Benchmarking of Regenerative Braking for a Fully Electric Car

B. J. Varocky
Report No. D&C 2011.002

January 2011

Internship Report

Supervisors:
Prof. dr. Henk Nijmeijer (TU/e)
Sven Jansen M.Sc (TNO)

Coaches:
Dr. Ir. Igo Besselink (TU/e)
Remco Mansvelders M.Sc (TNO)

TNO Automotive, Helmond
Integrated Safety Department

Eindhoven University of Technology
Department of Mechanical Engineering
Automotive Technology Master track

Abstract

Short range of electric vehicles is one of the stumbling blocks in the way of electric cars to gaining wide user acceptance and becoming a major market player. The possibility to recover vehicle energy otherwise lost as heat during braking is an inherent advantage of a hybrid electric or a fully electric vehicle. Regeneration has the potential to answer this problem by aiding in range extension with recuperation of vehicle energy during braking. The control and dynamics of braking undergoes a major change as compared to a conventional vehicle with friction braking, due to the addition of motor-generator. In this research two regenerative braking concepts namely serial and parallel have been studied and implemented on an electric vehicle. Also a point of interest is to find if any additional states are required from the TNO Vehicle state estimator (VSE) which would aid in regeneration. From the results obtained we try to draw a conclusion on the difference in energy recuperation level in the two strategies with consistent pedal feel in mind. The proposed brake torque distribution strategy has been tested through the simulation on the New European Driving Cycle (NEDC) drive cycle and straight line braking scenario. Care has been taken to observe and adjust brake torque such that wheel lock up is prevented and hence regeneration is un-interrupted. The research couldn't come with any additional parameters to be added to VSE. However, it would be worthwhile to employ VSE to achieve a more accurate estimation of the braking force, which may aid in prolonging regeneration time and hence more energy recuperation. The results provide a good case to invest more time and money into developing serial regenerative braking as it clearly out-performs parallel regenerative braking strategy. The simulation tests conducted in this research are for a longitudinal braking scenario. Further investigation is required to study effects with lateral motion and cornering maneuvers.

Table of Contents

List of Figures

Acknowledgements

I would like to thank my supervisor Prof. dr. Henk Nijmeijer for the allowing me to do my internship at TNO. And also for guiding me in the right direction by giving feedback on the progress of my work and the report. Dr. ir. Igo Besselink for extending the opportunity to work on the topic of benchmarking of regenerative braking systems for a fully electric vehicle at TNO.I would like to thank my supervisor at TNO, Mr. Sven Jansen for the support and cooperation. My deepest gratitude towards my coach Mr. Remco Mansvelders for his encouraging, patient, consistent and tireless support for the completion of the internship. The experience at TNO have taught me very well the approach and methodology to be applied in solving a problem successfully. Glad to say that the experience of working in TNO has been thoroughly satisfying and pleasant. The atmosphere and attitude of colleagues are worth mentioning and would recommend as good start especially for any new graduate to nourish and develop. Lastly but not the least I would like to thank my friends for their support and help in overcoming tricky problems.

Eindhoven, University of Technology
January 5, 2011

Bobby Johny Varocky

Chapter 1

Introduction

1-1 Motivation

As the global economy strives towards clean energy in the face of climate change, the automotive industry is researching into improving the efficiency of automobiles. Electric vehicles Electric Vehicle (EV) are an answer to the crisis the world is about to face in the near future. But the question that is being constantly asked is, How can the driving range of electric vehicles be increased?

The answer to this question lies in the success of the research for an efficient and power packed energy source like a magic battery or success with fuel cells, efficient regenerative braking systems etc. In conventional braking system, kinetic and potential energy of a vehicle is converted into thermal energy (heat) through the action of friction. Studies show that in urban driving about one-third to one-half of the energy required for operation of a vehicle is consumed in braking. With regenerative braking, this kinetic energy can be converted back into electrical energy that can be stored in batteries for reuse to propel the vehicle during the driving cycle [2]. Therefore, regenerative braking has the potential to conserve energy which will improve fuel economy while reducing emissions that contribute to air pollution.

1-2 Aim of the project

In this project two regenerative braking concepts have to be studied in order to find an optimal way to combine a regenerative braking with a conventional frictional braking system to achieve maximal energy recuperation.

Generally, the regenerative braking torque cannot be made large enough to provide all the required braking torque of the vehicle to ensure vehicle stability. In addition, the regenerative braking system may not be used under many conditions, such as with high state of charge State of Charge (SOC) or high temperature of the battery.

In this HTAS Powertrain-EVT project, benchmarking of various regenerative braking concepts will be performed. Additionally, an integration of TNO's Vehicle state estimator (VSE) with the regenerative braking system will be made to study if it can improve the amount of energy recuperation. The VSE is capable of estimating tyre slip, slip angles and various other parameters which are otherwise difficult to measure. Further improvements to VSE with regard to improving regeneration would be studied in this project.

1-3 Current status

Conventional regenerative braking systems can be serial and parallel. In the parallel strategy the regenerative braking is always active and extends the total braking power depending on the brake pedal position. The parallel braking system in which the friction-based system and the regenerative braking system are operated in tandem, without integrated control which means that neither the friction braking nor the regenerative braking force can be adjusted easily. The serial braking system contains an integrated control which estimates the deceleration required by the driver and distributes the required braking force between the regenerative braking system and the mechanical braking system. Most strategies estimates wheel slip based on tyre friction curve or a simple tyre model. There are no standard procedures to indicate the regenerated energy to compare various regenerative braking strategies.

1-4 Outline of the report

The report consists of 5 chapters. Chapter 2 introduces the electric vehicle, the emergence and the advantages of using an electric motor driven automobile is listed. Further the two concepts of regenerative braking employed in this research is explained. Besides, the method for estimation of effectiveness of regenerative braking is explained. Lastly, the role of VSE in a car and how it can benefit regenerative braking is discussed.

Chapter 3 explains the modeling strategy used for electric vehicle modeling in Matlab/Simulink environment. The various subsystems modeled, equations and parameters used are described in this chapter.

Chapter 4, first section presents a case study of regenerative braking for a couple of deceleration cases. The aim is to determine the maximum deceleration possible with pure electric braking (regenerative) and hence highlight the limitation that pure electric braking cannot always produce the necessary brake torque desired. Second section shows the results of the simulation for various brake pedal inputs in a straight line braking scenario. Further the plots and regenerative ratios for driving and braking on the New European Driving Cycle (NEDC) driving cycle is shown.

Chapter 5 gives the conclusion and recommendations for future work.

Finally, in the appendix pictures of the overall simulation model and various subsystems as described in chapter 3 are included.

Chapter 2

Literature survey

2-1 Electric vehicle

Electric Vehicle (EV)'s enjoyed popularity between the mid-19th century and early 20th century, when electricity was among the preferred methods for automobile propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. The Internal combustion engine (ICE) is the dominant propulsion method for automobiles, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types. During the last few decades, increased concern over the environmental impact of the petroleum-based transportation infrastructure, along with the spectre of peak oil, has led to renewed interest in an electric transportation infrastructure. EV's differ from fossil fuel-powered vehicles in that the electricity they consume can be generated from a wide range of sources, including fossil fuels, nuclear power, and renewable sources such as tidal power, solar power, and wind power or any combination of those. The electricity may then be stored onboard the vehicle using a battery, flywheel, or supercapacitors. A key advantage of electric or hybrid electric vehicles is their ability to recover energy normally lost during braking known as regenerative braking. Also, quick and precise torque generation of the electric motor holds an important advantage with respect to the performance and drivability of an EV.

We can summarize the advantages of the EV into the following three points [3]:

1. Torque generation of an electric motor is very quick and accurate

   This is an essential advantage. The electric motor's torque response is several milliseconds, Viz. 10-100 times as fast as that of the internal combustion engine or hydraulic braking system. This enables fast responsive feedback control and hence we can change vehicle characteristics without any change in characteristics from the driver. Moreover, an Anti-lock braking systems (ABS) and Traction control system (TCS) can be integrated, because a motor can generate both acceleration or deceleration torques. A "Super Antilock Brake System (ABS)" will be possible. Also if we can use low-drag tires, it will greatly contribute to energy saving.

2. A motor can be attached to each wheel

   Small but powerful electric motors installed into each wheel can generate even the anti-directional torques on left and right wheels. Distributed motor location can enhance the performance of Vehicle Stability Control (VSC) such as Direct Yaw Control (DYC).

3. Motor torque can be measured easily

   There is much smaller uncertainty in driving or braking torque generated by an electrical motor, compared to that of an IC engine or hydraulic brake. It can be known from the motor current. Therefore, a simple 'driving force observer' can be designed and we can easily estimate the driving and braking force between tire and road surface in real time. This advantage will contribute greatly to application of new control strategies based on road condition estimation. For example, it would be possible to alert the driver with warnings like, "We have now entered a slippery surface!" in a more efficient and timely manner. Traction control becomes a much simpler problem to solve when you have precise and instant control over the motor torque.

Some of the disadvantages of an electric motor for cars include high initial cost and complicated motor speed controllers. However, the advantages of the electric motor will open new possibility for novel vehicle motion control for electric vehicles.

2-2 Regenerative braking

Regenerative braking allows electric vehicles to use the motor as a generator when the brakes are applied, to pump vehicle energy from the brakes into an energy storage device. Regenerative braking is an effective approach to extend the driving range of EV and can save from 8% to as much as 25% of the total energy used by the vehicle, depending on the driving cycle and how it was driven [4]. Generally, the regenerative braking torque cannot be made large enough to provide all the required braking torque of the vehicle. In addition, the regenerative braking system may not be used under many conditions, such as with a high state of charge State of Charge (SOC) or a high temperature of the battery. In these cases, the conventional hydraulic braking system works to cover the required total braking torque. Thus, cooperation between the hydraulic braking system and the regenerative braking system is a main part of the design of the EV braking control strategy and is known as torque blending. This torque blending strategy helps to avoid the driveline disturbances [5].

The two broad classifications of regenerative braking control strategies are as depicted in the (figure: 2-1). The yellow region represents regenerative braking and region in red represents friction braking. The small yellow portion at the bottom which reads compression regen refers to regeneration when accelerator pedal is released and the car coasts in the absence of brake pedal input. Service regen region represents regeneration when brake pedal is applied and it goes into the red region, when the maximum capacity of generator torque is reached in the case of serial strategy and simultaneous friction braking activation for parallel strategy.

2-2-1 Serial regenerative braking

Serial regenerative braking is based on a combination of friction-based adjustable braking system with a regenerative braking system that transfers energy to the electric motors and batteries under an integrated control strategy (see figure: 2-1). The overall design is to estimate the deceleration required by the driver and distribute the required braking force between the regenerative braking system and the mechanical braking system [2]. Serial regenerative braking could give an increase of 15-30% in fuel efficiency. It requires a brake-by-wire system and has more consistent pedal feel due to good torque blending capability.

2-2-2 Parallel regenerative braking

Parallel braking system is based on a combination of friction-based system and the regenerative braking system, operated in tandem without an integrated control. The regenerative braking force is added to the mechanical braking force which cannot be adjusted. The regenerative braking force is increasing with the mechanical braking force (see figure : 2-1). The beginning pedal travel is used to control the regenerative braking force only, the normal mechanical braking force is not changed. The regenerative torque is determined by considering the motor capacity, battery state of charge SOC, and vehicle velocity. The regenerative braking force is calculated from the brake control unit by comparing the demanded brake torque and the motor torque available. The wheel pressure is reduced by the amount of the regenerative braking force and that supplied from the hydraulic brake module [2]. Parallel regenerative braking could give an increase of 9-18% in fuel efficiency. It can be added onto a conventional braking systems. However it could compromise the pedal feel and hence requires more work in achieving good torque blending.

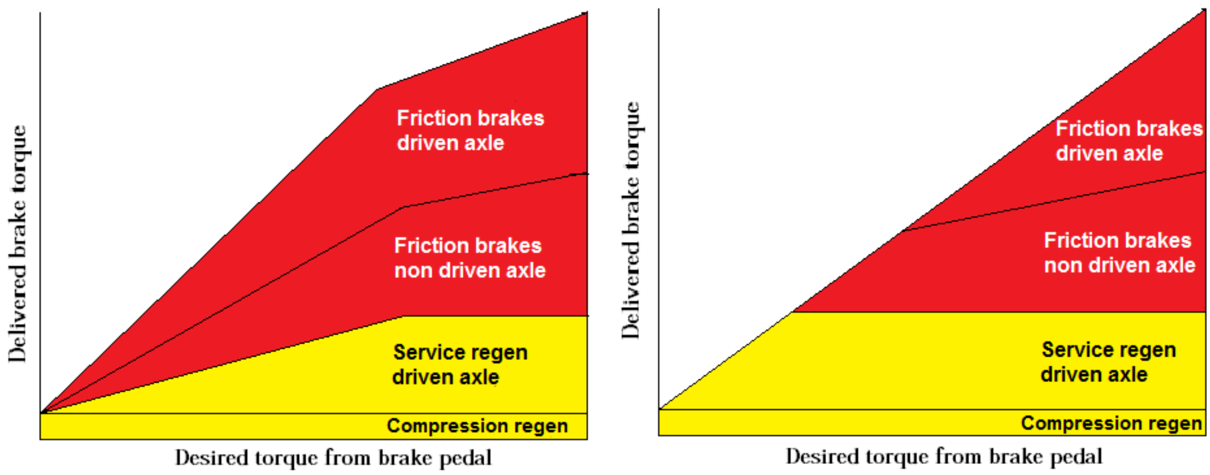

Figure 2-1: Parallel and Serial regenerative braking control respectively

2-3 Energy balance

Within the bounds of the present research the question of qualitative evaluation of regenerative power during electric vehicle braking is of fundamental importance. Estimation of recovered energy is very important at the design stage since it helps to find out which scheme is more effective for a particular type of vehicle. An indication of effectiveness of regenerative braking for various regenerative strategies is estimated by the following method [6].

- Regenerative ratio

  In the braking process on a flat road, the vehicle's kinetic energy and regenerative electrical energy are calculated by the following [5]:

$$\epsilon = \frac{\sum E_{bat}}{\sum E_{kin}} \tag{2-1}$$

with,

$$\text{Kinetic energy}, E_{kin} = \sum \frac{1}{2} m \left(V_2^2 - V_1^2 \right) \tag{2-2}$$

$$\text{Electrical energy}, E_{bat} = \int_{t=0}^{t=end} \left(E_k - I(t)R(t) \right) I(t) dt \tag{2-3}$$

where,

E_k is the battery voltage, $I(t)$ is the battery current, $R(t)$ is the charging resistance, V_1 is the initial velocity, V_2 is the final velocity

In order to improve the effectiveness of regeneration, it is preferable that the majority of braking at high speeds be regenerative. The reasoning behind this strategy is that higher generator torque is necessary for braking at higher speeds, which conveniently allows for higher battery charging efficiencies. At lower speeds, relatively little current is being produced by the generator to ensure desirable battery recharge efficiencies. Therefore, at these speeds, the frictional brakes are applied to decrease electrical cycling through the generator and batteries. It has been implied in the literature that the life of the electrical system, especially the batteries, is adversely effected by this 'micro-cycling' process where the battery pack is subjected to short-term charge and discharge cycles, thereby reducing life and efficiency. [7].

2-4 Vehicle state estimator (VSE)

For effective braking and optimal regeneration, it is important to estimate the maximum braking force that could be applied without leading to a wheel lock situation. A dynamic vehicle state estimation using VSE has the potential to estimate that maximum permissible limit of braking force, the peak value (figure: 2-3) that could be applied without wheel lock.

This is where a VSE could score better than traditional braking strategies where a brake force distribution curve is followed to ensure vehicle stability during braking. Using VSE we will

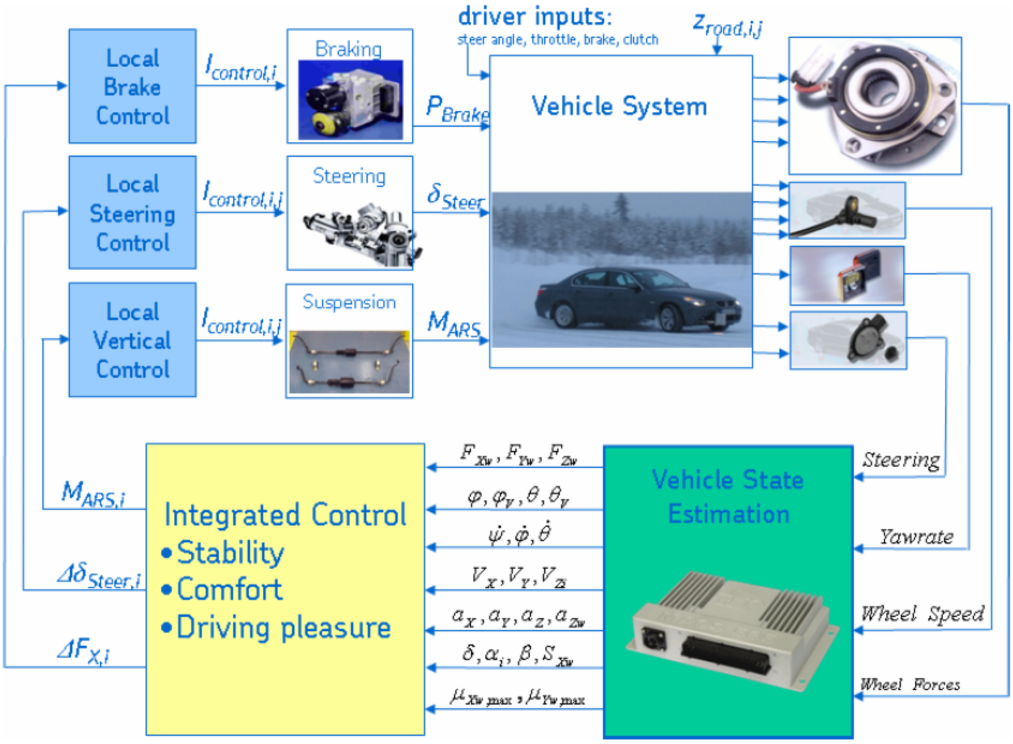

Figure 2-2: Vehicle dynamics control system [1]

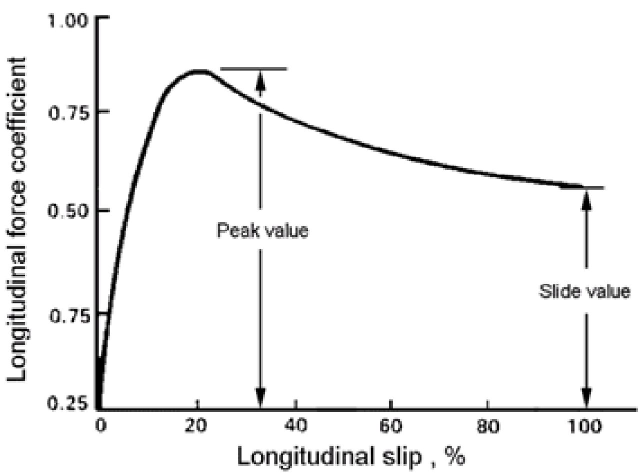

Figure 2-3: tyre-road friction v/s slip curve

be able to push that limit to the last bit and hence achieve regeneration for longer time. The vehicle state estimator VSE helps in determining those parameters that are otherwise difficult to measure like the body slip angle β, road friction coefficient μ, longitudinal velocity V_x etc. These are estimated based on the signals from the various sensors used in modern cars like the wheel speed sensor, yaw rate sensor, steering angle input etc. Using these parameters,

we can easily calculate tire braking force F_x using (4-10), wheel slip k using (4-11), normal force on tire F_z using (4-12). Hence determine accurately the brake force distribution for optimal energy recuperation while maintaining vehicle stability.
From this research it is understood that no additional state(s) needs to be included in the VSE from an optimal regeneration point of view. Having said that, application of VSE alongwith the high torque response of the electric motor (refer section 2-1) may be advantageously used to delay the action of other vehicle stability systems available in the market now like ESP, ABS etc, but within the safety limits and hence aiding in optimal energy recuperation.

Chapter 3

Electric Vehicle Modeling

The modeling of the electric vehicle has been done in Matlab/Simulink. The driver block makes a torque request which propagates through various powertrain components and realizes vehicle motion.

System-level simulators have been modeled using empirical data that are based on measurements supplied by component manufacturers or extended from measurements obtained from literature sources. These are modeled in Simulink as Look-up tables. Other component models are physical or analytical in nature and are modeled using mathematical equations.

The electric vehicle modeled weighs about 1325 $[kg]$ inclusive of battery (figure 3-1). Vehicle has a frontal area of 2.57 $[m^2]$ with a drag coefficient of 0.26 $[-]$ and rolling resistance of 0.008 $[-]$. The values assigned are based on a rough estimate of a mid-sized car. The electric motor chosen is a Permanent magnet synchronous machine (PMSM) with peak power of 40 $[kW]$. The battery pack comprises of 19 modules of Li-Ion battery. It has a nominal voltage of 213 $[V]$, with energy content of 1.57 $[kWh]$ and weighs around 22 $[kg]$. The battery pack is modeled so as to run just an instance of New European Driving Cycle (NEDC) i.e., about 11 $[km]$ in the State of Charge (SOC) range of maximum 80% and minimum of 30%.

3-1 Driver subsystem

The driver block delivers the desired drive torque and the desired brake torque upon the activation of accelerator and brake pedal respectively. If the driver wishes to accelerate the vehicle, he depresses the accelerator. Depending on the amount of depression of the accelerator pedal, a corresponding driver torque request is sent to the vehicle through various powertrain systems like the battery and motor model. The regeneration starts only when the brake pedal is pressed. Once the brake pedal is depressed and depending on the position of the brake pedal a corresponding proportion of brake torque is applied. Now this brake torque depending on the regenerative brake control strategy is divided between regenerative braking and friction braking.

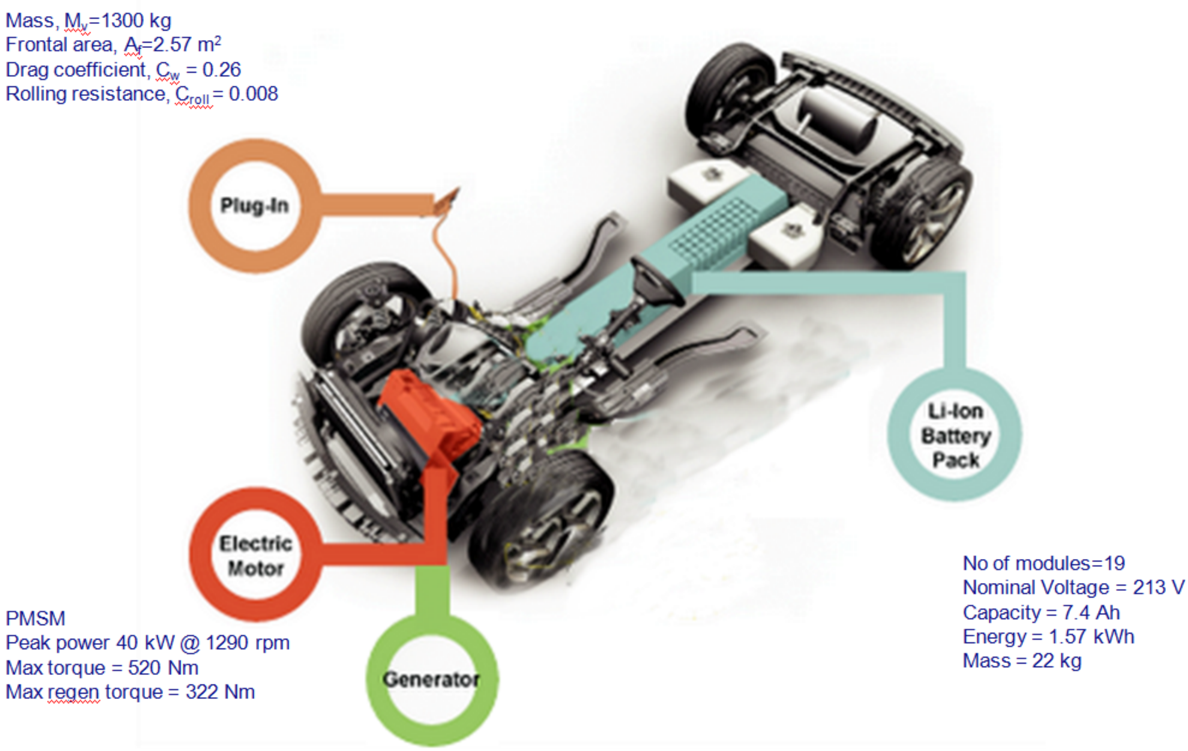

Figure 3-1: Electric car specs

In order to test the vehicle on various driving cycles, this driver block is replaced by another, which calculates the required drive/brake torque depending on the velocity profile. From the velocity of the profile of driving cycle and the following equations, we determine the power required to overcome various vehicle energy losses and hence propel the vehicle at the desired speed.
In Europe, the Urban driving cycle (ECE) consists of three start-and-stop maneuvers as seen in figure 3-2. The combined cycle, i.e., the NEDC repeats the ECE four times (the first with a cold start) and adds an Extra Urban driving cycle (EUDC).

The amount of mechanical energy consumed by a vehicle when driving a pre-specified driving pattern mainly depends on three effects:

- the aerodynamic friction losses
- the rolling friction losses
- the energy dissipated in the brakes.

The elementary equation that describes the longitudinal dynamics of a road vehicle has the following form

$$m_v \frac{dv(t)}{dt} = F_t(t) - (F_a(t) + F_r(t) + F_g(t)) \tag{3-1}$$

Characteristics	Unit	ECE 15	EUDC
Distance	km	4x1.013=4.052	6.955
Duration	s	4x195=780	400
Average speed	km/h	18.7(idling)	62.6
Maximum speed	km/h	50	120

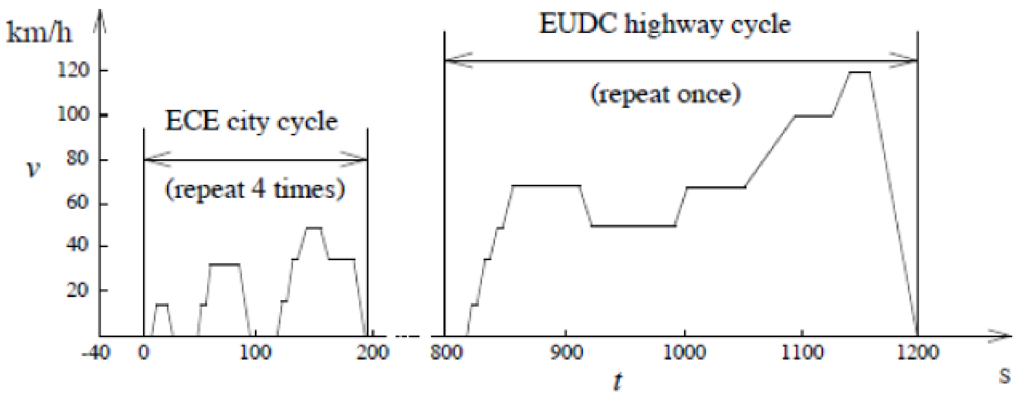

Figure 3-2: European test cycle - NEDC

where
m_v is the vehicle mass $[kg]$,
v is the vehicle speed $[m/s^2]$,
F_a is the aerodynamic friction $[N]$,
F_r is the rolling friction $[N]$,
F_g is the force caused by gravity when driving on non-horizontal roads $[N]$

The traction force F_t is the force generated by the prime mover minus the force that is used to accelerate the rotating parts inside the vehicle and minus all friction losses in the powertrain.

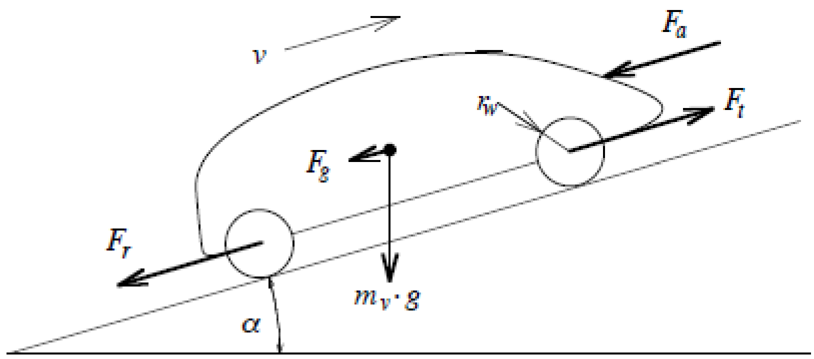

Figure 3-3: Schematic representation of the forces acting on a vehicle in motion

- **Aerodynamic friction losses**

  Usually, the aerodynamic resistance force F_a is approximated by simplifying the vehicle to be a prismatic body with a frontal area A_f . The force caused by the stagnation pressure is multiplied by an aerodynamic drag coefficient c_d that models the actual flow conditions

$$F_a(v) = \frac{1}{2}\rho_a A_f C_d v^2 \tag{3-2}$$

  Here, v is the vehicle speed $[m/s^2]$and ρ_a the density of the ambient air $[kg/m^3]$. The parameter C_d is the coefficient of drag estimated using Computational fluid dynamics (CFD) programs or experiments in wind tunnels. For the estimation of the mechanical energy required to drive a typical test cycle this parameter may be assumed to be constant.

  Rolling friction losses

- The rolling friction is modeled as

$$F_r = C_r m_v g cos(\alpha) \tag{3-3}$$

  where
  m_v is the vehicle mass $[kg]$,
  g is the acceleration due to gravity $[m/s^2]$,
  C_r is the rolling friction coefficient $[-]$ and
  α is the slope angle $[deg]$

  The rolling friction coefficient C_r depends on many variables. The most important influencing quantities are vehicle speed v, tire pressure p, and road surface conditions. For many applications, particularly when the vehicle speed remains moderate, the rolling friction coefficient C_r may be assumed to be constant.

  Uphill driving force

- The force induced by gravity when driving on a non-horizontal road is conservative and considerably influences the vehicle behavior. In this text this force will be modeled by the relationship

$$F_g = m_v g sin(\alpha) \tag{3-4}$$

3-2 Brake strategy subsystem

The required power and torque values are fed into this subsystem, which ensures the implementation of a braking strategy namely serial and parallel braking strategy. The division of braking torque between front and rear is split at a ratio of 70:30.

Implementation of serial braking strategy
Once the brake pedal is pressed and depending on the level of depression, a brake torque is sent. Now this brake torque passes into the brake control strategy block. Here, firstly it is checked if battery state-of-charge is below 80% which is set as the maximum permissible

level of charge. If that condition is satisfied, then the battery is recharged. The brake torque requested is compared to the maximum regenerative torque limit of the motor-generator. If the overall brake torque requested is less than or equal to the maximum regenerative torque, then the vehicle brakes purely on regenerative torque and the battery is charged. The amount of charge ultimately put in depends also on the motor-generator operation efficiency and the battery charging efficiency. If the overall brake torque requested is greater than what the motor-generator can provide, then the friction brakes kick-in. Now since the vehicle is front driven, it is checked if the total brake torque requested from front is less than or equal to maximum regenerative torque capability of motor-generator. If yes, then front braking is provided purely by regeneration and rear (non-driven axle) by friction. Once the total brake torque request increases further, then front friction brakes (driven axle) comes into play in combination with rear friction brakes and front regenerative braking, to satisfy the overall brake torque demand. This has been represented in a flow chart manner in the figure 3-4

Implementation of parallel braking strategy

Once the brake pedal is applied and a desired overall brake torque request is sent from the driver block. This brake torque on passing through the brake control strategy gets divided between regeneration and friction braking at all times. The strategy is so modeled with the comfort and brake pedal feel in mind. As a parallel regenerative braking is an add-on to the conventional systems, it is devoid of any integrated control. So to make the transition and co-performance of regenerative braking with friction smooth, it is assigned in such a way that, there is a clear division between the amount of brake torque that will be achieved from regeneration and friction braking. On application of brakes and in keeping with the design of the motor-generator, it is designed to operate generator in a constant generator torque region. Motor-generator can provide a maximum of 322 Nm of generator torque at or under the base speed. The generator is scaled such that the base speed of the generator corresponds to a velocity of 124 [kmph], which is the maximum speed limit on most highways. Hence regeneration works, as long as the vehicle is braking from a speed of under 124 [kmph] and the requested brake torque on the front driven wheels, after the front-rear brake split is greater than or equal to maximum generator torque. If that condition is satisfied, then regenerative and friction braking operates in tandem else it's just the friction brakes at the driven and non-driven axle. This has been represented in a flow chart manner in the figure 3-5

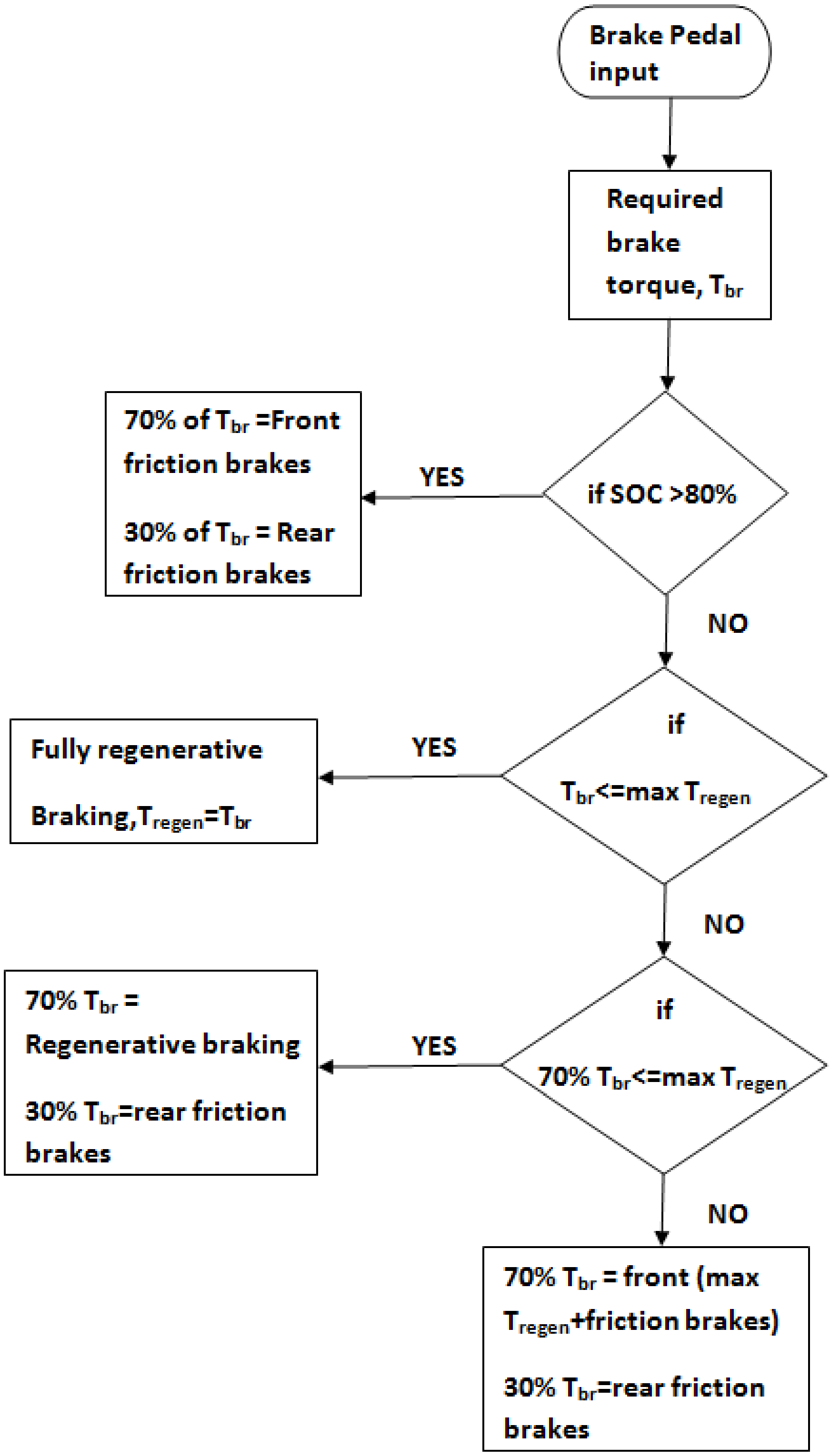

Figure 3-4: flow chart representation of serial regenerative braking (front wheels)

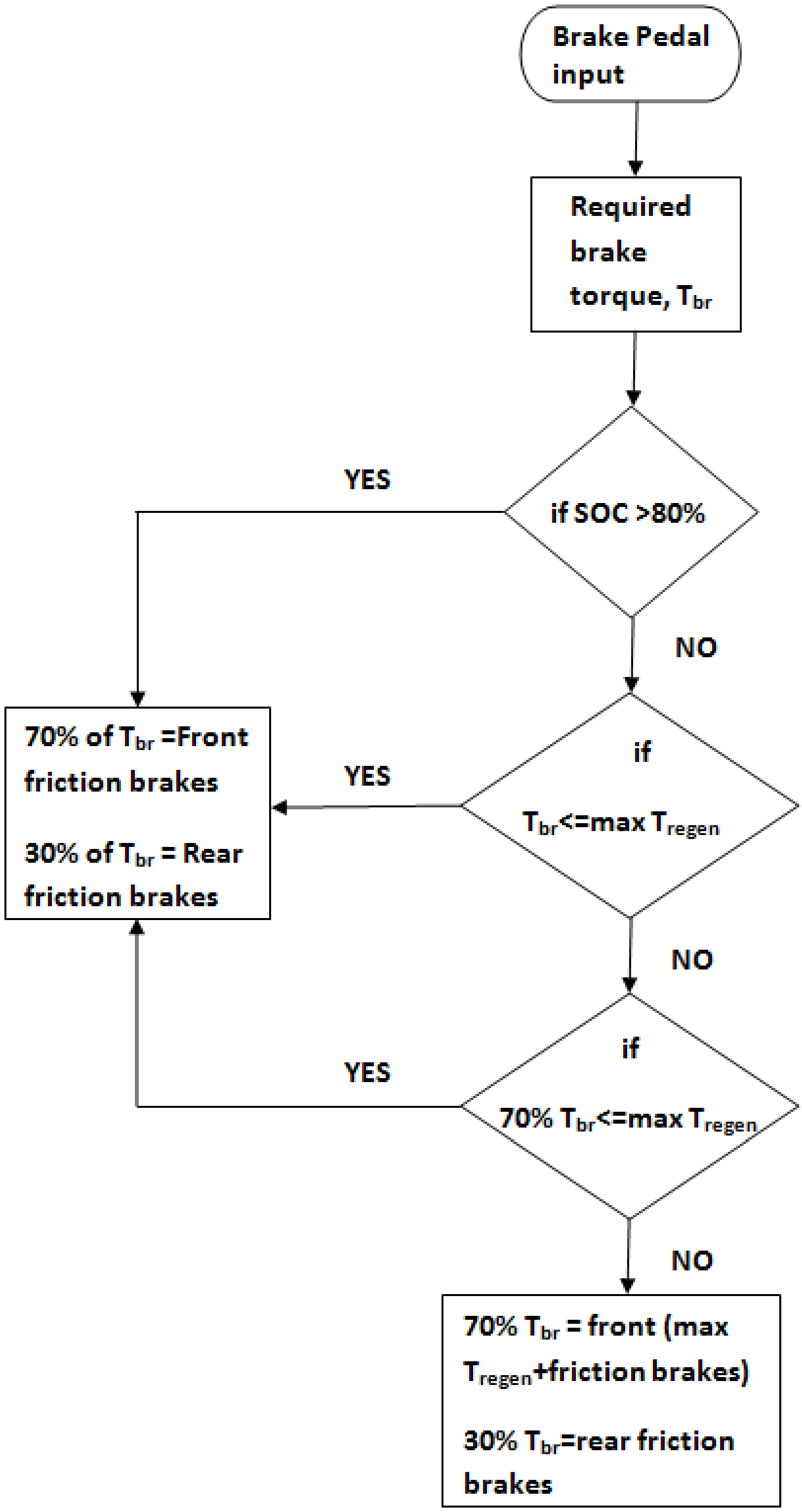

Figure 3-5: flow chart representation of parallel regenerative braking (front wheels)

3-3 Battery subsystem

The power request from the driver block after translating through the brake control strategy subsystem reaches the battery subsystem. Here the positive power discharges the battery and the negative power charges the battery. The battery is modeled as a look-up table with battery characteristics of a Lithium-Ion (ESS_Li7) battery from ADVISOR 3.0. ADVISOR (ADvanced VehIcle SimulatOR) is a powerful vehicle simulation tool developed by the U.S. Department of Energy's National Renewable Energy Laboratory's (NREL) Center for Transportation Technologies and Systems. It's a flexible modeling tool that rapidly assesses the performance and fuel economy of conventional, electric, hybrid, and fuel cell vehicles. The user can obtain datasheets, make changes to vehicle and component specifications and run them on various test conditions.

The battery is set with an initial SOC of 80%. When the positive power flows in, it enables the discharge block. In the discharge block depending on the SOC level,we get the maximum module voltage that can be supplied, from the plot of SOC vs Voltage of the battery module. This module voltage is then multiplied with the number of cells in series to get the battery pack voltage. Then from the power demand and the maximum possible voltage at that SOC, we calculate the current that can be supplied to the motor. This current is limited by the maximum amount of current that the motor can handle.
When a negative power is fed in, the charge block gets enabled. In the charge block depending on the SOC level and as explained above we calculate the maximum possible battery voltage and current that can be fed into the battery. This current is again limited by the maximum current capability of the generator.
When the power request is zero i.e., vehicle comes to rest or when the braking power is very low such that no significant current can be generated, the battery idle block is enabled. No current is withdrawn or put back during this phase.

3-4 Electric machine

The power from the battery drives the electric machine (EM). The EM works as a motor to propel the vehicle when positive power is fed in. And as a generator when negative power is fed in. EM is modeled as a look-up table with motor-generator characteristics (efficiency curve) of a permanent magnet synchronous machine (MC_PM49) of 49 kW from ADVISOR. This motor is downsized to that of a 40kW to meet the specifications provided. Down sizing is done by reducing the torque with a scale factor determined by the ratio of the default power (49kW) and the required power (40kW). A reduction gear has also been implemented, which is calculated using the maximum torque that the motor can provide and the maximum torque required to drive the NEDC.

3-5 Vehicle subsystem

The electromechanical torque produced by the motor is fed into the vehicle subsystem to propel the vehicle. The vehicle model used is TNO Delft tyre sim mechanics vehicle model. This model has a central body subsystem and four tyre subsystems. Tyre subsystems is designed based on Prof. Pacekja's famous Magic Formula for describing tyres. Tyres properties are derived from the file TNO_car205_60R15.tir. Tyres have the dimension of 205/60 R15. The road surface is dry asphalt and the coefficient of friction offered by the surface is 1. Various other road properties are contained in the file TNO_PolylineRoad.rdf. The Delft-tyre model helped in keeping a watch on the variation of longitudinal slip and hence making sure that at no point during the simulation wheel lock occur. A wheel-lock is undesirable as it would prevent regeneration and destabilize the vehicle. A snap-shot of this sim-mechanics vehicle model is included in the appendix.

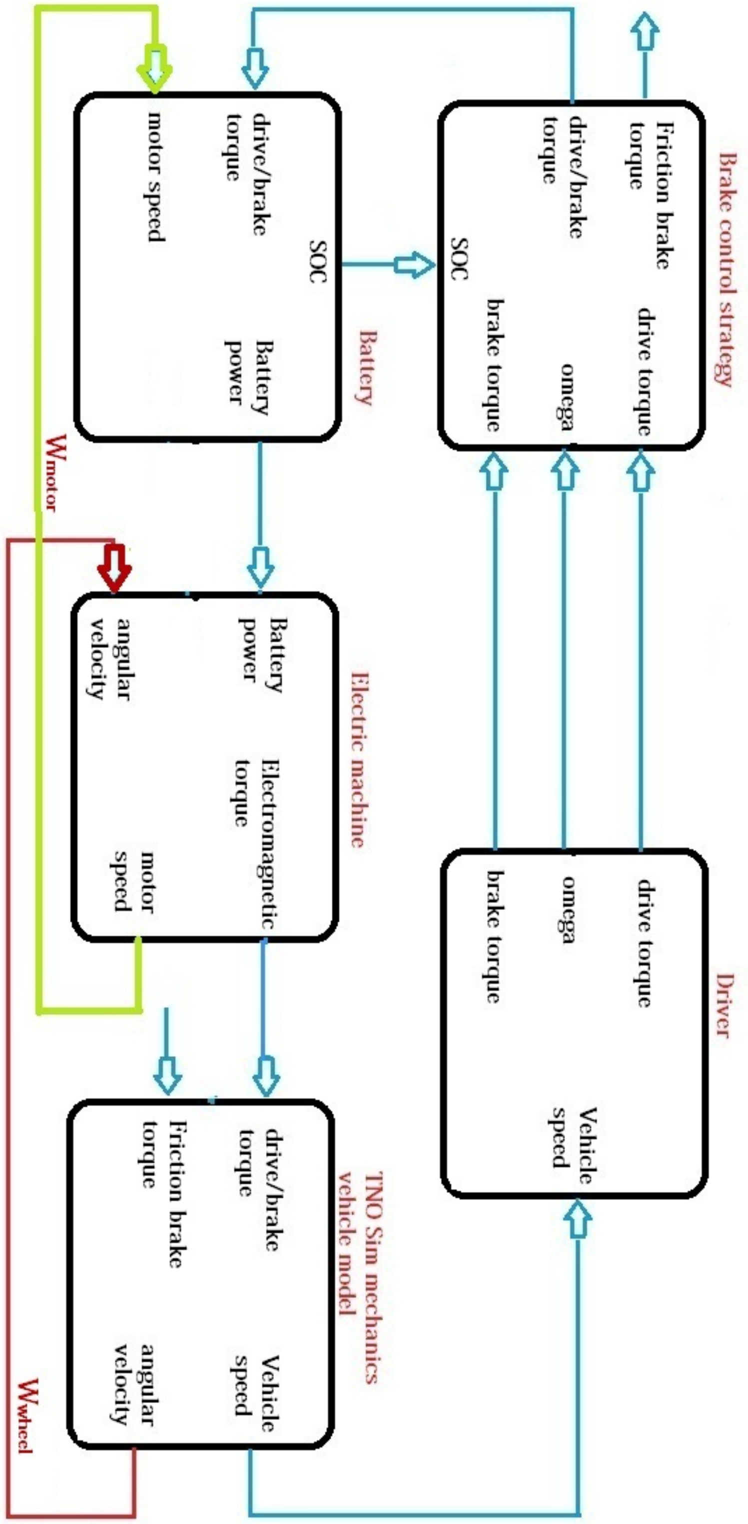

Figure 3-6: Schematic representation of the entire electric car model

Chapter 4

A Case study and Results of regenerative braking

4-1 A case study of energy flow and brake forces

In this case study we examine the various forces acting on a car as represented in figure 3.4. Then the amount of brake force required and the maximum decelerations possible is calculated. We also try to show the flow of energy from one form to another in terms of equations. The vehicle is modeled to resemble a mid-sized car. Car specs given in the table below are purely fictional. The motor-generator datas are derived from ADVISOR 3.0 for a 49 kW electric machine. They are then downscaled to meet the design criteria of a 40 kW electric machine as proposed in the HTAS project.

Energy flow

The kinetic energy of the vehicle during braking is used to rotate the motor in reverse direction. Thus the very same motor used for propulsion now acts as a generator, feeding the battery with power as represented by the equations below. The flow of energy takes place in the following order:

kinetic energy of the vehicle is transformed into electric energy produced by generator, which is transformed into energy input for battery

Vehicle Characteristics		
Parameters	values	
Mass of the vehicle,M_v	1325	$[kg]$
Frontal area, A_f	2.57	$[m^2]$
Drag coefficient, C_w	0.30	$[-]$
Air density, ρ	1.2	$[\frac{kg}{m^3}]$
Radius of the wheel, R_w	0.3	$[m]$
Rolling resistance coefficient, C_{roll}	0.008	$[-]$

- kinetic energy of the vehicle,

$$E_{kin} = \frac{1}{2}M_v(V_2^2 - V_1^2) \tag{4-1}$$

- Considering electro-mechanical power equality

$$\tau = I\alpha \tag{4-2}$$
$$\omega = \frac{U}{\alpha} \tag{4-3}$$
$$P_{mech} = \tau\omega = (I\alpha)\left(\frac{U}{\alpha}\right) = P_e \tag{4-4}$$

The effective power produced by the motor depends on the efficiency of the generator. Therefore, $P_{e,actual} = \eta_{gen}P_e$ η_{gen} is derived from the efficiency plot of the generator, obtained from ADVISOR 3.0.

- Now depending on the battery Voltage-State of Charge (SOC) characteristics, the internal resistance (R_i)and the configuration of the battery pack, we determine the maximum possible current that can be fed into the battery. The Lithium-Ion (ESS_Li7) battery from ADVISOR is used in this model. The battery characteristics plots as obtained from ADVISOR 3.0 are shown below.

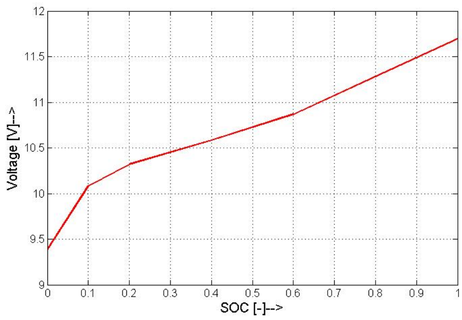

Figure 4-1: Voltage-SOC plot

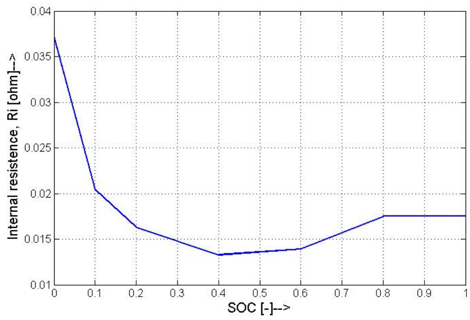

Figure 4-2: Internal resistance-SOC plot

For a given SOC, we get a particular value of voltage V_{module} for the battery module. This voltage is multiplied by the number of modules in series to get the total voltage V_{batt}.

$$P_{batt} = \eta_{batt}P_{e,actual} \tag{4-5}$$
$$I_{batt} = P_{batt}/V_{batt} \tag{4-6}$$

This current I_{batt} recharges the battery. The recharge and discharge current limit is set according to the maximum current limit of the electric motor-generator.

Brake force

The following equations are used to calculate the amount of brake torque required to stop the vehicle in the stopping distance prescribed by the drive cycle.

Motor Characteristics		
Parameters	values	
Power, P_e	40	$[kW]$
Maximum current, I_{max}	400	$[Amp]$
Minimum voltage, V_{min}	60	$[volt]$
Maximum motor torque, T_m	520.88	$[Nm]$
Maximum regenerative torque, T_{reg}	322.7	$[Nm]$

$$\text{Required brake force, } F_x = M_v a + \frac{1}{2}\rho C_w A_f V^2 + C_{roll} mg \tag{4-7}$$

$$\text{Required brake torque, } T_b = F_x R_w \tag{4-8}$$

Tire model can be given as:

$$F_x R_w - T_b = I_w \dot{\omega} \tag{4-9}$$

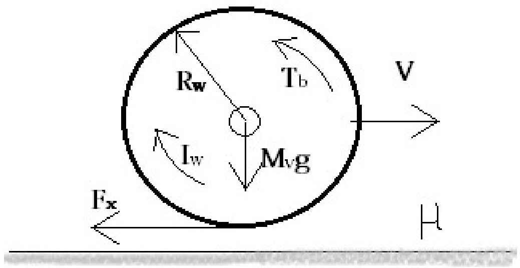

Figure 4-3: wheel longitudinal dynamics

The tire braking force can be calculated by:

$$\text{Tire braking force, } F_x = \frac{\mu M_v g}{4} \tag{4-10}$$

$$\text{Slip ratio, } k = \frac{R_w \omega - V_x}{V_x} \tag{4-11}$$

$$\text{Normal force on tire, } F_z = \frac{F_x}{\mu} \tag{4-12}$$

μ can be given by the Vehicle state estimator (VSE) or taken from a table of μ vs slip ratio(s).

Case 1: (4 wheel braking at small decelerations)

Consider an all-wheel drive vehicle. Suppose the vehicle comes to rest from 25$[m/s]$ at a deceleration of -3$[m/s^2]$. Here, we calculate to check if the required braking torque can be provided fully by the generator or not.

- The required braking force using (4-7):

$$F_x = (1325 \times -3) + (0.5 \times 1.2 \times 0.26 \times 2.57 \times 25^2) + (0.008 \times 1325 \times 9.81) = -3620.43[N] \tag{4-13}$$

- The force per wheel on rear axle:

$$F_{x,wheel} = \frac{-3620.43}{4} = -905.10[N] \tag{4-14}$$

- The required braking torque per wheel (4-8):

$$T_{b,wheel} = -905.10 \times 0.3 = -271.53[Nm] \tag{4-15}$$

Since the required braking torque per wheel is below the maximum regenerative torque capable of the generator T_{reg}, braking can be fully regenerative depending on the braking strategy applied.

Case 2: (4 wheel braking at large deceleration)

Suppose the vehicle comes to rest from $25m/s$ at a deceleration of -$8m/s^2$

- The required braking force (4-7):

$$F_x = (1325 \times -8) + (0.5 \times 1.2 \times 0.26 \times 2.57 \times 25^2) + (0.008 \times 1325 \times 9.81) = -10245.43[N] \tag{4-16}$$

- The force per wheel:

$$F_{x,wheel} = \frac{-10245.43}{4} = -2561.35[N] \tag{4-17}$$

- The required braking torque per wheel (4-8):

$$T_{b,wheel} = -10245.43 \times 0.3 = -768.40[Nm] \tag{4-18}$$

Since the required braking torque per wheel is above the maximum regenerative torque capable of the generator T_{reg}, braking cannot be fully regenerative. Hence friction braking is applied in combination with regeneration.

Case 3: (max deceleration possible with regenerative braking)

Now let us calculate the maximum possible deceleration on an all-wheel drive with purely regenerative braking.

- The maximum regenerative torque by the generator as given in the table above, $T_{gen} = 322.7Nm$ =maximum braking torque per wheel, T_b

- The force per wheel:

$$F_{x,wheel} = \frac{322.7}{0.3} = -1075.67[N] \tag{4-19}$$

- The total longitudinal force:

$$F_{x,total} = -4302.68[N] \tag{4-20}$$

- The maximum deceleration possible:

$$a = (F_{x,total} - C_{roll} M_v g) / (M_v) = -3.43[m/s^2] \tag{4-21}$$

similarly, the maximum deceleration with regenerative braking on 2 wheels is 1.7 $[m/s^2]$. From the above case study, it can be understood that for harder braking purely regenerative braking would fail to give the desired deceleration. The maximum decelerations possible for various combination and number of motors, with the specification used in this research is calculated. Using the above case study, the amount of friction braking required can be easily determined.

4-2 Results of the simulation

The results have been derived from simulations for different braking scenarios. The simulation is run for a period of 25 $[sec]$. The car reaches a maximum velocity of 10.5 $[m/s^2]$ and then it starts braking. Regenerative braking is only in the front as the car is front driven.

1. **Small brake pedal input**
   In this case a small brake pedal input is applied. The deceleration achieved is very small, depicting a congested city traffic scenario. The brake pedal input is just close to about 10% applied at the 10th second. The plots below represent regeneration in both serial and parallel regenerative cases.

   The subplots in figure 4-4 represent serial regenerative case. It is evident from the plots that when the brake pedal is depressed, the vehicle starts decelerating at a small rate. The brake torque corresponding to this brake pedal input is small, such that the entire braking torque could be provided by the generator. Hence we observe in the second subplot, the braking is just purely regenerative and hence an appreciable SOC increment is observed in the 3rd subplot. The vehicle comes to a halt in about 14 $[sec]$ after the activation of brake pedal.

   The subplots in figure 4-5 represent parallel regenerative case. It can be observed that for such small deceleration and hence a small brake torque request, brakes are purely conventional ones. There is no regeneration as it is assigned to start only when appreciable brake torque is requested in order to ensure a consistent pedal feel as explained in the prior chapter. Hence the battery is not charged at these small decelerations in case of parallel regenerative braking implemented in the simulation.

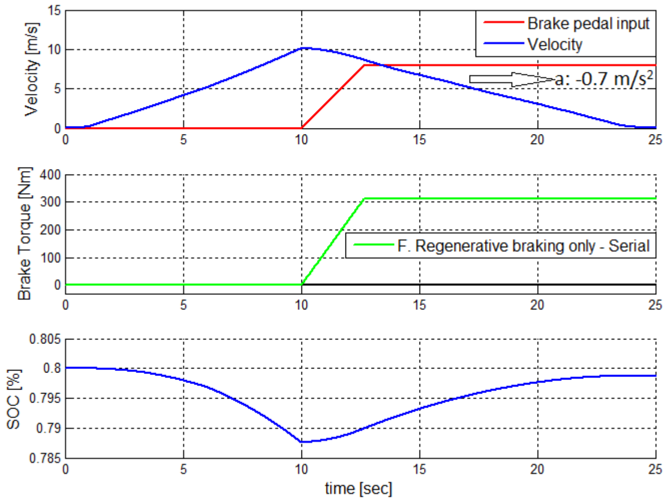

Figure 4-4: Serial regenerative braking at small brake input

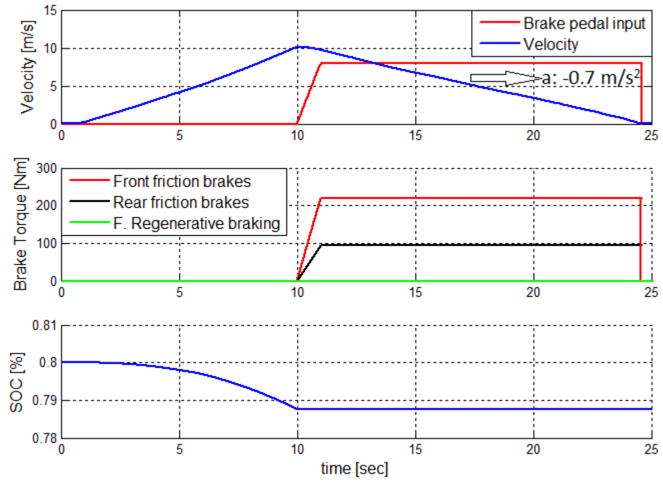

Figure 4-5: Parallel regenerative braking at small brake input

2. **Full brake pedal input**
   In this case the brake pedal is applied to the full extend. The deceleration achieved in this case is at a significant rate. The brake torque applied is the maximum that could be applied without wheel lock-up and is approximately 3900 $[Nm]$ divided among four wheels in this case.

   The subplots in the figure 4-6 represent serial regenerative braking. We observe that the vehicle comes to a stand-still much quicker in about 1.5 $[sec]$ and hence regeneration is small as time available for recuperation is less. Here we observe that both regenerative and friction braking are acting together.

   However, zooming in on the sequence of activation of brake torque as shown in figure 4-7, we can see that it starts with regenerative braking. Once regeneration alone cannot

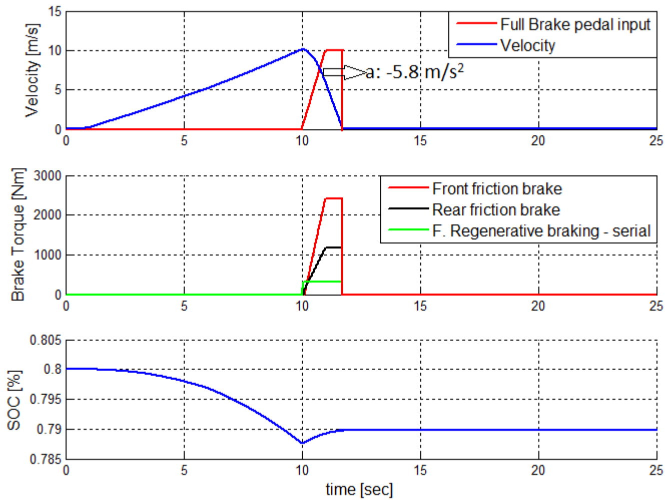

Figure 4-6: Serial regenerative braking at full brake input

provide the required braking torque, then the non-driven axle (rear) begins to brake so as to maintain appropriate brake torque distribution. If application of rear friction brakes along with regenerative braking do not satisfy the desired brake torque, then front friction braking begins to act. Hence vehicle is brought to rest within appropriate stopping distance.

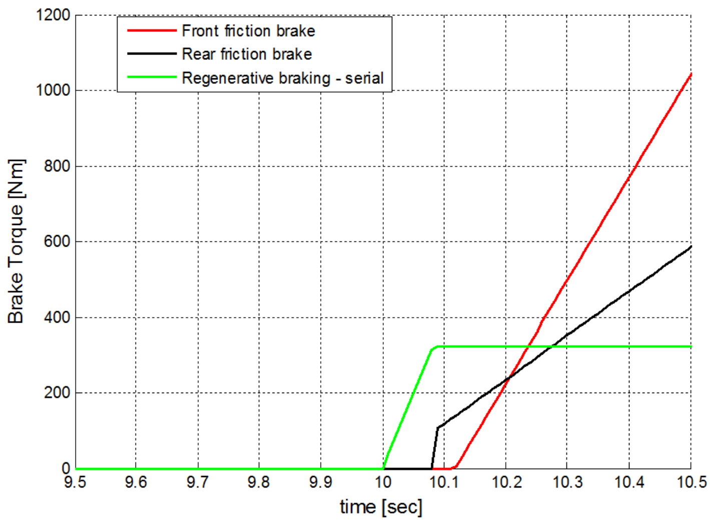

Figure 4-7: Serial regenerative braking-close up on brake torque activation

The subplots in figure 4-8 represent parallel regenerative braking. We observe a similar response as serial.

However, zooming in at the brake torque activation (figure 4-9), we can observe that braking starts with friction until it becomes greater than or equal to the amount that could be provided by the generator. This is done so as to operate generator in the

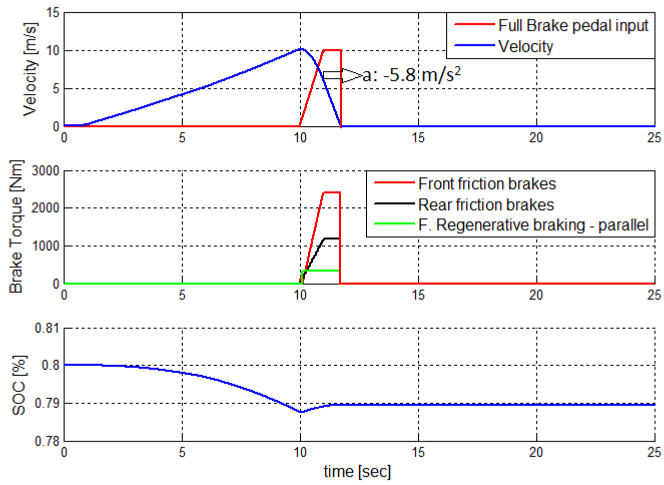

Figure 4-8: Parallel regenerative braking at full brake pedal input

constant torque region and thus ensure consistent pedal feel. Here the brake torque split has a fixed division between regenerative and conventional friction braking. In order to do this, the generator is always expected to operate at speeds equal to or below the base speed of the motor where the torque characteristic is a constant maximum line. At all braking scenarios provided the vehicle speed is below the base speed of the motor, the generator gives the maximum regenerative torque capable by the motor-generator selected which is around -322.7Nm. This brake torque division ensures smooth transition and co-existence between friction and regenerative braking. Such a brake division was performed due to the fact that there is no integrated control in such vehicles as compared to those with serial regenerative braking with brake by-wire technology.

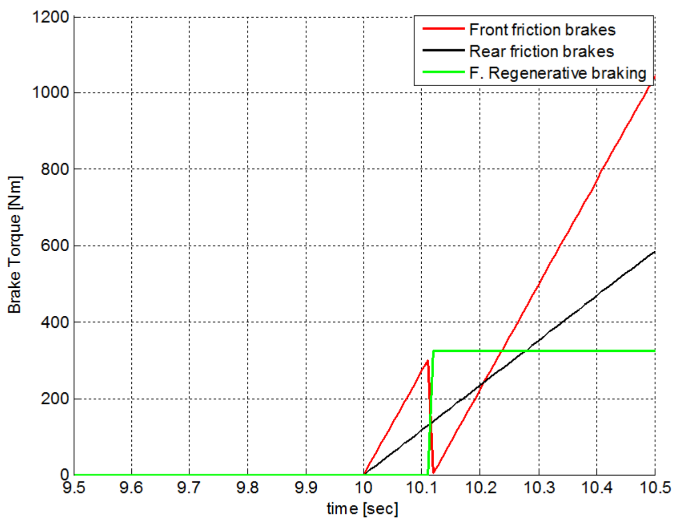

Figure 4-9: Parallel regenerative braking-close up on brake torque activation

In figure 4-9 we observe that in the initial phase when brake torque is just building up, only friction braking is active. As the brake torque becomes larger, regeneration kicks in and then both regenerative and friction braking co-exist. At about 10.1 [*sec*] we observe that the brake torque is equal to what regeneration can provide and hence we see decrease in friction braking at the front and subsequent increase in regenerative braking in a very complimentary manner. The moment brake torque is higher than what regeneration can provide, we observe the increasing assistance of friction braking again.

3. **Partial brake pedal input**
In the following result, we have attempted to showcase a comparison between a conventional vehicle braking (friction only), pure electric regenerative braking, serial regeneration and parallel regeneration. The brake pedal is depressed to half its potential. It can be observed from the plot that for a fully regenerative braking scenario, the vehicle takes longer to come to a rest due to the limitation in the maximum regenerative braking torque capability of the generator. But we see a much better regeneration in that case as the vehicle runs longer. In other cases, the vehicle comes to rest in a similar fashion as the total required brake torque can be provided by the combination used. It can be seen from the plot that serial regeneration scores slightly over parallel in the present scenario. This is mainly attributed to the fact that time of activation of regenerative braking torque differs for both strategies.

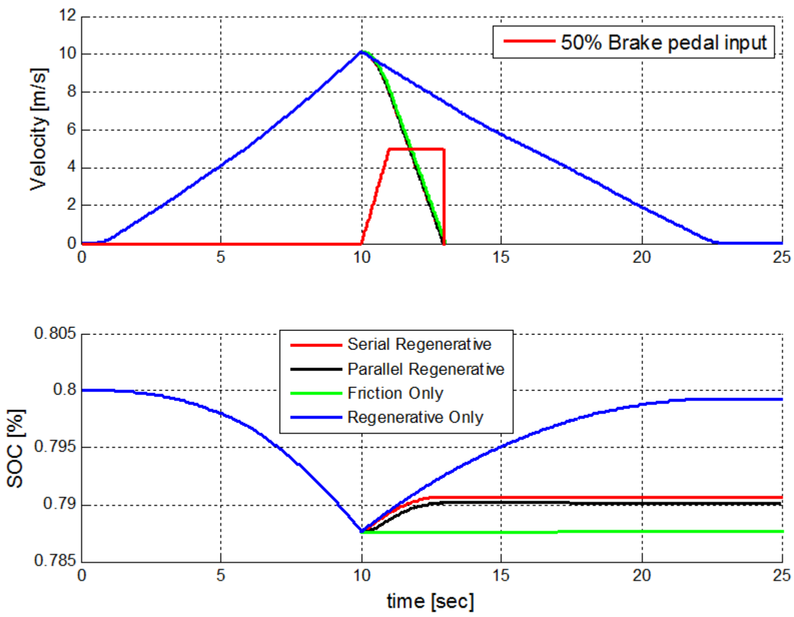

Figure 4-10: Various braking scenarios at 50% brake pedal input

The effectiveness of regenerative braking is determined by calculating the regenerative ratio.

$$\text{Serial regenerative ratio,}\epsilon = \frac{\sum E_{bat}}{\sum E_{kin}} = 20.5\% \tag{4-22}$$

$$\text{Parallel regenerative ratio,}\epsilon = \frac{\sum E_{bat}}{\sum E_{kin}} = 18.4\% \tag{4-23}$$

4. **New European Driving Cycle (NEDC) drive cycle**
   Simulations for both regenerative strategies have been performed on NEDC driving cycle. The velocity and SOC trends for the city part Urban driving cycle (ECE)-15 are as depicted in figure 4-11

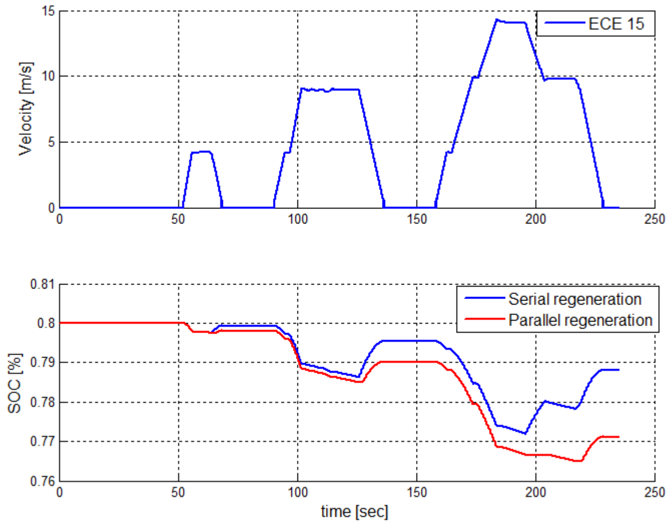

Figure 4-11: Regenerative trends in ECE-15

The velocity and SOC trends for the highway part Extra Urban driving cycle (EUDC) are as depicted in figure 4-12

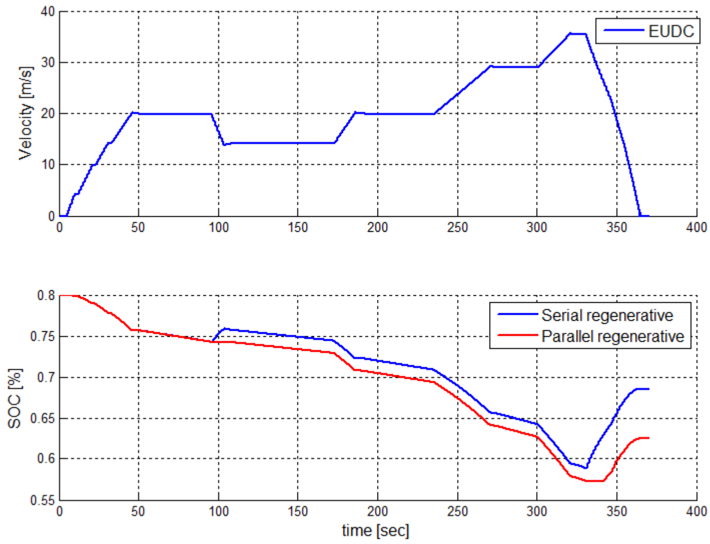

Figure 4-12: Regenerative trends in EUDC

NEDC drive cycle consists of four instances of ECE-15 pattern and a single instance of EUDC. The effectiveness of NEDC drive cycle is:

Total kinetic energy during braking in NEDC, $\sum E_{kin} = 1.75\ [MJ]$

Total electric power recuperated with parallel regeneration, $\sum E_{bat} = 0.52\ [MJ]$

Total electric power recuperated with serial regeneration, $\sum E_{bat} = 1.21\ [MJ]$

$$\text{Serial regenerative ratio,}\epsilon = \frac{\sum E_{bat}}{\sum E_{kin}} = 69.68\% \tag{4-24}$$

$$\text{Parallel regenerative ratio,}\epsilon = \frac{\sum E_{bat}}{\sum E_{kin}} = 30.25\% \tag{4-25}$$

It can be safely concluded from the various simulations that serial is more effective than parallel in recuperating energy during braking. Serial with adjustable friction brakes and integrated control has the freedom to operate in the entire range of generator torque. Thus aiding in regeneration at all speeds. While parallel with no integrated control has limitations in the activation of regenerative braking. The range extension and hence electric driving is particularly beneficial for city driving as its already mostly over-polluted leading to smog and other health hazards. Simulating the European driving cycle with the braking strategies modeled it is found that serial regenerates way higher than parallel. With the amount of recuperated energy, serial offers a range extension of about 5.3[km] whereas parallel gives only about 2.3[km] following ECE-15 driving profile.

Chapter 5

Conclusion and Recommendations

5-1 Conclusion

In this internship, the two regenerative braking concepts has been studied and implemented in Matlab/Simulink. The driver block simulates a driver by pressing the accelerator pedal to drive and brake pedal to stop the car. Depending on the position or the amount of depression of the pedals certain torque is applied. Maximum brake torque applied is calculated considering the wheel dynamics and hence ensures no wheel lock. A wheel lock-up prevents regeneration and also could throw vehicle into instability.

For serial regenerative, on the application of brake pedal a certain brake torque is requested. Now this brake torque upon feeding to the brake control strategy block, gets split between regenerative and friction braking. In the initial phase of brake application, when the brake torque requested is small, then we find only the regenerative braking. Once the brake pedal has been depressed further signalling a bigger deceleration, then friction brakes comes into play in combination with regenerative braking to aid in stopping the vehicle. Serial regenerative braking has adjustable friction braking with integrated control and hence can utilize the entire range of generator torques for regeneration.

For parallel regenerative, on the application of brake pedal a certain brake torque is requested. Now this brake torque is split between regenerative and friction considering consistent pedal feel. It is observed that generator operates at constant torque below the base speed. Hence the regenerative braking in case of parallel is active only when braking from a speed equal to or less than the base speed of the generator. That way, it is possible to give a clear cut division of brake torques between friction and regenerative, thus aiding in consistent pedal feel.

Regenerative braking holds a good potential to extend driving range while ensuring no occurrence of wheel lock-up. As is evident from this research serial regenerative braking has better recuperation capability as compared to parallel regenerative braking. However, a parallel system could be mounted onto a conventional vehicle without incurring much costs as compared to serial which requires a brake by-wire system and an integrated control to ensure efficient torque blending between regenerative and friction braking. As is understand from literature & autoblogs, brake by-wire system isn't matured enough at the moment for a widespread application in automobiles. Some of the other stumbling block in the way of brake by-wire systems is the cost of implementation, lack of awareness in people about its advantage and hence not willing to pay extra for the technology, safety and reliability issues and after-sales serviceability. So it would take some more time before we see brake by-wire systems gain momentum in the automotive market. This is why parallel regenerative braking strategy would be interesting for today's electric and hybrid manufactures, who wish to push sales by keeping the costs low or just slightly higher than the conventional vehicles.

With regard to combining TNO's Vehicle state estimator (VSE) to improve regenerative braking. From the mathematical formulations of brake torque and wheel dynamics, it is found that no additional states are required from VSE at present to improve regenerative braking. VSE could be proven more useful in the implementation of serial regenerative braking, as we would be able to take full advantage of fast responsiveness of electronic systems like brake by-wire and the torque response of electric motor-generator. Once we set-up serial regenerative braking with brake by-wire, VSE could be used to estimate accurate braking force limits before which an instability condition could occur on any road conditions. This way we would be able to fine tune the recuperation by prolonging regeneration with the aid of VSE and thus delaying the intervention of other safety critical systems like the Electronic Stability Control (ESC) or the Anti-lock braking systems (ABS). Some of the other limitations in terms of regeneration is the state-of-charge of the battery pack and the regenerative capability of electric motor-generator and the configurations (in-wheel motor, front driven, rear driven, all wheel drive etc). In order to prolong battery life it is advised not to over-charge or under-charge the battery. Hence at times when battery State of Charge (SOC) is at maximum limit, regeneration is not possible. In such scenarios you could either let regeneration continue but instead of feeding it into the battery you simply have to burn it off using resistors or employ full friction braking. From the electric motor-generator's perspective, each motor-generator manufactured comes with a certain limitations in the maximum amount of motor-generator torque. Keeping this in mind it would be worthwhile to investigate the configuration of the motor-generators in a car such that we ensure good recuperation, the safety aspects of front driven, rear driven, all wheel drives etc, expense in production and maintenance. The vehicle considered in this research is a front driven with a single central motor-generator.

5-2 Recommendations

This work is just a start in the direction of learning the advantage of serial and parallel regenerative concepts. In order to make the these concepts more robust I would like to recommend some further investigations in the direction listed below.

- The simulations done so far take into consideration only longitudinal motion and forces. However it is of importance to consider vehicle stability during lateral movements like a lane change maneuver, turning, cornering and mu-split conditions. Hence it would be interesting to add ESC and ABS algorithms to the simulations to study the intervention of these systems to maintain vehicle stability in maneuvers and how it effects regeneration.

- Vehicle handling behavior at times when a particular wheel has a higher probability of locking compared to the rest or in times when a complete wheel lock-up is predicted. We could investigate the possible benefits of regenerative braking taking over in order to prevent an instable situation. While studying this, it would also be advised to keep in mind the possible damage to battery pack due to the frequent charge-discharge cycle i.e., micro-cycling. You could either choose to recharge the battery in such situations or simply burn them off.

- Simulation results are not always the correct depiction of a real-life scenario. It just aids in providing an approximate idea of whether the chosen strategy has enough potential for implementation in real life. Hence it is recommended to test the simulation strategies on a real vehicle or a test bench to further refine the recuperation values.

- A more advanced battery and electric motor-generator modeling taking into consideration various operational dynamics. The battery and electric motor-generator model in the simulations uses the various efficiency plots obtained from laboratory tests and found in the ADVISOR 3.0 program. The tests on battery do not take into consideration, the performance variation with respect to temperature. The battery module used in this simulations study is Saft 6Ah Lithium Ion (ESS_Li7) battery. The electric motor-generator modeled is based on the efficiency map of permanent magnet synchronous motor MC_PM49 of 49kW. This motor specs are linearly scaled down to resemble a motor of 40kW as per the requirements. It is not exactly an accurate way to scale down a motor-generator linearly but the simulation performed is with the assumption that it would not differ much. Hence when you have chosen the latest in battery technology and an appropriate motor-generator that you will work with, feed in those specifications for a more precise results.

- The highest efficiency of motor-generator is achieved at a region beyond the base speed. Suppose we include a transmission systems like a Continuously Variable Transmission (CVT) [8] which could maintain the generator operation at the highest efficiency spot. Then it would be interesting to investigate and compare the recuperation benefits for a parallel regenerative system. Of course there would be some amount of transmission loss and also a lot would depend on the smoothness and effectiveness with which the transmission can maintain a constant regenerative torque in the most efficiency region.

Appendix A

Simulink Figures

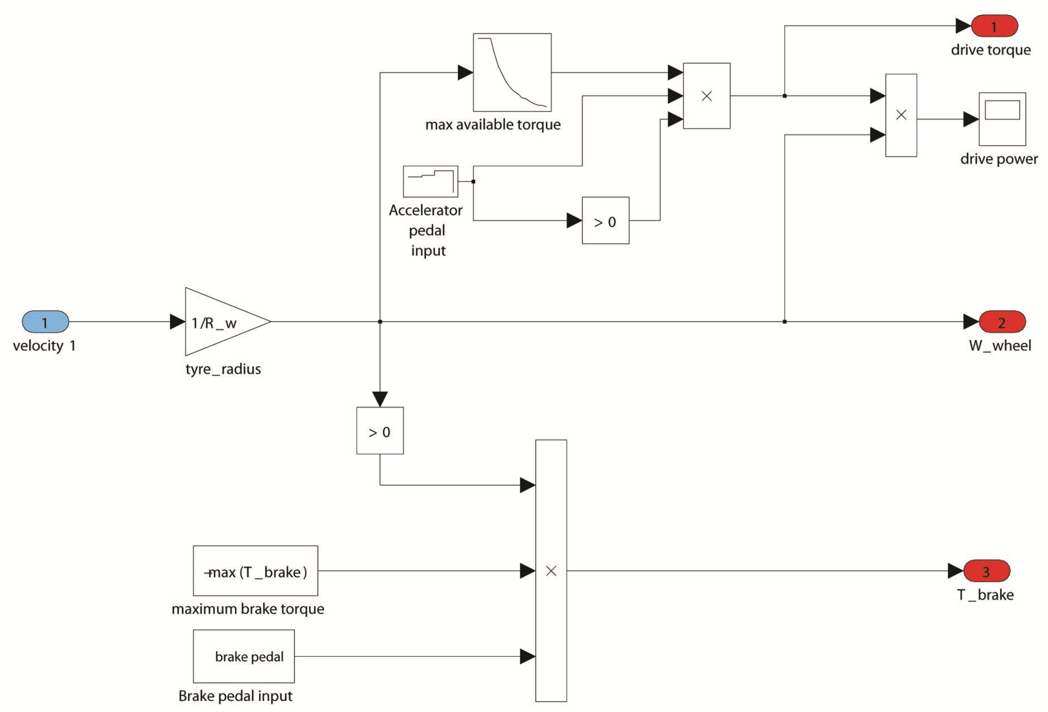

Figure A-1: Driver block

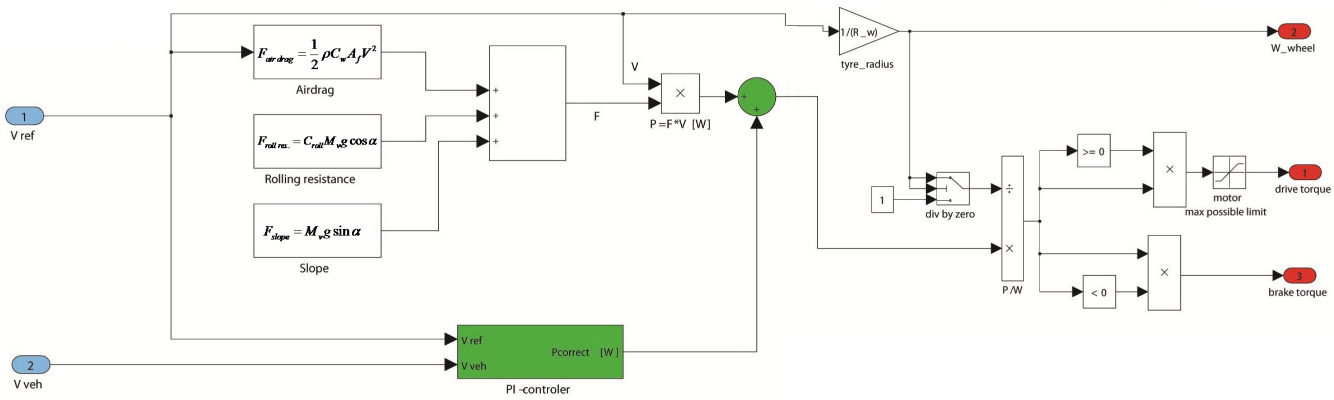

Figure A-2: Implementation of driver subsystem for NEDC

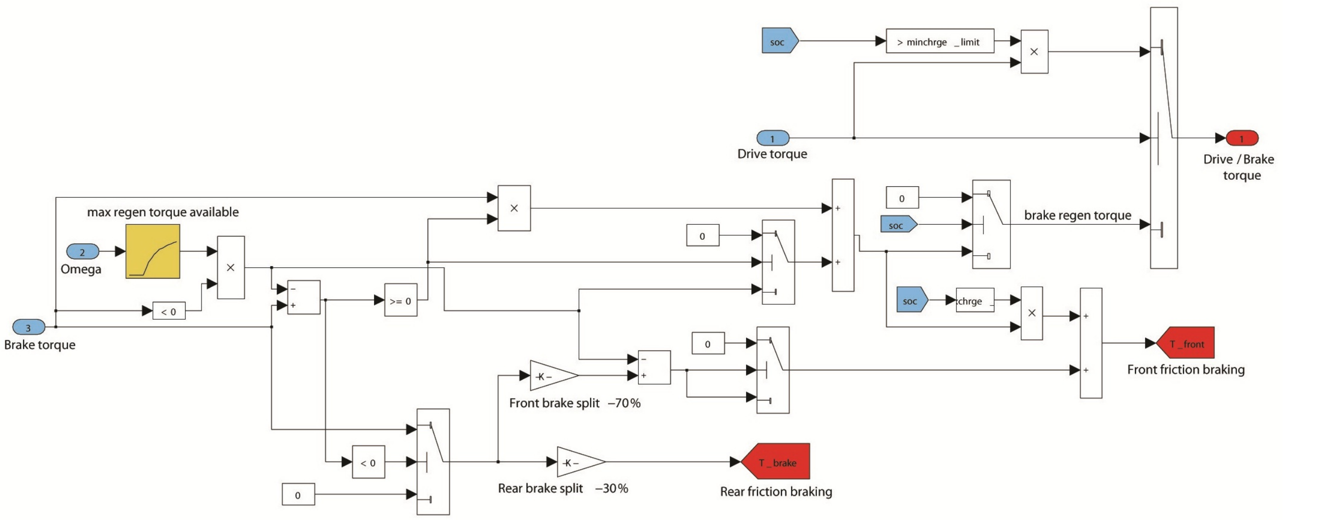

Figure A-3: Implementation of serial braking

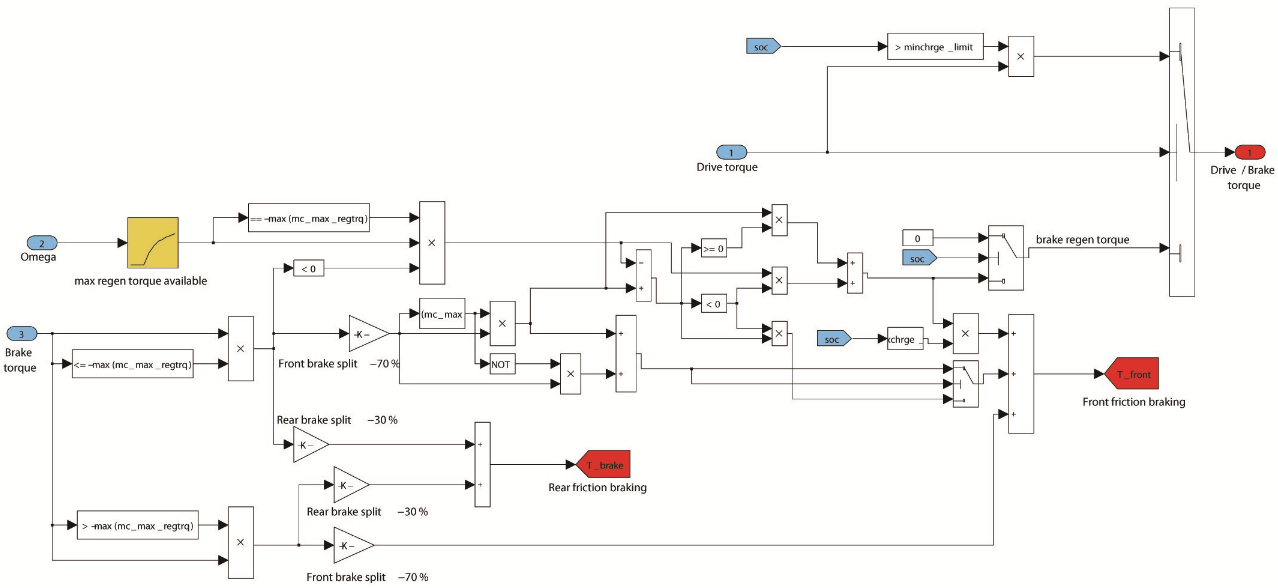

Figure A-4: Implementation of parallel braking

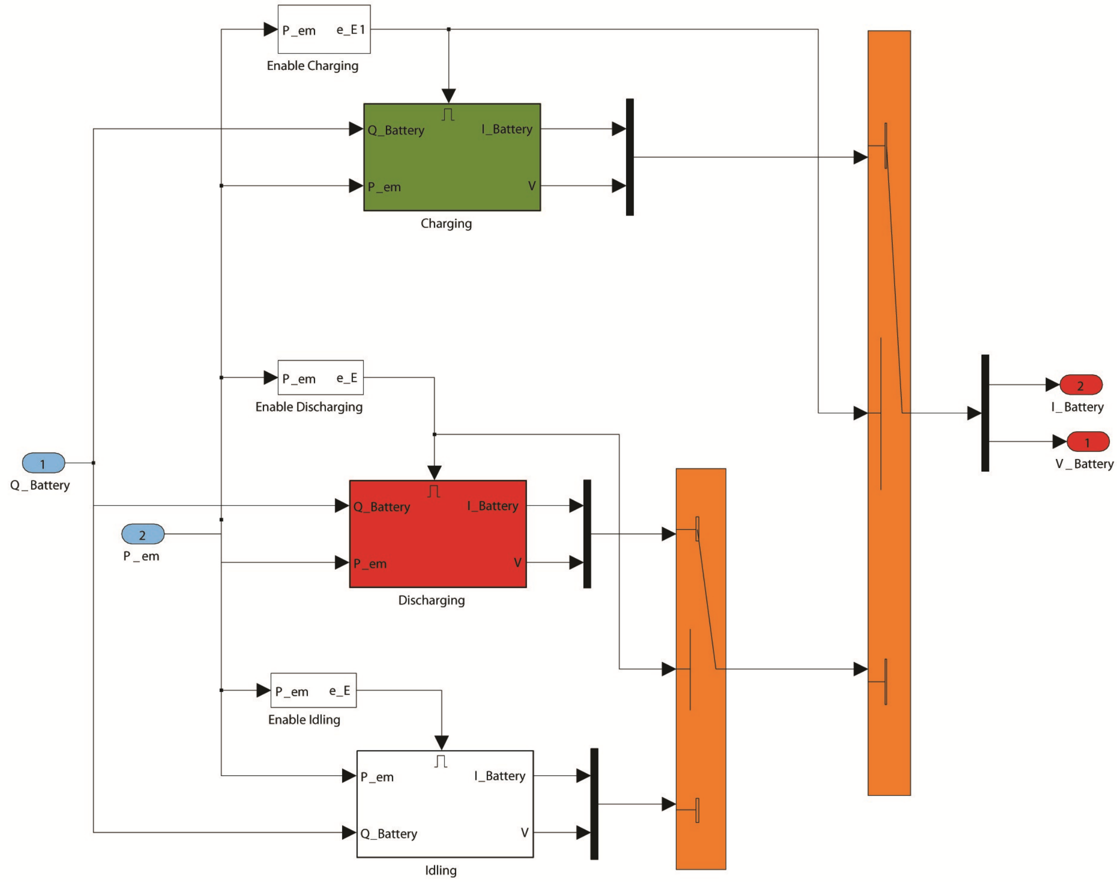

Figure A-5: Implementation of battery model

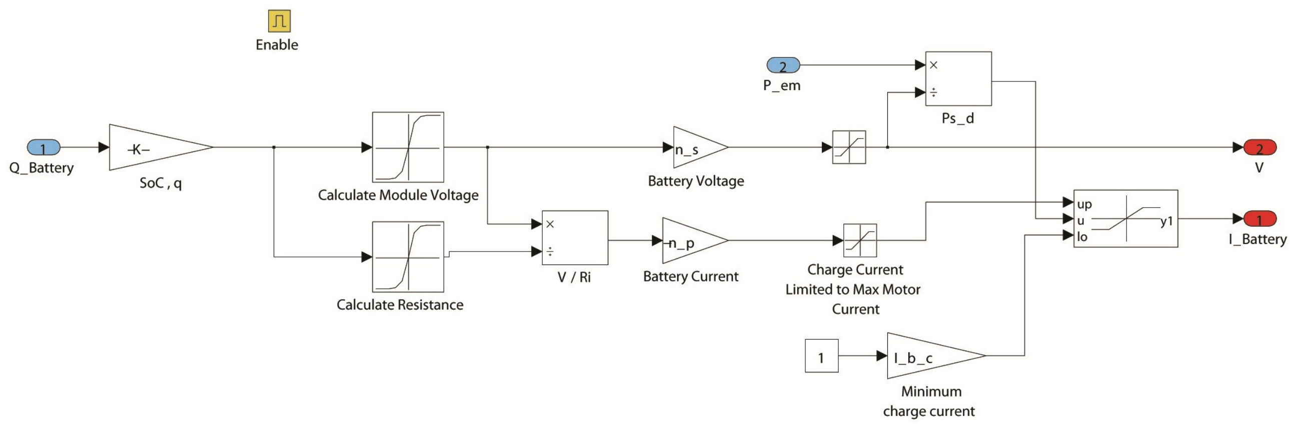

Figure A-6: Implementation of charging block

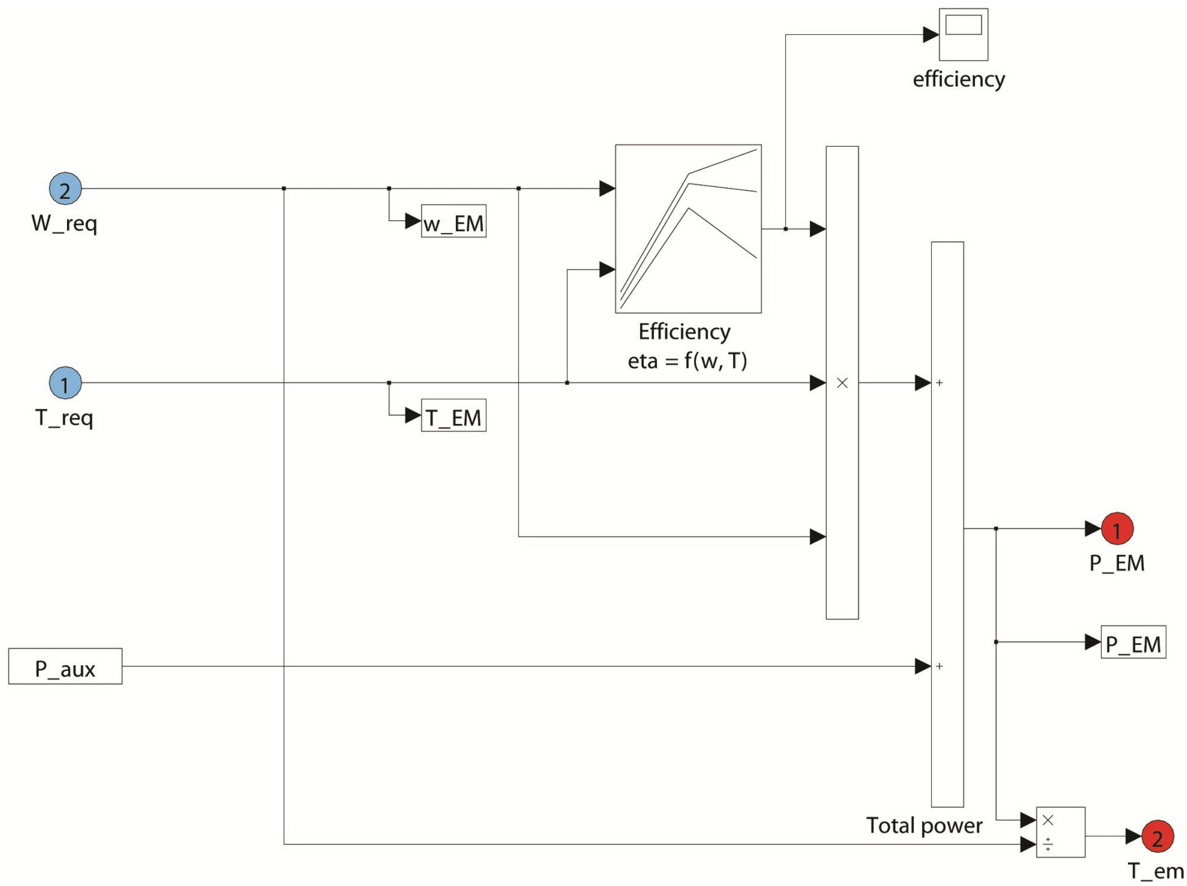

Figure A-7: Implementation of electric machine block

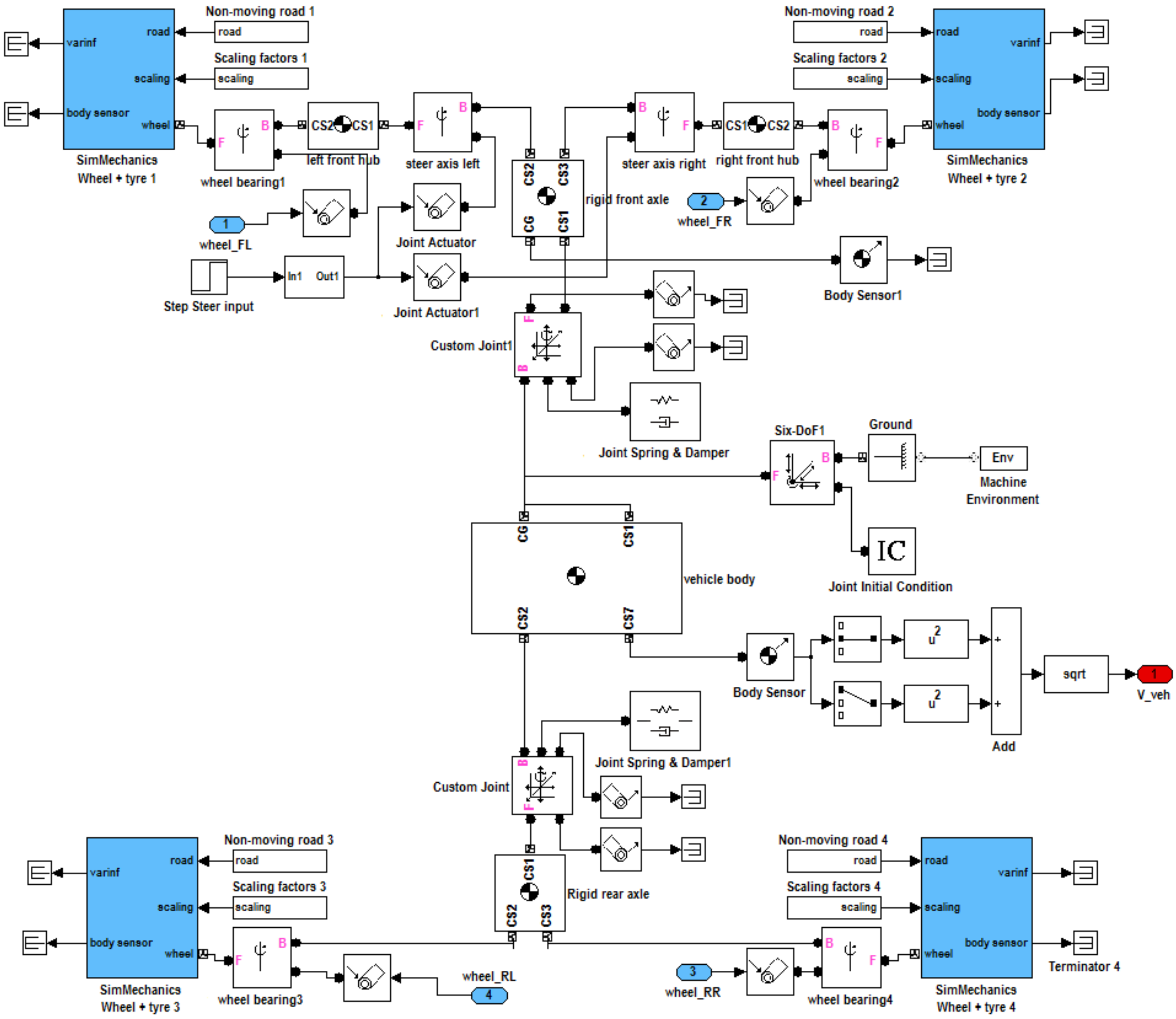

Figure A-8: TNO Delft tyre vehicle model

Bibliography

[1] "Vehicle dynamics control system." http://www.htas.nl/files/presentaties/Vehicle%20Dynamics%20Edward%20Holweg.pdf.

[2] J. Zhang, X. Lu, J. Xue, and B. Li, "Regenerative braking system for series hybrid electric city bus," *The World Electric Vehicle Journal*, vol. 2, no. 4, 2008.

[3] Y. Hori, "Future vehicle driven by electricity and control research on four-wheel-motored - uot electric march ii," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, 2004.

[4] Z. F. Bai, S. X. Li, and B. G. Cao, "$h\infty$ control applied to electric torque control for regenerative braking of an electric vehicle," *Asian Network for Scientific Information*, vol. 5, 2005.

[5] D. Peng, Y. Zhang, C. Yin, and J. Zhang, "Combined control of a regenerative braking and antilock braking system for hybrid electric vehicles," *International Journal of Automotive Technology*, vol. 9, no. 6, 2008.

[6] S. Kliauzovich, "Analysis of control systems for vehicle hybrid powertrains," *TRANSPORT VGTU*, vol. XXII, no. 2, 2007.

[7] M. Panagiotidis, G. Delagrammatikas, and D. Assanis, "A development and use of a regenerative braking model for a parallel hybrid electric vehicle," *SAE Technical Paper Series*, 2000.

[8] H. Yeo, H. Kim, and S. Hwang, "Regenerative braking algorithm for a hybrid electric vehicle with Continuously Variable Transmission (CVT) ratio control during deceleration," *Proceedings of the instituition of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 220, no. 11, 2006.

Glossary

List of Acronyms

EV Electric Vehicle

SOC State of Charge

ABS Anti-lock braking systems

VSE Vehicle state estimator

ICE Internal combustion engine

PMSM Permanent magnet synchronous machine

CFD Computational fluid dynamics

ECE Urban driving cycle

EUDC Extra Urban driving cycle

NEDC New European Driving Cycle

VSC Vehicle Stability Control

DYC Direct Yaw Control

TCS Traction control system

ESC Electronic Stability Control

CVT Continuously Variable Transmission