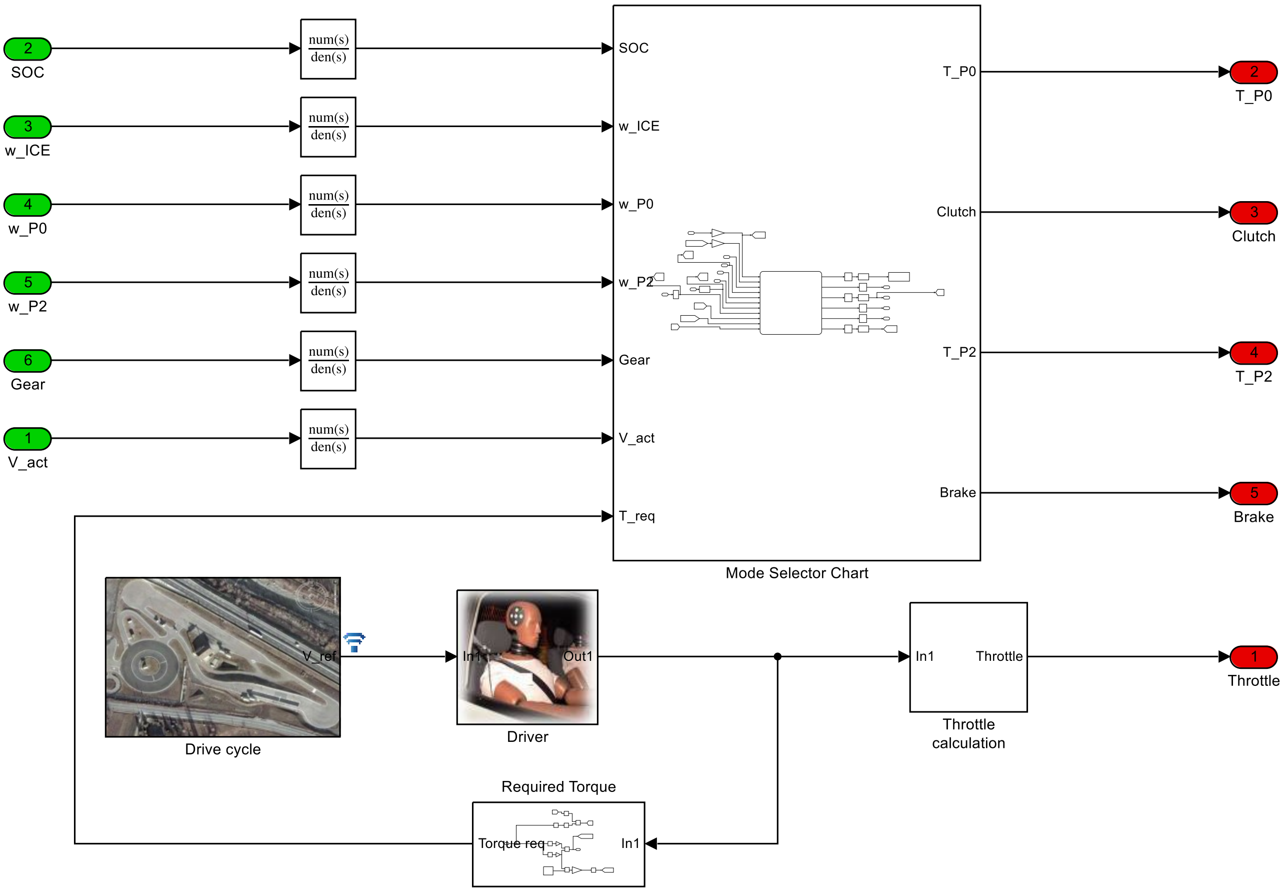

Figure 3.2: Forward model controller

The controller has 6 inputs coming from the vehicle model indicated in green in figure 3.2 and 5 outputs used to command the vehicle model indicated in red. The inputs are the following:

1. V_act: The vehicle speed
2. SOC: The battery state of charge
3. w_ICE: The internal combustion engine angular speed.
4. w_P0: The P0 motor angular speed
5. w_P2: The P2 motor rotational speed
6. Gear: The gear selected in the transmission.

In addition to these inputs the controller also receives the brake and throttle position from the driver which get translated into a throttle request.

Meanwhile the outputs are:

1. Throttle: The throttle requested from the ICE control unit which controls the intake valve. The throttle output varies from zero which corresponds to no engine torque to one which corresponds to max possible torque from the engine at that speed.
2. T_P0: The torque requested from the electric motor P0.
3. Clutch: Controls the clutch position, can only assume the two discrete values zero, which corresponds to a disengaged clutch, and one which corresponds to an engaged or closed clutch.
4. T_P2: The torque requested from the electric motor P2.
5. Brake: Controls the pressure at the brakes.

Since it's a forward model, the model needs to include a driver model which is simulated with a PI loop: a proportional integral loop as shown in figure 3.3:

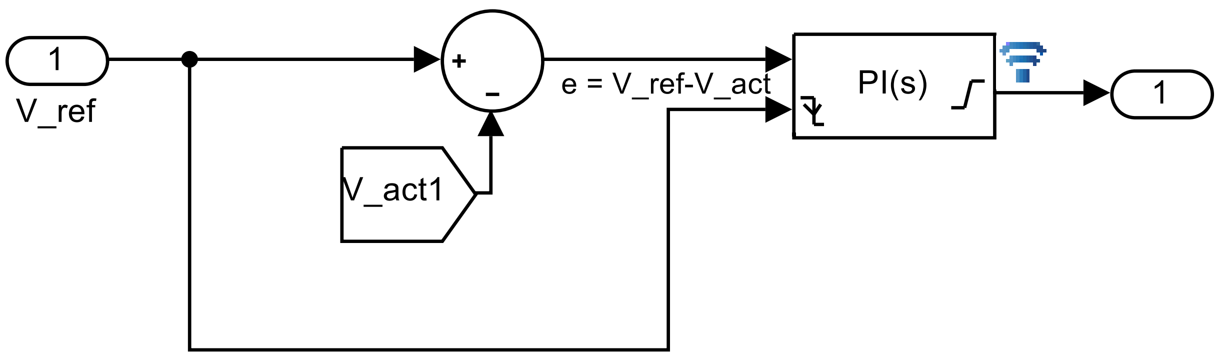

Figure 3.3: Driver model

The PI acts on the difference between the vehicle actual speed and the reference speed, i.e. the speed that the vehicle should theoretically follow and that is taken from a certain driving cycle. The New European Driving Cycle NEDC and the Worldwide harmonized Light-duty vehicles Test Cycles WLTC were used to test the model. The integrator is reset every time the reference speed decreases, this serves as a form of anti-windup.

The output of the controller varies from -1 to 1 with:

- -1 to 0 to represent the brake pedal, with -1 representing a brake pedal fully pressed.
- 0 to 1 to represent the accelerator pedal with 1 representing a fully pressed accelerator pedal.

The inputs from the pedal get later converted into torque requests.

In the preliminary version of the controller, the torque request was then sent to the mode selector which consisted of switches and Simulink blocks. Figure 3.4 shows a short portion of the mode selector to give an idea of the overall structure.

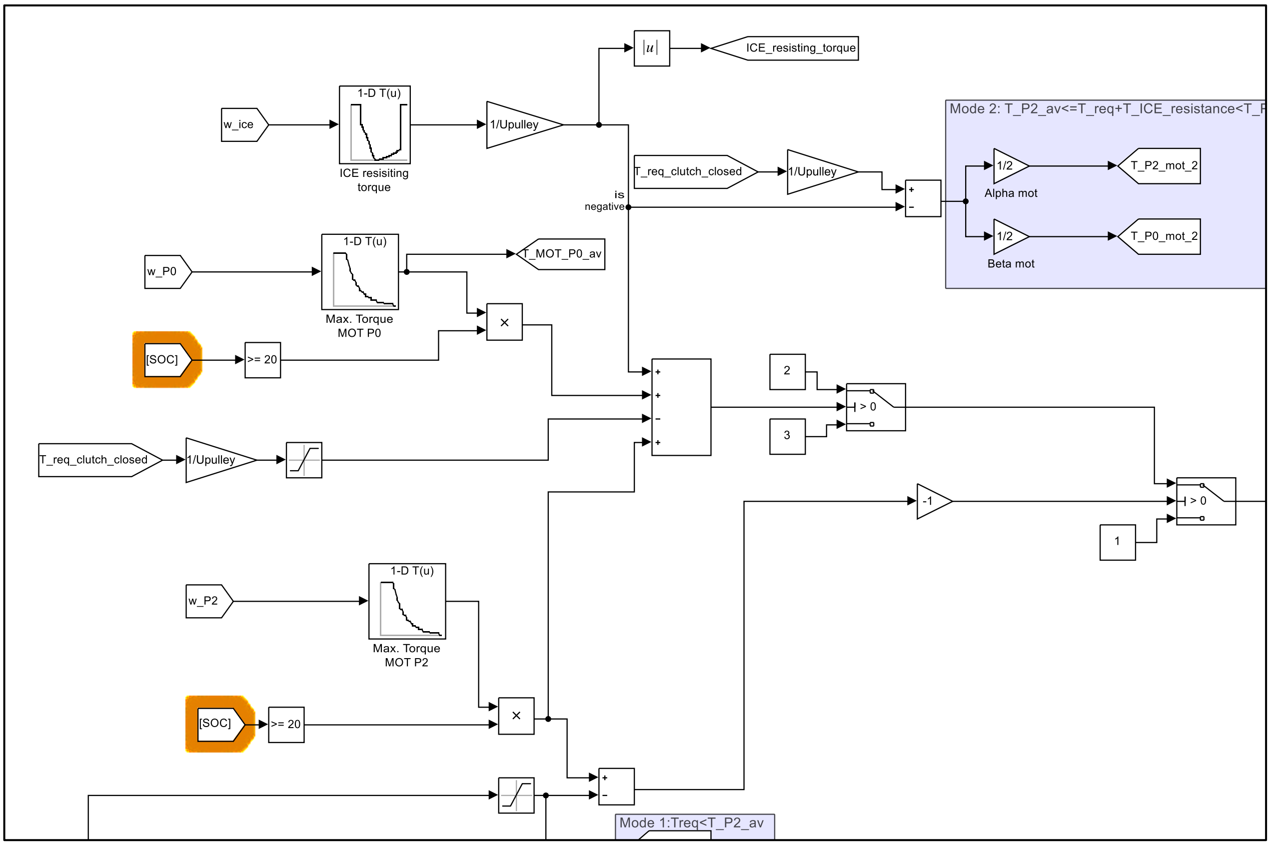

Figure 3.4: Preliminary mode selector

The mode selector gets all the conditions as inputs, and the switches such as that shown in figure 3.4 takes care of the logic: deciding on which mode to operate and what actions to take.

However, to allow a more stable, faster and better structured controller the mode selector was converted from Simulink blocks to a Stateflow chart as shown in figure 3.5. Stateflow charts are better equipped to handle logic and state machines, which is the case as shown in section 3.1.

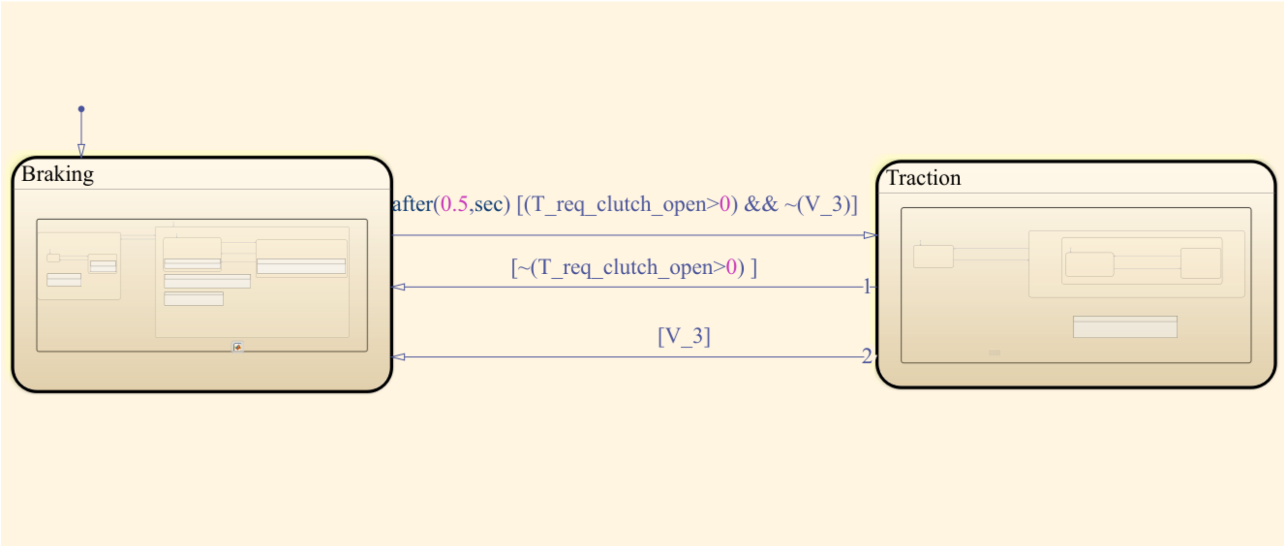

Figure 3.5: Stateflow mode selector

Only the first level of the chart is shown in figure 3.5. Depending on the conditions represented on the arrows the chart dictates in what mode (state) to operate and accordingly what actions to take. The states are represented by the blocks in figure 3.5.

3.3 Plant model:

The plant model of the vehicle, i.e. the vehicle mechanical model, was implemented using the Simscape toolbox. In this section a description of the model and the constituting equations will be given.

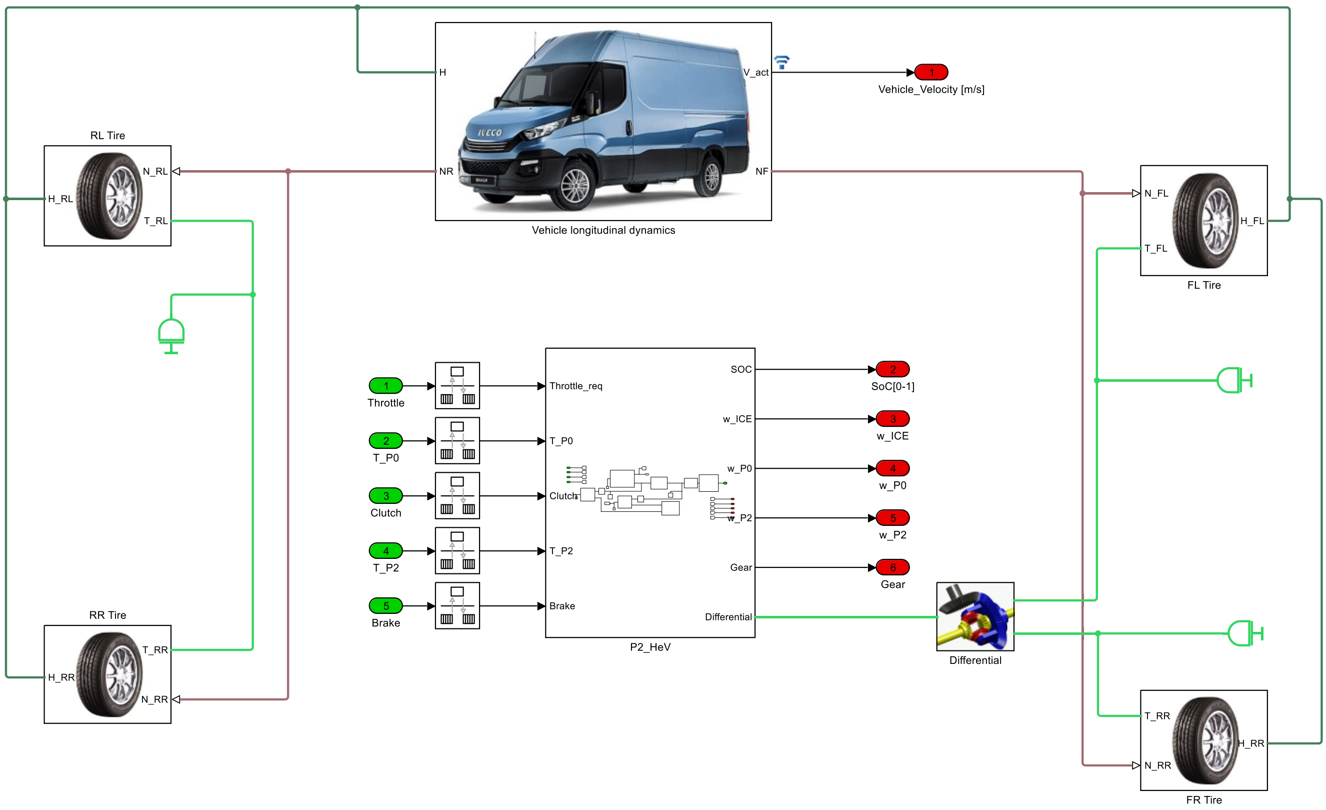

Figure 3.6: Plant Model

Figure 3.6 shows an overall view of the plant model. The green and red ports show the inputs and outputs coming from and to the controller respectively. Said inputs and outputs have been already discussed in section 3.2.

3.3.1 Vehicle Longitudinal dynamics:

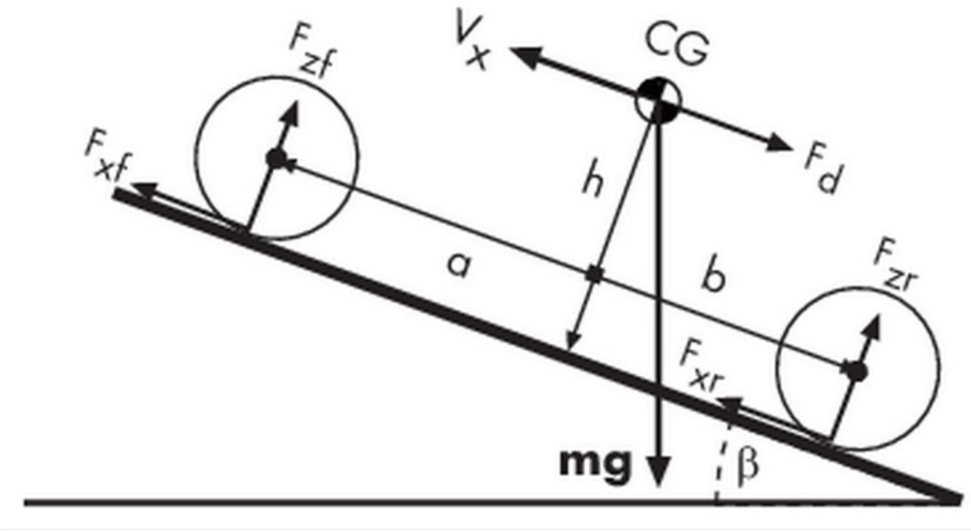

Figure 3.7: Vehicle Longitudinal Dynamics

The first upper block takes into account the vehicle longitudinal dynamics, i.e. the forces acting on the frame of the vehicle as shown in figure 3.7. The forces are summarized in the following equation:

$$m\dot{V}_x = F_x - F_d - mg\sin\beta$$

Where:

- m is the mass of the vehicle
- $\dot{V}_x$ is the vehicle acceleration, V_x is the vehicle speed
- F_x is the longitudinal force on the wheel
- F_d is the air drag
- β is the incline angle

The air drag F_d is represented with the following equation:

$$F_d = \frac{1}{2}C_d\rho A V_x^2$$

Where:

- C_d is the aerodynamic drag coefficient
- ρ is the air density

3.3.2 Tires:

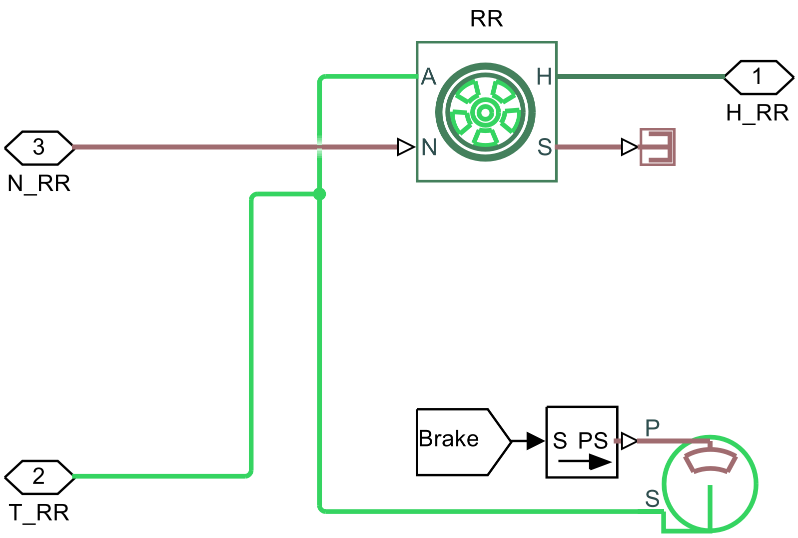

Figure 3.8: Tire model

The tire block (upper block in figure 3.8) transforms the angular speed of the shaft into the translational speed of the vehicle. It also models the slip and the roll resistance with the following equations:

- For the slip (for $V_x \geq V_{th}$):

$$V_x = r_w \Omega - \kappa V_x$$

Where:

- V_x is the vehicle speed
- r_w is the wheel radius
- Ω is the wheel angular speed
- κ is the constant slip coefficient, limited between 0 and 1 where 0 represents a perfect rolling wheel with no slip and 1 represents a fully locked wheel
- V_{th} represents the threshold speed above which the aforementioned equation is valid. For smaller speeds the block extrapolates between a fully locked wheel, i.e. $\kappa = 1$,and the nominal value of κ.

- For the rolling resistance:

$$F_R = \lambda F_z$$

Where:

- F_R represents the rolling resistance of the wheel (longitudinal force)
- F_z represents the vertical load on the tire.
- λ represents the constant rolling resistance coefficient.

3.3.3 Brakes:

The brake block (lower block in figure 3.8) models a disc brake installed on the wheels. The torque applied on the wheels by the brakes is modeled with the following equation:

$$T = \frac{\mu P \pi D_b^2 R_m N}{4}$$

Where:

- T is the torque being exerted by the brakes on the wheel
- μ is the friction coefficient, it changes from the static friction coefficient μ_S when the angular speed is null to the dynamic friction coefficient μ_k when then angular speed is different than zero, with $\mu_k < \mu_S$
- P is the pressure applied to the brakes
- D_b is the brake actuator cylinder diameter
- R_m is the mean radius of the brake pads
- N is the number of brake pads

As shown in figure 3.8 the pressure at the brakes, and therefore the torque, is commanded by the control unit.

The central block in figure 3.6 represents the powertrain. A detailed scheme of it is shown in figure 3.9:

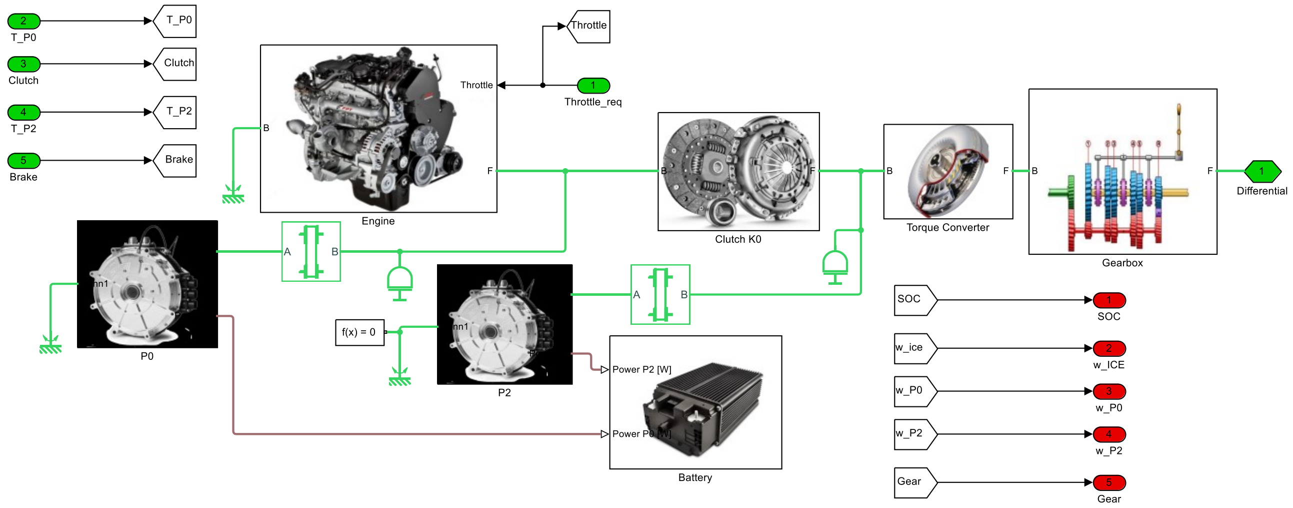

Figure 3.9: Powertrain components

As always, the inputs are represented in green on the left side while the outputs are represented in red at the right side.

3.3.4 Engine:

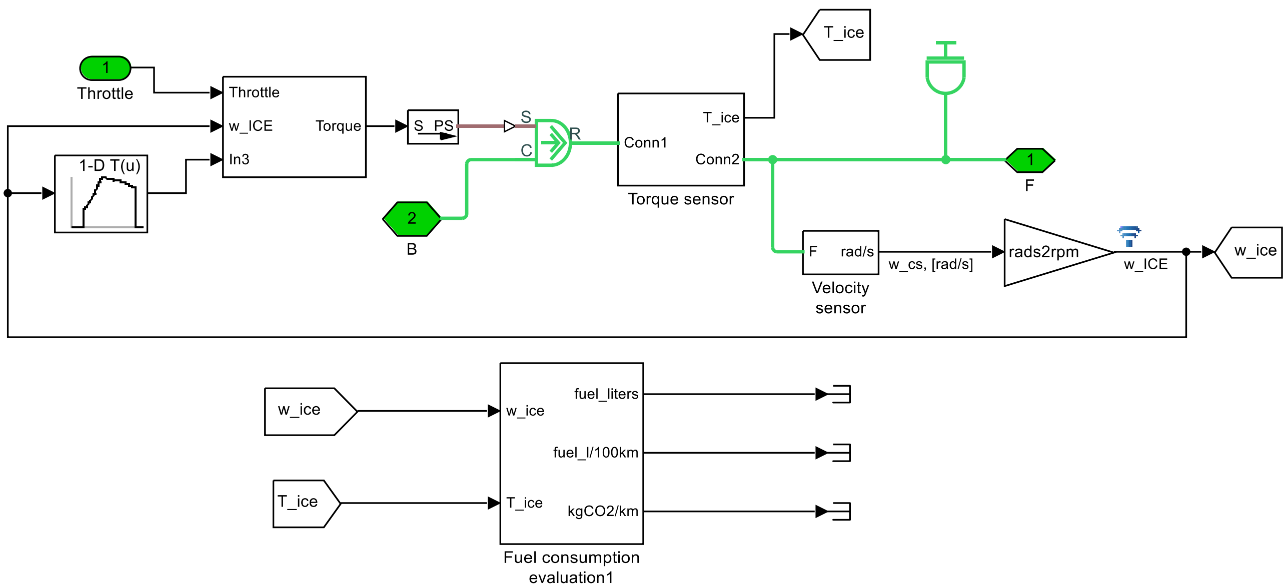

Figure 3.10: Engine block

The engine block receives the throttle as an input and produces power. The block uses the torque map shown in figure 2.4 alongside the throttle and the current engine angular speed to decide how much torque to produce. The inertia of the flywheel is also represented in this block. The engine produces positive torque in the case of traction and negative torque to represent engine brake and pumping losses.

The lower block uses the torque, angular speed and the fuel map of figure 2.4 to determine the instantaneous fuel consumption, and from there the cumulative fuel consumption and CO_2 emissions.

3.3.5 Motors:

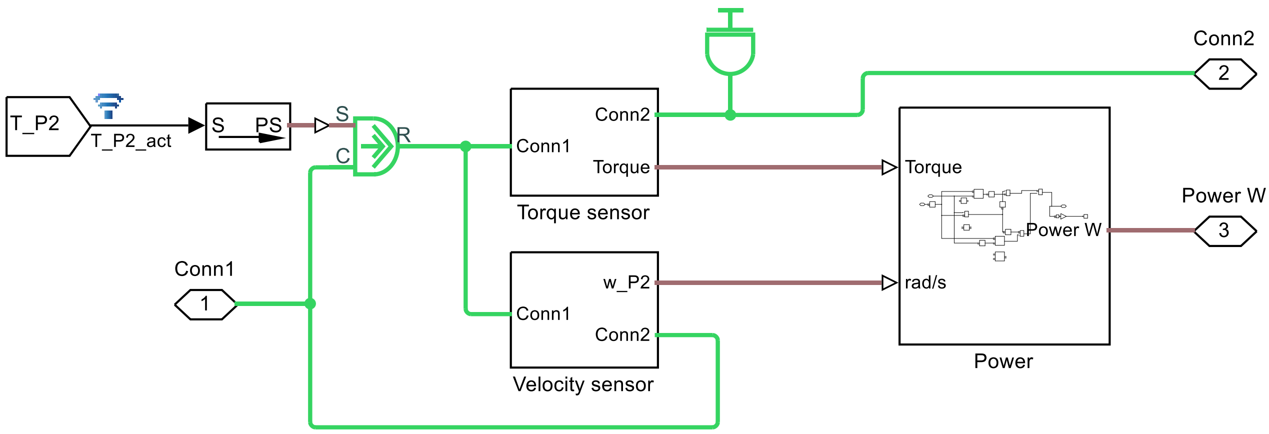

Figure 3.11:Electric motor block

Figure 3.11 shows how the electric motor has been modeled. The block receives the torque it needs to produce as an input from the controller. The torque command is consistent with the torque map shown in figure 2.3. The torque produced, and by extension the power, is positive in case of traction and negative in the case of regeneration.

The block to the right takes into account the efficiency map of figure 2.3 to calculate the power drawn or stored in the battery.

The motors are connected to the main shaft via a belt drive with constant ratio and constant efficiency.

3.3.6 Battery:

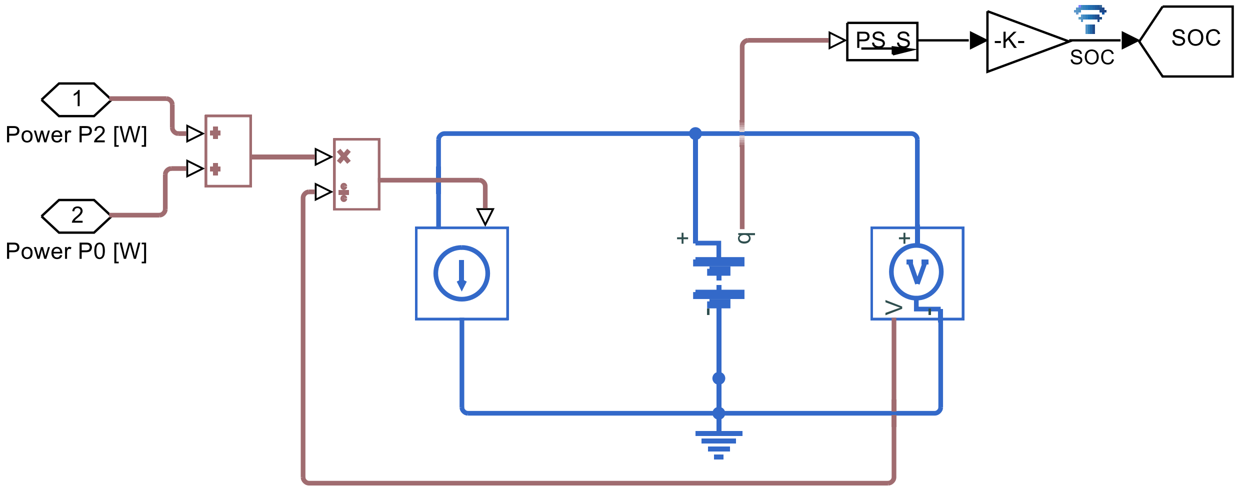

Figure 3.12: Battery model

The battery block takes as an input the power drawn or generated by the electric motors. The total power is then divided by the instantaneous voltage measured at the battery to determine the current. The current is positive if power is drawn and negative if power is regenerated. The battery model also includes a constant series resistance.

The voltage of the battery varies with the state of charge according to the following equation:

$$V = V_0 \left(\frac{\mathrm{SOC}}{1 - \beta(1 - \mathrm{SOC})} \right)$$

Where:

- V is the voltage
- V_0 is the nominal voltage when the battery is fully charged
- SOC is the state of charge that varies between 0 and 1
- β is a constant parameter

Figure 3.18 shows an example of the voltage variation as a function of the state of charge following the above equation:

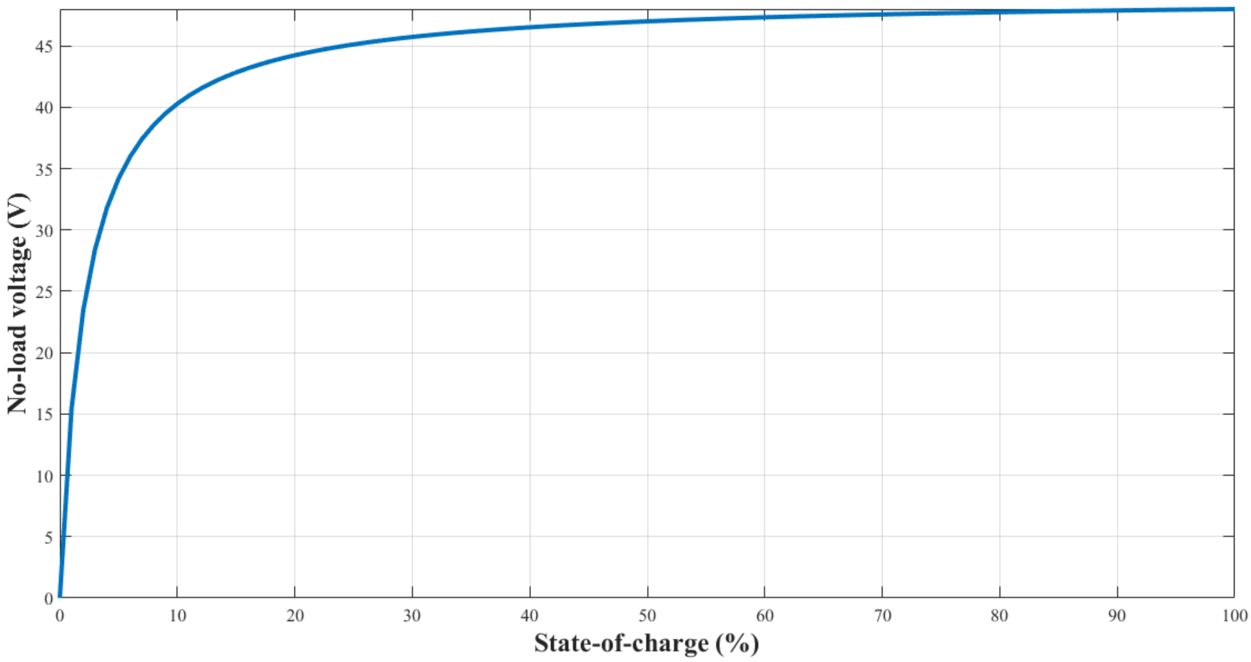

Figure 3.13: Battery voltage characteristic

3.3.7 Clutch:

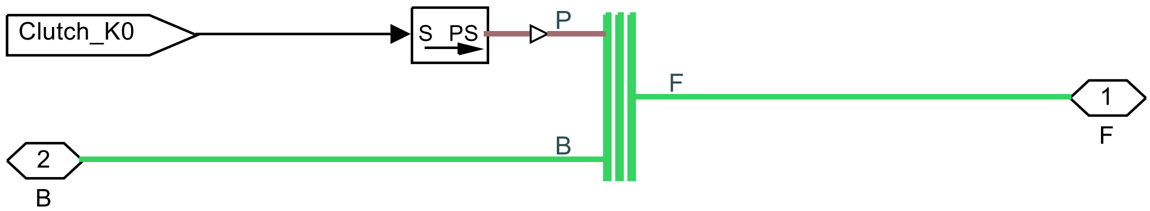

Figure 3.14: Clutch block

The clutch K0 has the function of decoupling the engine from the rest of the powertrain when the engine is not in use to limit loses. The clutch is modelled using a disk friction clutch model. The torque transmitted by the clutch is calculated with the following equation:

$$T = kNr_{eff}PA$$

Where:

- T is the torque transmitted by the clutch
- k is the friction coefficient, which varies from the static friction coefficient k_S when the relative speed between the two plates is null, to the dynamic friction coefficient k_D.if the slip is not null, with $k_S > k_D$
- N is the number of friction surfaces
- r_{eff} is the effective torque radius
- P is the applied pressure at the clutch
- A is the area of the friction surfaces

3.3.8 Torque converter:

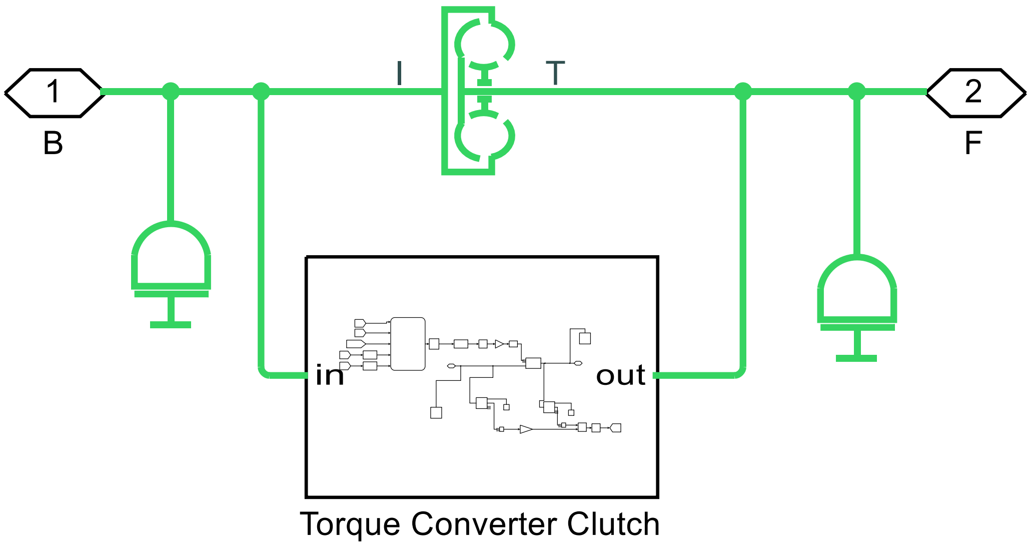

Figure 3.15: Torque converter

The torque converter has the function of decoupling the engine and motors from the transmission during cranking and gear change to avoid the engine turning off or excessive vibrations. The torque converter is formed of two parts:

- The impeller I from the engine side
- The turbine T from the transmission side

The torque converter was modelled using the following characteristic:

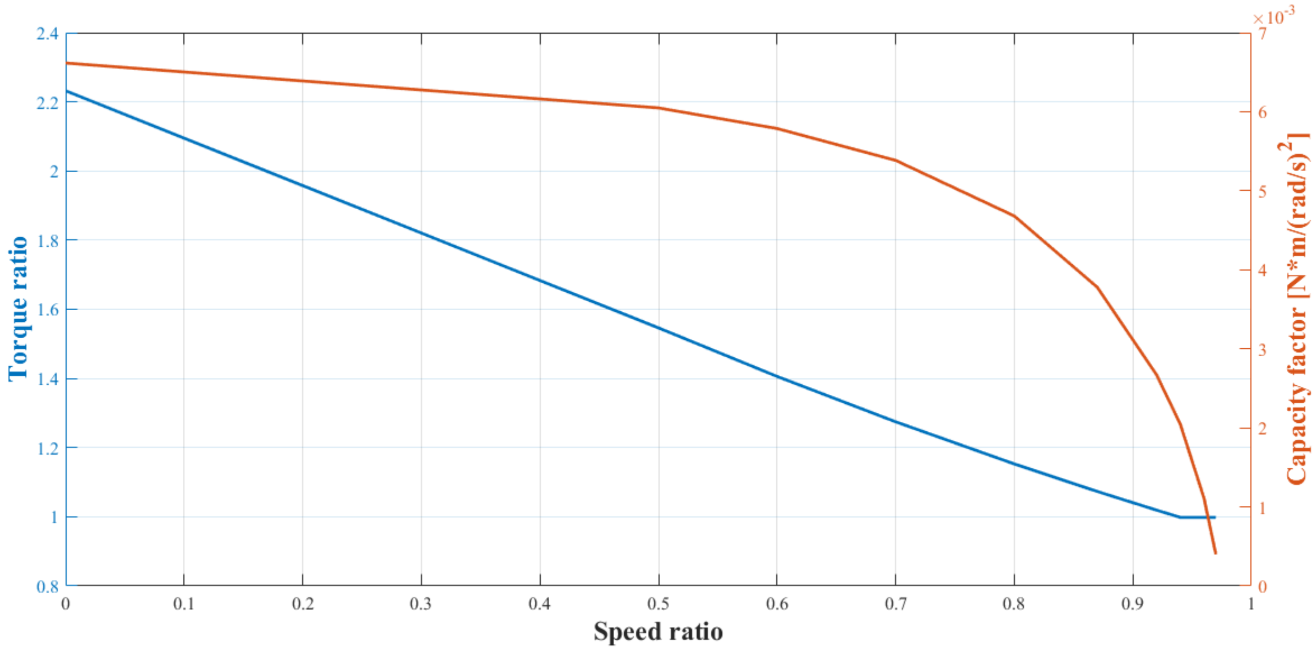

Figure 3.16: Torque converter characteristic

Where:

- The speed ratio $R_\omega = \omega_T/\omega_I$ with ω_T the turbine angular speed and ω_I the impeller angular speed
- The torque ratio $R_T = T_T/T_I$ with T_T the turbine torque and T_I the impeller torque
- The capacity factor $K = T_I/\omega_I^2$. The capacity factor is a measure of the torque converter capacity to transmit or absorb torque.

By using the R_ω as the independent variable, the torque can be determined using the characteristic and the following equations:

$$T_I = K(R_\omega).\omega_I^2$$

$$T_T = T_I.R_T(R_\omega)$$

The torque converter also includes a clutch with the following functions:

1. Allowing braking energy regeneration: since the torque converter only allows power transfer in one direction, some other coupling method is necessary to transfer the kinetic energy from the wheels to the electric motors to allow it to be recovered
2. Reducing losses: the torque converter transfers power using a fluid that permeates the turbine and impeller. This causes viscous losses and reduces the efficiency. When the speed ratio R_ω is close to one and therefore no decoupling is needed, the clutch closes to allow a one to one ratio and greater efficiency

The same model used for the K0 clutch was used for the torque converter clutch.

3.3.9 Transmission:

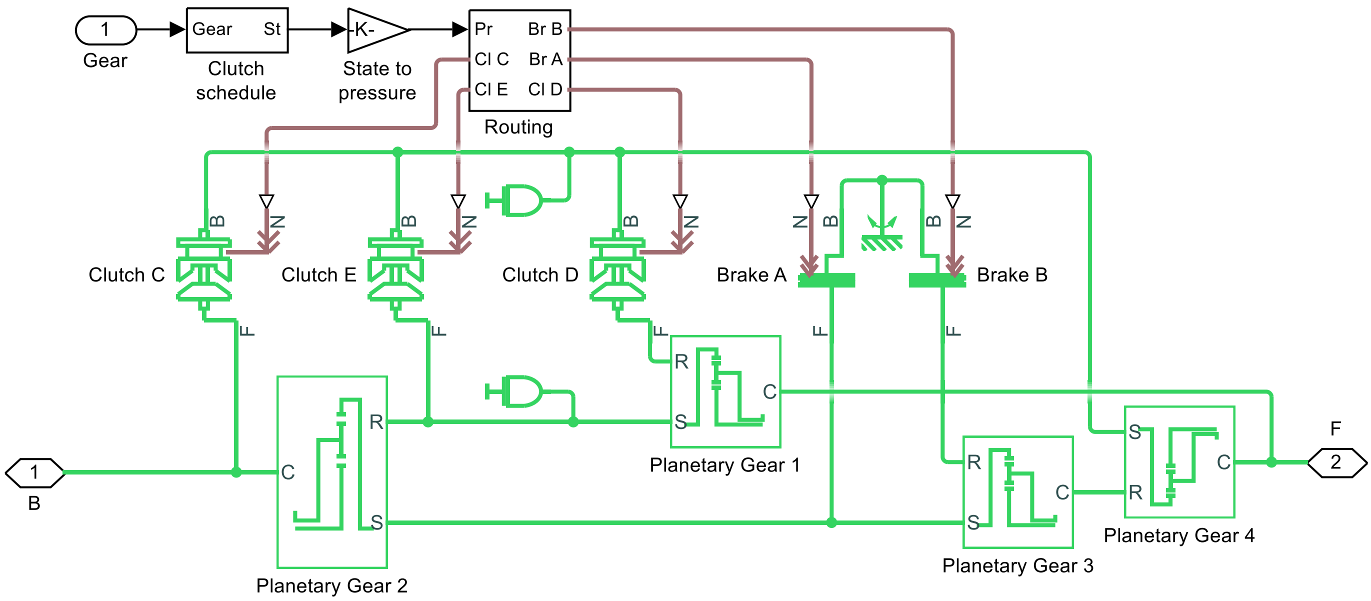

Figure 3.17: 8 speed gearbox

To model the 8-speed automatic transmission a set of planetary gears and clutches were used. By engaging and disengaging certain clutches, it is possible to block or free certain gears as well as couple different planetary sets, thus varying the transmission ratio. A constant efficiency has been considered for the entire gearbox.

The gear changes as a function of speed following the map shown in figure 3.18:

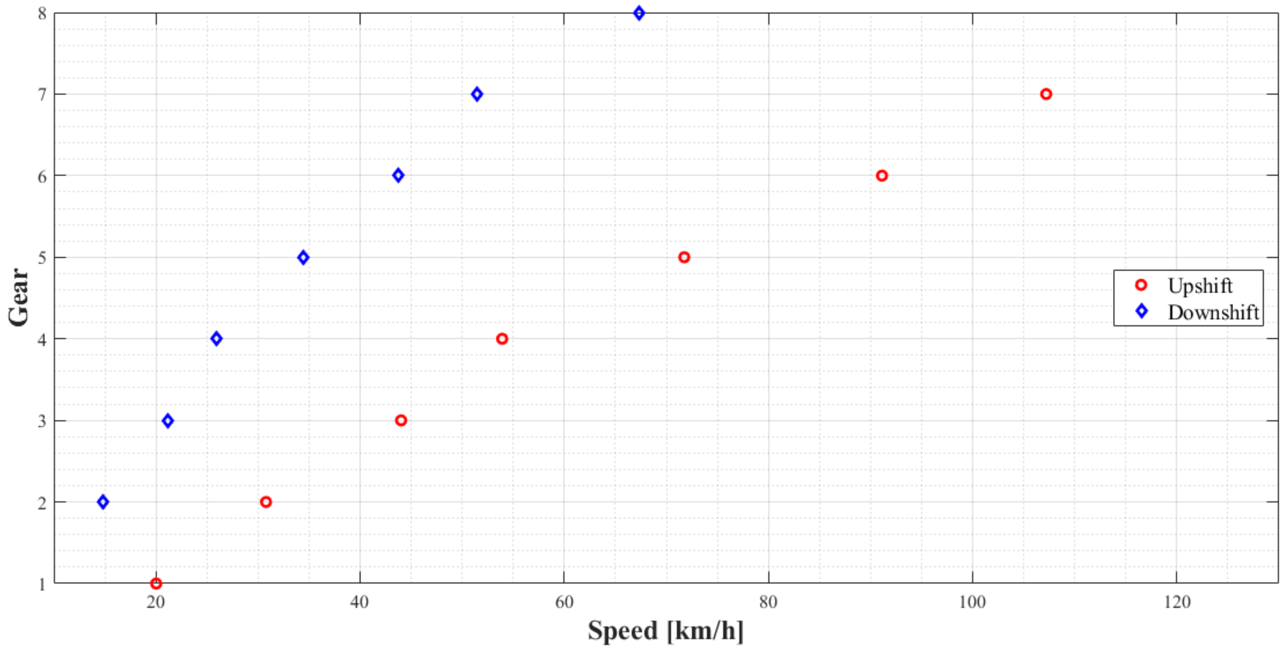

Figure 3.18: Gear shift map

Once the speed reaches a red dot, the gear shifts up, and once it reaches a blue dot, the gear shifts down.

3.3.10 Differential:

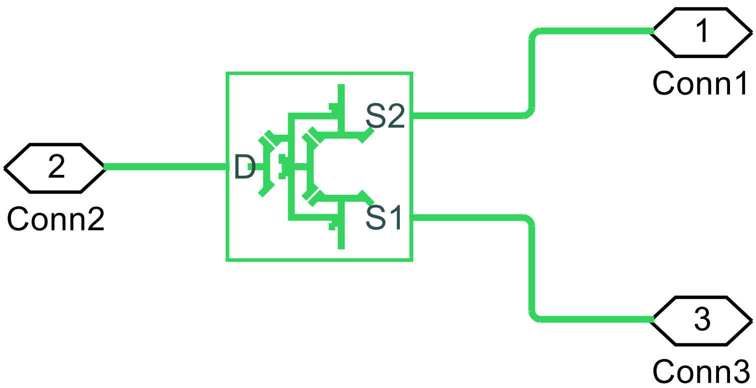

Figure 3.19: Differential block

The differential has the function of transmitting power from the powertrain to the wheels. It also lets the wheels spin at different speeds, which is necessary to allow the vehicle to turn. The differential block includes a constant transmission ratio which represents the final drive ratio.

Chapter 4

Results and HIL implementation

4.1 Results

In the following section the results of the simulations will be presented and later a comparison between the forward model results and the backward model results will be made.

4.1.1 Forward model results:

After assembling the forward model, the model was tested on the NEDC cycle and the WLTC cycle. Figure 4.1 and figure 4.2 show the speed profile on these two cycles.

As evident, the vehicle is able to follow the speed profiles in a satisfactory manner, which indicates that the PI has been tuned properly enough.

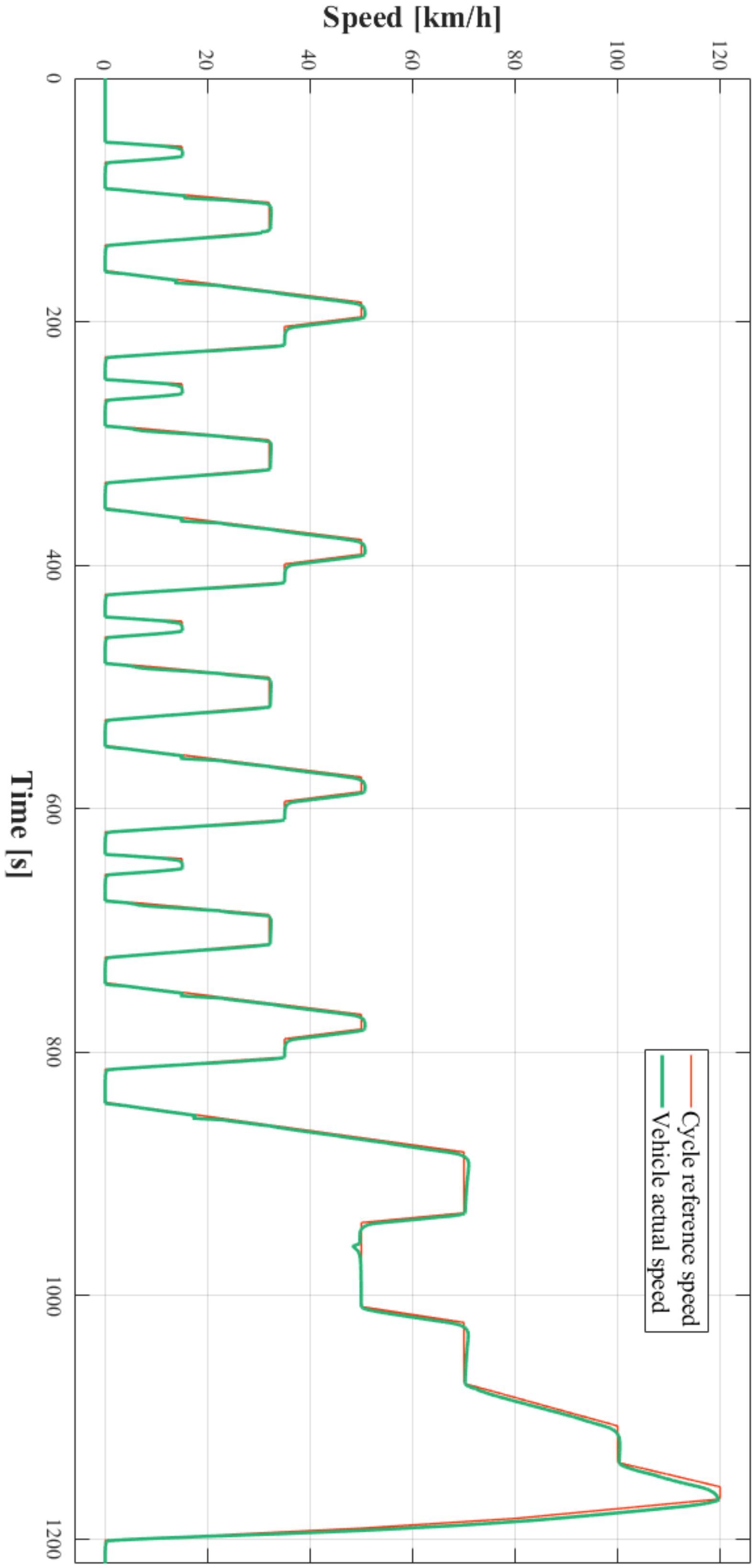

Figure 4. 1: Vehicle speed vs Cycle speed: NEDC

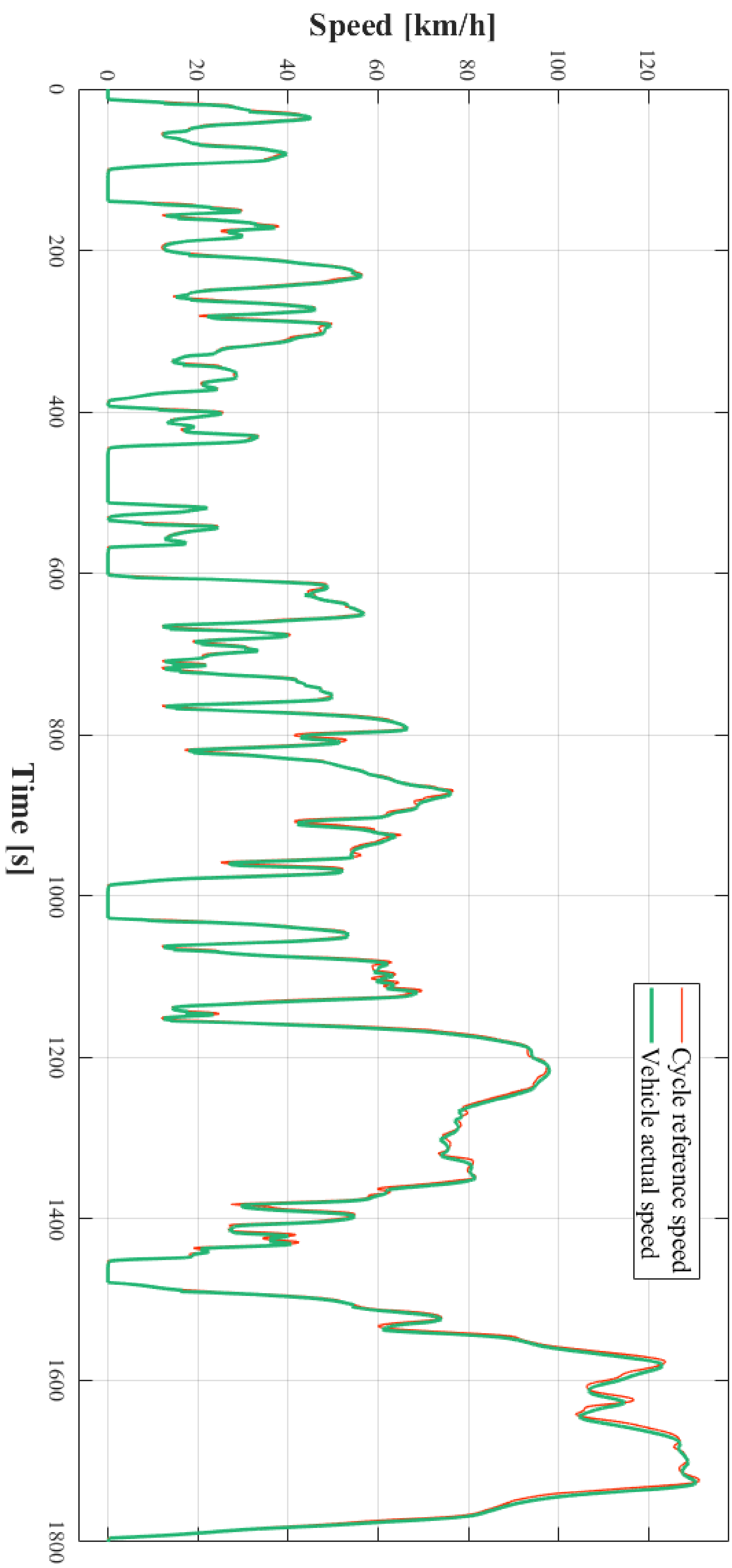

Figure 4. 2: Vehicle speed vs Cycle speed: WLTP

4.1.2 Forward and backward model comparison:

In the next tables will compare the results obtained in the backward model with the results obtained in the forward model with regard to fuel consumption and emissions:

NDEC			
Configuration	Parameters	Backward	Forward
Baseline	Fuel consumption [l]	0.816	0.796
	Fuel consumption [l/100km]	7.46	7.29
	CO_2 emission [gCO_2/km]	197	193
P2P0 15 kW	Fuel consumption [l]	0.756	0.735
	Fuel consumption, [l/100km]	6.916	6.73
	CO_2 emission [gCO_2/km]	183	178
Fuel consumption reduction [%]		-7.35%	-7.68%
CO_2 emission reduction [gCO_2/km]		14	15

Table 4.1: Result comparison between backward and forward model-NEDC

WLTP			
Configuration	Parameters	Backward	Forward
Baseline	Fuel consumption [l]	5.47	5.25
	Fuel consumption, [l/100km]	7.83	7.53
	CO_2 emission [gCO_2/km]	207	199
P2P0 15 kW	Fuel consumption [l]	5.09	4.58
	Fuel consumption, [l/100km]	7.3	6.96
	CO_2 emission [gCO_2/km]	193	184
Fuel consumption reduction, [%]		-6.95%	-7.57%
CO_2 emission reduction [gCO_2/km]		14	15

Table 4.2: Result comparison between backward and forward model-WLTP

As evident, the results are quite similar, with the forward model results being smaller than the backward facing model. That is because while in the backward model the speed of the cycle is considered to be exactly the speed of the vehicle, and from there power and therefore fuel consumption are calculated, in the forward model the speed of the vehicle may differ from that of the cycle. In particular, while at steady speed the forward model speed mostly matches that of the cycle, the forward model differs during speed variation and lags behind. Therefore, in the NEDC cycle where big part of the speed profile is constant as shown in figure 4.1, the results are closer than in the WLTC cycle where the profile presents a lot more variation as shown in figure 4.2.

Overall the results are close enough and the forward model is validated. In addition, the 7-8% fuel consumption reduction indicates that there's good potential in this P0 P2 configuration and better results can be obtained with a more developed control strategy.

4.2 Hardware in the loop simulation:

4.2.1 Definition:

Hardware in loop HIL simulation is a technique used in testing of control systems [7]. It consists in running the control algorithm on an embedded controller while simulating part or the entire model of the controlled system on a real time machine. The controller acts and operates in the same conditions as if it was running on the actual real system.

The HIL simulation can present several benefits and is usually carried out for the following reasons:

1. Increase safety: Testing using a simulated model instead of a real one allows to perform tests in conditions that could be dangerous to people or the machine. For example, simulating failure or testing the controller behavior outside normal range of operation.
2. Enhance quality: Using the HIL approach the controller can be tested extensively to uncover bugs and potential problems in the code thus enhancing the quality of the controller even at early stages of development. In addition, the testing process can be automated to run every time a change is made to the controller.
3. Save time: with HIL simulation, the controller can be tested even at the early stages of development even before the machine has been built thus allowing to save time.

In addition, modifications to the controller can be implemented rather quickly and effortlessly allowing a faster workflow.

4. Save money: Testing on a real machine or prototypes can be very expensive, especially when testing for safety features or testing at out of normal operation range conditions which can damage the machine. HIL simulation allow to save money by allowing to run tests without the need of a machine. In addition, modifications at late stages of development can be very expensive and time wasting. By HIL testing at early stages, a lot of time and money can be saved.

4.2.1 Implementation:

In our case, the hardware in the loop simulation aimed at testing the controller time response while connected with the mean of a CAN bus to the real time machine running the plant model.

C++ code was generated from the controller shown in section 3.2. After some software in the loop testing where the code generated was compiled and run to test for bugs and errors, the control algorithm was transferred to a New Eagle Raptor controller.

Similarly, the plant model was first readied for real time execution, where small modifications were made to the blocks parameters to make sure the plant could run on a fixed time step. After testing the plant on a fixed time step and choosing the best solver configuration and parameters, the plant was then transferred to the dSpace Microlabbox real time machine. Figure 4.3 shows the described setup:

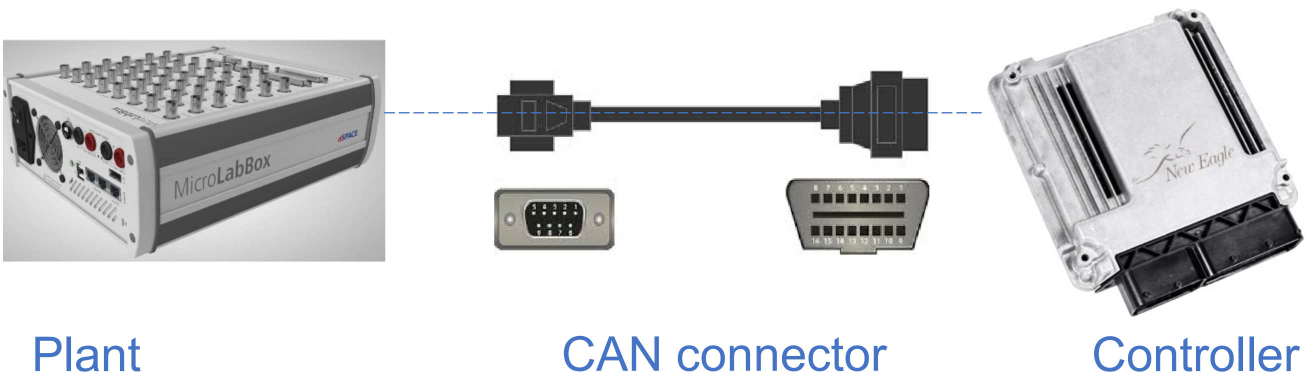

Figure 4.3: Hardware in the loop implementation

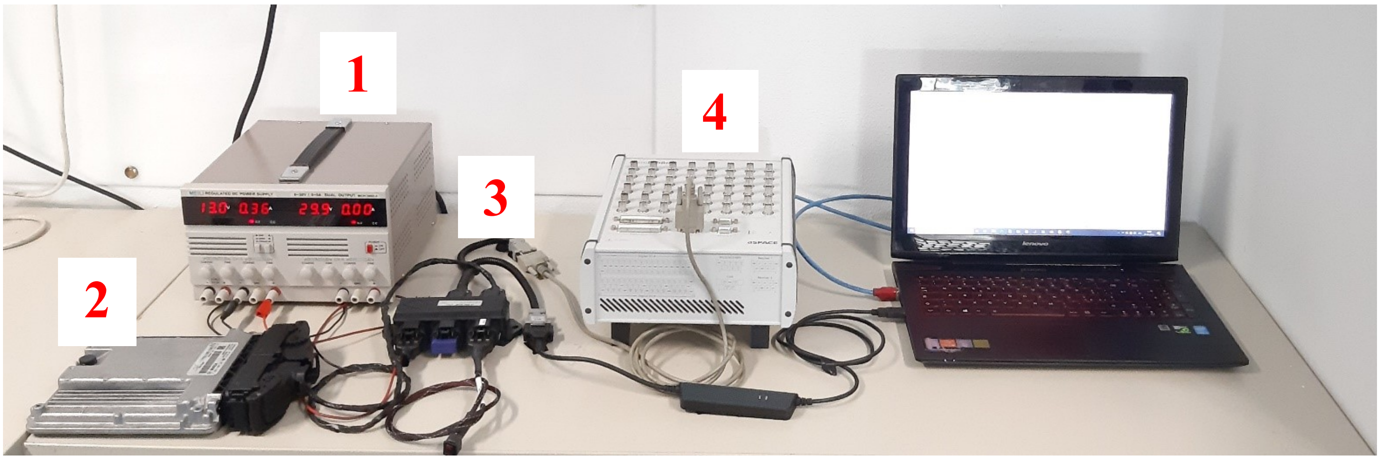

Figure 4.4: Hardware int the loop physical setup

Figure 4.4 shows a picture of the actual physical setup. The components shown in the picture are as follows:

1. Power supply
2. Raptor control unit
3. CAN Bus
4. dSpace Microlabbox

The results were shown and recorded on the adjacent PC.

4.2.2 Results

After the setup has been completed the test was started and the controller was given the duty of driving and managing the vehicle. During the test the results and signal exchanged were monitored on the nearby PC to check for possible anomalies and faults. Figure 4.5 shows an example of such results.

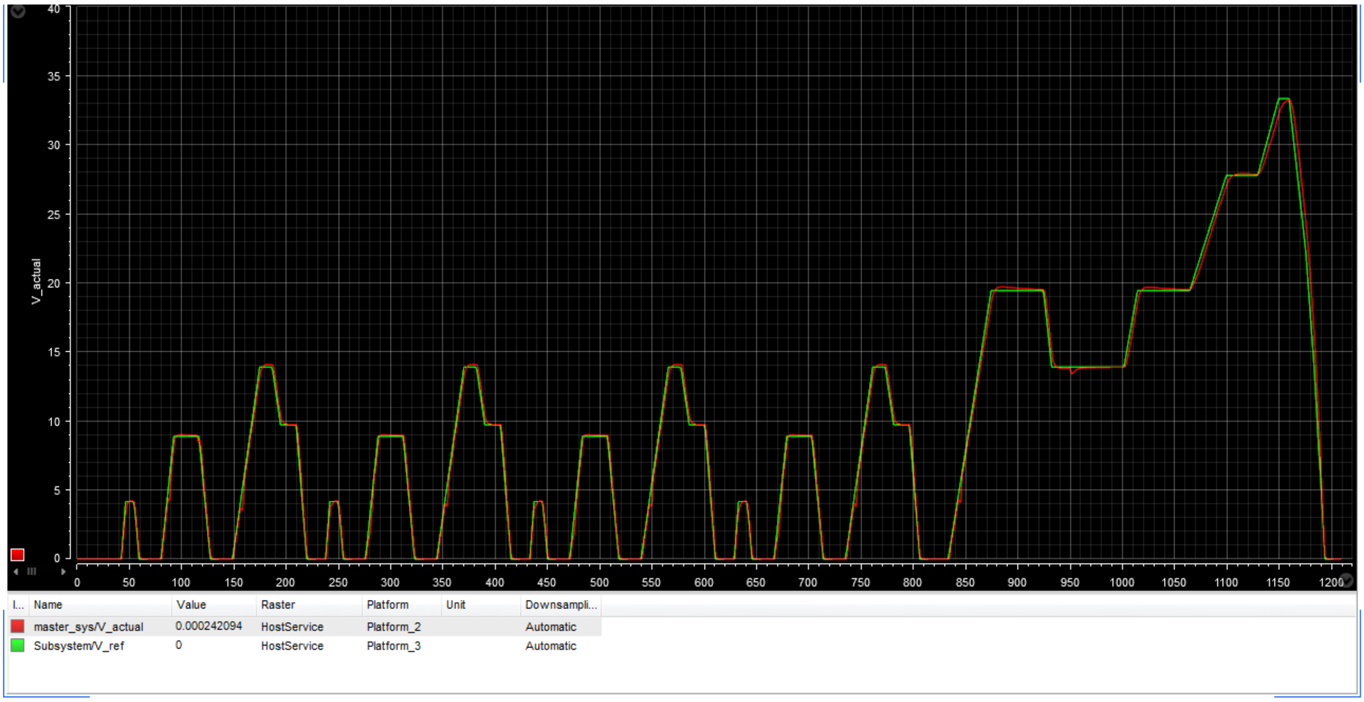

Figure 4.5: HIL speed profile

The figure shows the actual speed profile of the vehicle and the desired speed profile from the NEDC cycle. As shown the vehicle was able to follow closely the desired speed and the results matches the profile in figure 4.1, which means that the controller was able to complete all processes in the fixed time step of 10 ms and the test a success.

4.3 Future prospect

The following next steps will be taken to further this research activity:

- Developing a better control strategy centered around minimizing emissions as much as possible and increasing possible functionalities, such as on demand electric only drive and boosting.
- Considering different architectures and studying their cost to efficiency ratio, for example a on axis or off axis P2 configuration, configurations with bigger batteries, etc.

- Validating the developed model on a test bench. Using the physical model will provide a better understanding of the limits and dynamics of a real-world system allowing a better tuning of the controller.
- Performing vehicle tests. This is considered to be the final step in the development of the control strategy and will encompass all possible factors that could come into play.

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