CHALMERS

Effects of driving style on energy usage in battery electric vehicles

Master's thesis in Mechanical Engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Environmental problems such as emissions and greenhouse gases have put pressure on the automotive industry. There is a growing interest in energy efficient electric vehicles and model-based approach is a powerful tool to design new electric vehicles.

This thesis employs system-level simulations to investigate the effects of driving aggressiveness on energy usage in battery electric vehicles. A Lithium-Ion battery pack is designed in GT-AutoLion and integrated into the existing electric vehicle model in GT-SUITE. Five different drive cycles; HWY, UDDS, LA92, NEDC and WLTC were used to represent highway, urban, city driving and their combination. The driving aggressiveness is modeled by separately modifying velocity and acceleration. This by scaling the time and speed traces with following scaling factors; 0.8, 0.9, 1.0, 1.1 and 1.2. All simulations are carried out using GT-SUITE.

The result shows the effects of driving aggressiveness and how it can be analyzed based on the sensitivity of energy consumption to different driving styles. The energy consumption sensitivity trends are explained in relation to energy losses and energy recovered by regenerative braking.

The main findings of this work are that the relation between the energy consumption sensitivity for the drive cycles are linear. HWY has the highest energy consumption sensitivity and UDDS the lowest when modifying the velocity. When modifying the acceleration UDDS has the highest energy consumption sensitivity and HWY has the lowest. It is shown that driving aggressiveness has a great impact on the energy consumption and its sensitivity. The main conclusion is that simulations can predict the energy consumption considered given drive cycles and driving aggressiveness.

Keywords: Lithion Ion battery, Energy Consumption, Battery Electric Vehicle model, Drive cycle, Driving aggressiveness, Electric Vehicle simulation, GT-SUITE, GT-AutoLion

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Emma Berglund, Gothenburg, 2019

Contents

Nomenclature

α Angle of road grade (°)

ρ Density of air ($1.2kg/m^3$)

σ Mass correction factor

a Vehicle acceleration (m/s^2)

A_F Frontal area of the vehicle (m^2)

BEV Battery Electric Vehicle

C_D Coefficient of drag

C_r Coefficient of rolling resistance

C_{rated} Rated capacity

EV Electric Vehicle

F_{TR} Tractive Force (W)

g Gravitational acceleration ($9.81m/s^2$)

GHG Greenhouse Gas

HWY Drive cycle based on Highway driving

I_b Battery current (A)

I_{loss} Current consumed by the losses (A)

$LA92$ Drive cycle based on Los Angeles driving in 1992

$Li-Ion$ Lithium-Ion

$LiFePO4$ Lithium-Ion Phosphate

M Vehicle mass (kg)

$NEDC$ New European Drive Cycle

P Tractive power (kW)

S Sensitivity

SOC State Of Charge (%)

t Time (seconds)

$UDDS$ Urban Dynamometer Driving Schedule

v Vehicle speed (m/s)

W_{wheel} Wheel Work (Wh/km)

$WLTC$ Worldwide harmonized Light vehicle Test Cycle

1 Introduction

1.1 Background

Transportation is a significant source of greenhouse gases (GHG) and air pollution. Emissions from vehicles have direct and indirect implications on the environment and human health. It is stated that emissions from the transport sector are not reducing fast enough to limit their climate impacts. A solution to this would be to increase the use of different types of electric vehicles (EVs). Combining EVs with renewable energy can provide sustainable transport technologies that help reducing GHG emissions, air pollution and health risks. If the electricity instead is generated from non-renewable sources, the emissions may not be reduced in the end. Therefore, we should aim for zero emissions when electrified vehicles operate and use only electricity generated by renewable sources. [1, 2]

Electro-mobility is a growing market that puts a lot of focus on development and research. Beside the environmental aspects, other parameters, like economics and quality, are important to expand. All parts of the propulsion system can be investigated; the battery is an example of a subsystem that has great potential to be improved. Another aspect that needs to be considered is the testing method. Going from traditional methods, like test rigs, to virtual methods will decrease development time and costs.

Automation and mobility have important roles and functions in our communities. As these areas increase and expand, higher demands are placed on the associated industry. By adding more resources to development in earlier stages of the process, a higher degree of complexity regarding modern power trains can be managed. The emphasis is on optimization and cost reduction without having to compromise on safety and quality.

1.2 Motivation and Objectives

Combining electric vehicles (EVs) with renewable energy can provide sustainable transport technologies that help reduce GHG emissions and air pollution. Automotive industry and battery manufacturers are facing great challenges to develop future vehicles. By employing a model based approach and virtual testing, a high degree of powertrain complexity can be handled at decreased time and costs. It is highly beneficial to have a common simulation tool that can be employed at different stages of development and testing.

The main objective of this thesis is to analyze the effects of driving styles and aggressiveness on electrical vehicle energy usage. This will be done by using vehicle simulations to study the sensitivity of energy consumption to driving aggressiveness. Lithium-Ion battery cells and pack will be modeled using the computational platform GT-AutoLion. The battery pack will then be integrated into an electric vehicle modeled in GT-SUITE. System-level simulations for different drive cycles will be computed and analyzed.

1.3 Overview

This report is divided in different chapters where the first one gives an introduction and an overview of the project. Chapter 2 introduces the theory important for understanding the implementation and simulations made in the project. Some sections are fairly brief and they describe techniques that are already implemented in the model and thus it is not a main part of the project. For more detailed information about the theory behind, use the referred sources. The method is introduced in chapter 3 where design steps in GT-AutoLion and GT-SUITE are described. This chapter also includes graphs to visually understand valuable steps towards the main result. The results from the simulations in GT-SUITE with additional graphs made in MATLAB from extracted values are presented in chapter 4. Finally, discussion and conclusion are presented in chapter 5 together with suggestions on improvements and future work.

2 Theory

2.1 Electric Vehicles

2.1.1 Challenges

A Battery Electric Vehicle (BEV) is a vehicle that runs on electricity only, powered by a battery pack and an electric motor. BEVs face important technological challenges as high initial costs, limited lifetime and relatively poor performance at low temperatures.[3, 4, 5, 6] The battery pack is the most expensive component which makes long-term research of battery technology very important.[7] The lifetime of the battery pack is often reduced due to the high power demand profile during acceleration and braking. By analyzing the effect of different drive cycles and driving behavior, the energy consumption can be related to the wheel work of the vehicle and explained by energy losses and regenerative braking.

In addition to the technical challenges, there also exists social concerns regarding vehicle range and charging time. The biggest fear is that BEVs would have inadequate range or not being suitable because of unplanned trips.[8, 9] The battery recharging time for a BEV takes hours compared to a gas tank that only takes minutes to refill. It is not enough even though it exist quick charging stations that can reduce the recharging time to 20 minutes for 80% of the battery capacity. The customers want convenience, leading to demands for large-scale installations of charging stations. [9]

2.1.2 Virtual Testing

Model-based approach and virtual testing takes a big part of the vehicle industry today. The main reason and goal is to shorten the product development in order to save time and money. It has been estimated that the use of model-based designs in the development and validation process reduce the production costs by approximately 40-60 %.[10]

Furthermore, virtual testing can address increased level of complexity which simplifies addressing difficulties. The challenge is to increase the accuracy while reducing the time and costs.

In system-level modeling the method is to divide the model into different levels. These are; vehicle level, subsystem level and component level. The levels are detailed differently and are based on each other. A simple illustration of this is shown in figure 2.1.

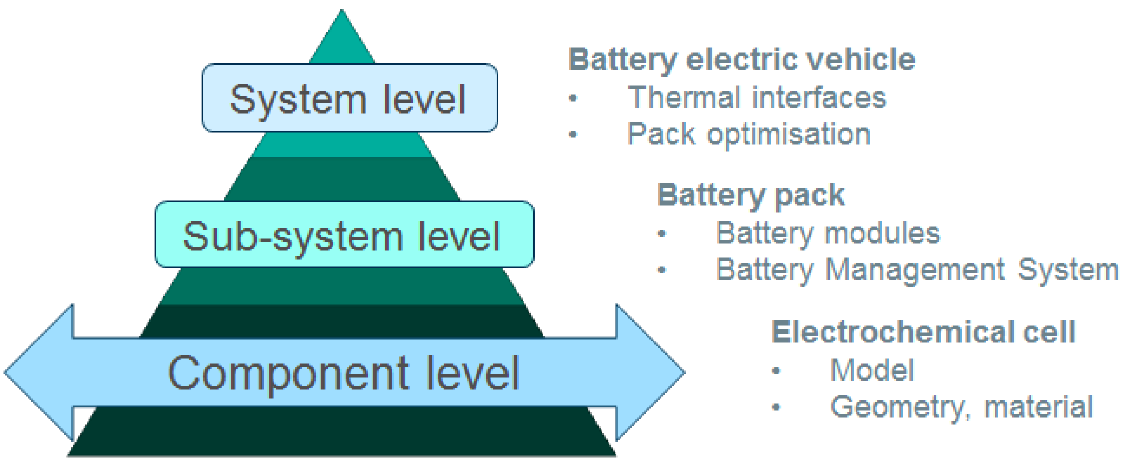

Figure 2.1: *System-level modeling of a Battery Electric Vehicle.*

2.2 Lithium-Ion Battery

A battery is an energy storage device that convert chemical energy into electrical energy by electrochemical reactions. Rechargeable Lithium-Ion batteries dominate the battery market within the industry of electrical vehicles. The reason is the combination of high energy density, high power density and its long-span life compared to other battery technologies such as Lead-Acid and Nickel among others.[11, 12]

Despite its advantages, Litium-Ion batteries still have short life spans and high market costs. Different chemistries of lithium-Ion batteries have been developed, each having both pros and cons, where Lithium-Ion Phosphate (LiFePO4) are considered to be one of the most valuable. This is due to their high energy density, long lifetime, lack of memory effect, lower self-discharge and greater amount of life cycles.[13]

The most important parameters when choosing anode material are efficiency, high capacity, stability, conductivity and low cost. The choice of cathode material is based on chemical stability over time and its voltage. The final cell voltage is based on the property of the materials and their potentials. The capacity of the cell is determined by the amount of active materials. The most common combination used in Li-Ion batteries is graphite for anode material and LiFePO4 as cathode material.[14]

2.2.1 Other Chemistries

Common battery chemistries are Lead-Acid, Nickel and Lithium-Ion. The major advantage with Lead-Acid is its low cost compared to other chemistries. The main disadvantages are its heavy weight, limited life cycle and self discharge.[15, 16] Nickel has the most stable performance over time and it is commonly used in BEVs because of its safety and power density.[17] However, the fluctuating price and its low energy density makes it less reliable compared to Lithium-Ion.[18, 19]

Lithium-Ion batteries have higher specific energy than Lead-Acid and Nickel as can be seen in table 2.1. Specific energy refers to the amount of energy stored per unit mass and energy density is defined as the amount of energy stored per unit volume. These parameters are used to explain the energy storage ability of the battery.[20, 21]

Figure 2.2 shows the energy density versus specific energy for different types of battery chemistries. As can be seen, Li-Ion has higher energy density and higher specific energy than both Lead-Acid and Nickel.

Table 2.1: Specific energy for battery chemistries.

Battery type	Lead-Acid	Nickel	Lithium-Ion
Typical specific energy (Wh/kg)	40	60-90	110-170

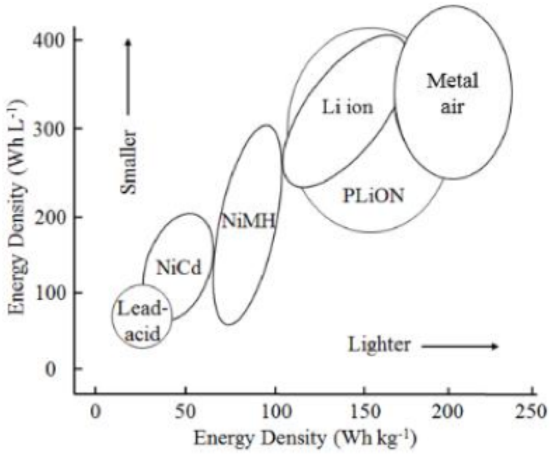

Figure 2.2: *Different battery chemistries in terms of energy density.[22]*

2.2.2 Cell Structure and Operation

A battery cell consists of five main elements; anode electrode, cathode electrode, current collector, electrolyte and an electrically insulating separator. The anode is a negative composite electrode and cathode a positive composite electrode and these serves as hosts for lithium-ion transport. During discharge, Li-ion travel from the anode through the electrolyte to reach the cathode. Electrons (current) are unable to go through the electrolyte and are thus discharged and return through the positive terminal instead. The electrons and Li-Ion are moving in reverse directions during charging. A graphical representation of a Li-Ion cell can be seen in figure 2.3.

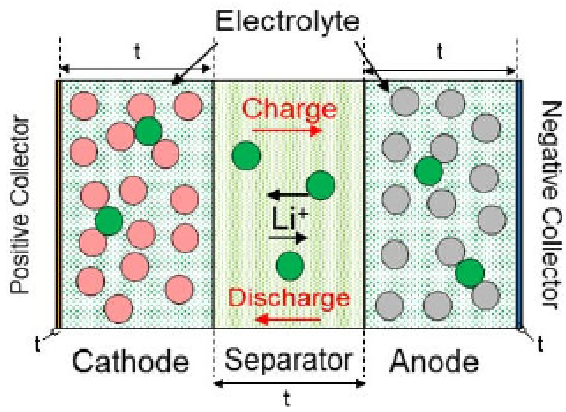

Figure 2.3: *A Lithium-Ion cell.[23]*

A Lithium-Ion cell can be constructed in four different types of packaging; cylindrical, pouch, coin and prismatic. All of them are illustrated in figure 2.4. The main types used in electrical vehicles are cylindrical and pouch. The parameters behind the choice are space, performance and operation conditions.[22]

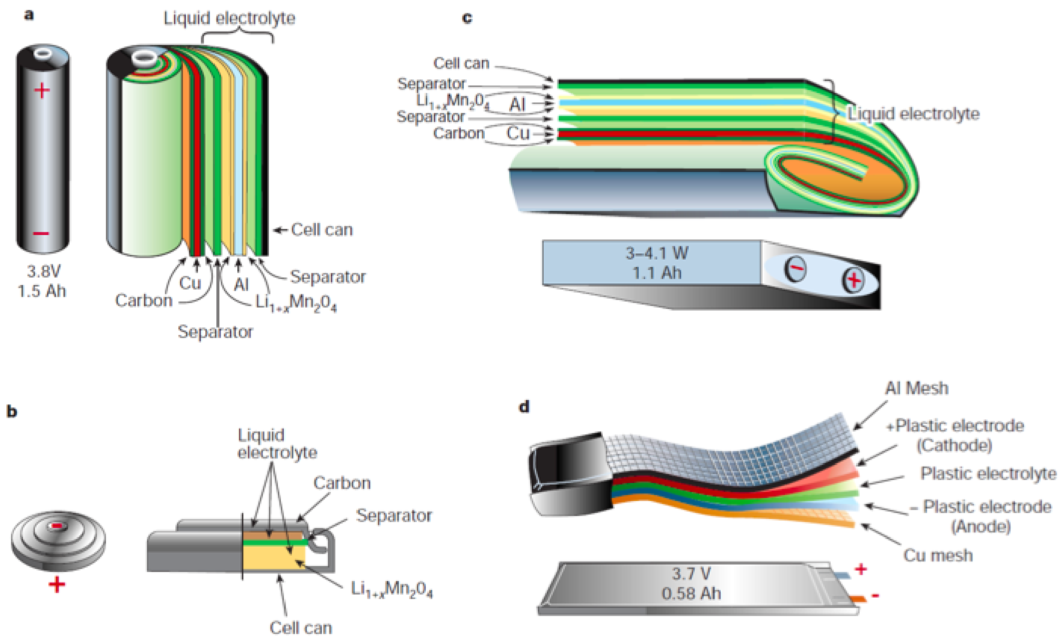

Figure 2.4: *Illustration of a) cylindrical, b) coin, c) prismatic and d) pouch packaging.[22]*

2.2.3 Battery Pack

A battery pack consists of modules created by battery cells connected in series and/or parallel in order to achieve a certain amount of capacity and voltage. Voltage and resistance increases in a series connection and a parallel connection accumulate the energy and power. The configuration and the amount of cells are based on the application needs for the battery pack. The benefit of using a pack system is that modules can be removed and replaced easily in case of damage. In BEVs it is common to have more than 100 cells in series to get the desired voltage of around 300-400 V.[24]

2.2.4 State of Charge

State of Charge (SOC) is defined as the remaining charge stored in a battery as a percentage of the amount that can be stored when it is fully charged. It is hard to accurately determine the SOC but it is commonly estimated using one of following three methods; Coulomb counting, Voltage method and Kalman filter method. The Coulomb counting method is used in GT-SUITE.

Coulomb counting is a method that measure the coulombs and current flowing in and out of the cell during all operation conditions. The battery current is integrated over the usage period where the SOC is calculated as

$$SOC = SOC(t_0) + \frac{1}{C_{rated}} \int_{t_0}^{t_0+\tau} (I_b - I_{loss})dt \qquad (2.1)$$

Where $SOC(t_0)$ is the initial SOC, C_{rated} is the rated capacity, I_b is the battery current and I_{loss} is the current consumed by the losses.[25]

2.3 Drive Cycle

A drive cycle is a speed-time trace used for evaluation and legislation of vehicle performance. Drive cycles are often based on real-world driving and provide a common test procedure to reduce the need of expensive on-road testing. There exist many standard drive cycles, both developed theoretically and as measurements of a real drive pattern.

Table 2.2 present the key characteristics of the drive cycles used in this thesis; HWY, UDDS, NEDC, WLTC and LA92. The abbreviations stand for Highway, Urban Dynamometer Driving Schedule, New European Drive Cycle, Worldwide harmonized Light vehicles Test Cycle and Los Angeles 1992. They are explained further in the method section.

Table 2.2: Drive cycle characteristics.

Drive cycle	HWY	UDDS	WLTC	NEDC	LA92
Total time [s]	765	1369	1800	1180	1435
Total Distance [km]	16.5	12.0	23.3	10.9	15.5
Avg. Speed [km/h]	77.5	31.5	46.5	18.9	32.7
Max. speed [km/h]	96.3	91.2	56.5/76.6	33.9	107.2
Max. acc. [km/h]	1.4	1.6	1.6	0.8	5.1

2.4 Vehicle Dynamics

2.4.1 Tractive Force

Tractive force is the force required at the wheels during driving. It is calculated by summing the force required due to rolling resistance, aerodynamic resistance, grade resistance and inertia, i.e.

$$F_{TR} = (C_r M g) + (\frac{C_D A_F v^2 \rho}{2}) + (M g sin\alpha) + (M \sigma a) \tag{2.2}$$

where, in the first term, C_r is the rolling resistance coefficient, M is the vehicle mass and g is the gravitational acceleration. The second term is for aerodynamic resistance where C_D is the drag coefficient, A_F is the frontal area of the vehicle, v is vehicle speed and ρ is density of air. The third term represents grade resistance where α is the road angle and sin α is the grade. The last term is for inertia where σ is a mass correction factor that accounts for that 4 rotating wheels must be accelerated both angular and linearly. σ is assumed to be constant at 1.04 and a is the vehicle acceleration. The simulations in this thesis will have no grade so that term will not be included. The values of the required parameters for estimating the tractive force have been selected from the GT-SUITE library for a typical passenger vehicle.

2.4.2 Tractive Power

Tractive power is the tractive force times the vehicle speed. The average positive power is the mean of tractive power when tractive power is positive, defined as

$$\bar{P} = \frac{\int (P)^{P>0} dt}{\int t^{P>0} dt} \tag{2.3}$$

where P is the power and t is the time.

2.4.3 Wheel Work

Wheel work is the positive energy required at the wheels expressed per unit distance. Wheel work is calculated by dividing the total positive tractive power by the total distance traveled as

$$W_{wheel} = \frac{\int (P)^{P>0} dt}{\int v dt}. \tag{2.4}$$

2.4.4 Regenerative Braking

Regenerative braking is a recovery mechanism in which kinetic energy converts to electric energy during braking.[26] When braking, the electric machine supplies the battery with a current which enables recharging during driving.[27] Regenerative braking is used to store energy otherwise dissipated in the form of heat when braking in both hybrids and electric vehicles. This is advantageous in city driving with lots of start-and-stops.

2.5 GT-SUITE and GT-AutoLion

GT-SUITE is a leading vehicle and powertrain simulation software developed by Gamma Technologies. It offers fast concept design to detailed system or sub-system/component design and analyses. GT-SUITE is a multi-physics platform based on a number of fundamental libraries, such as Flow, Thermal, Mechanical, Electrical and Chemistry among others.

The simulations made in GT-SUITE are viewed in a graphical interface called GT-POST. Except presenting the results, GT-POST enables various math operations and allows both the import and export of data. The interface gives the user many options, such as cross-plotting results from different simulations.

GT-AutoLion is a tool for physics-based modeling and design of Lithium Ion cells, capable of predicting how variations in material design, electrode design, and cell design can affect cell performance and life characteristics. If battery testing equipment is limited to a certain range of temperature, current or power, GT-AutoLion can be used to virtually test a cell outside of the given range. Additionally, because GT-AutoLion models can run much faster than real-time, they can be used to virtually test and expedite the testing of Lithium-Ion battery aging, giving predictive capacity fade and resistance growth much faster than physical testing.

GT-AutoLion is a very useful tool for predicting performance and degradation of a Li Ion cell or battery given any set of loading conditions. GT-AutoLion provide the user with a workflow to well calibrated models that are an accurate reflection of the physical cells, only requiring the information found on a typical cell specification sheet.

3 Method

3.1 Electric Vehicle Model

The vehicle simulations are carried out using the software GT-SUITE and GT-AutoLion. The model of the electrical vehicle used in GT-SUITE is shown in figure 3.1 where different subsystems can be seen. The battery pack model is integrated from GT-AutoLion where the design of the battery pack and cells are made. One of the inputs to the driver subsystem is to choose a drive cycle that will decide the drive style. There exists a library of different drive cycles to choose from with speed traces that represent several drive styles. It is also possible to implement a modified speed trace. The remaining subsystems and their settings are as in the original EV model.

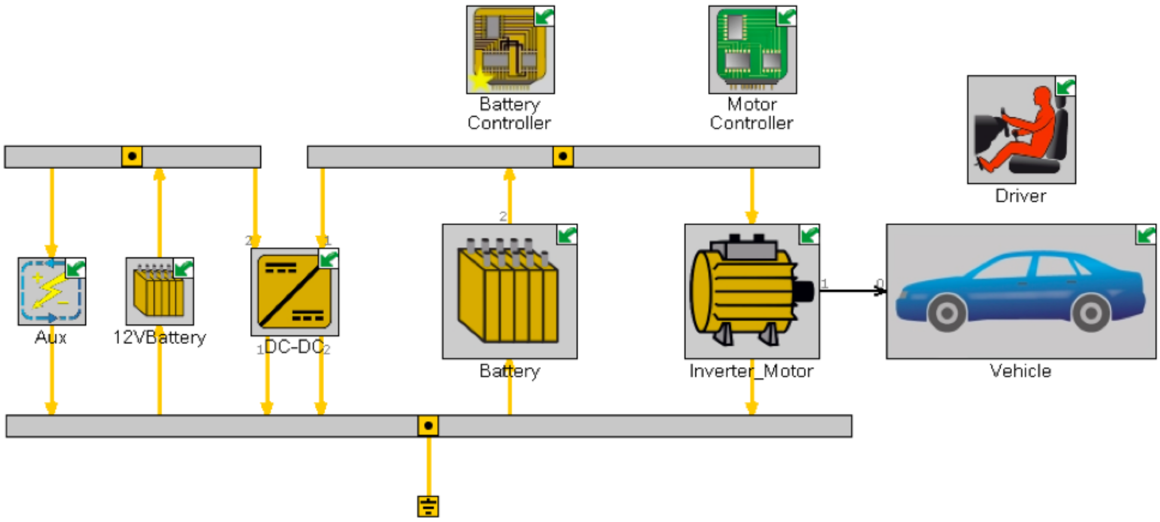

Figure 3.1: *Model of Battery Electric Vehicle in GT-SUITE.*

3.2 Battery Design

The battery cell chosen is a Nanophosphate Lithium Ion Prismatic Pouch Cell from the company A123 Systems, see Figure 3.2. The reason for choosing this battery is to represent what is used in the industry today and because of its benefits; high usable energy over a wide state of charge (SOC) range and very low cost per Watt-hour. The parameters for the cell has been taken from the cell specification which can be seen in table 3.1.

Figure 3.2: *Nanophosphate Lithium Ion Pristmatic Pouch cell AMP20 from A123 Systems.[28]*

Table 3.1: Cell specification for AMP20, A Lithium Ion cell from A123 Systems.[28]

AMP20 Cell Specifications	
Cell Dimensions (mm)	7.25 x 160 x 227
Cell Weight (g)	496
Cell Capacity (minimum, Ah)	19.6
Energy Content (nominal, Wh)	65
Discharge Power (nominal, W)	1200
Voltage (nominal, V)	3.3
Specific Power (nominal, W/kg)	2400
Specific Energy (nominal, Wh/kg)	131
Energy Density (nominal, Wh/L)	247
Operating Temperature	-30°C to 55°C
Storage Temperature	-40°C to 60°C

The dimensions, weight and capacity are taken from the cell specification and GT-AutoLion calculates the number of cathode and anode plates as well as the total coated area of the cathode and anode. In order to get the cell capacity right (20Ah), the loaded capacity for the cathode needed to be tuned. This calibration was done manually by making adjustments in the settings to get the design report to correspond to the specification. By making this one parameter at a time, the impact on the capacity could be determined and analyzed. A part of the design report can be seen in table 3.2.
.

Table 3.2: A part of the design report in AutoLion.

Cell Surface Area (cm^2)	782.52
Cell Volume (cm^3)	263.32
Cell Weight (g)	496.0
Cell Capacity (Ah)	19.9902

The battery cell is then implemented into the electrical vehicle model in GT-SUITE where a battery pack is created by choosing the amount of cells in series and parallel. The battery pack created has 126 cells in series and 5 in parallel. Some of the simulations required greater battery capacity where the battery pack was increased by having 9 modules in parallel.

3.3 Drive Cycles

Five drive cycles was chosen with different driving behaviour that are presented in table 2.2 in the theory section. Those are Highway (HWY), Urban Dynamometer Driving Schedule (UDDS), Worldwide harmonized Light vehicles Test Cycle (WLTC), New European Drive Cycle (NEDC) and Los Angeles 1992 (LA92). Highway driving represent free-flow traffic at highways with high average speed. Urban driving is city driving with frequent stops with low average speed and low acceleration. Los Angeles is low speed stop-and-go traffic conditions. The worldwide cycle represents one average vehicle journey consisting of four parts with low, medium, high and extra high speed. The European drive cycle is a synthetic drive cycle that also consists of four different parts and it is an older version that has been replaced by WLTC.

All drive cycles have different drive behaviours and the speed trace for WLTC can be seen in figure 3.3. One can see that WLTC both contains low and high speed parts as well as starts and stops. The speed traces for the other drive cycles can be found in appendix.

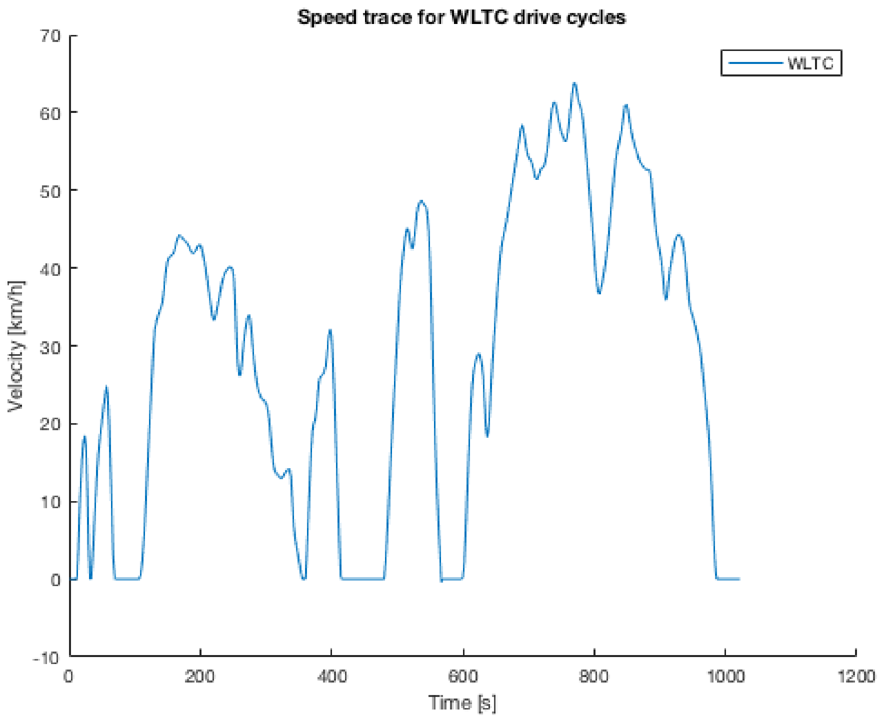

Figure 3.3: *Speed trace of drive cycle WLTC.*

3.3.1 Driving Aggressiveness

Driving aggressiveness is modelled by scaling the velocity and the acceleration of the speed traces. The velocity scaling was made by multiplying both speed and time vectors by a scaling factor. Figure 3.4 shows WLTC when the velocity is scaled. It can be seen that both time duration and distance of the cycle will change. When the velocity increases, so do the time and distance of the cycle. This happens in order to maintain the same acceleration which can be noted; the acceleration stays unchanged. This means that it is the same accelerations that occurs at higher speeds. In figure 3.5, the acceleration modified cycles for WLTC can be seen. Here, the velocity remains the same and the acceleration is scaled by modifying the time. This means shorter time gives higher accelerations and one can see that velocities remain the same but time and distance last longer when modifying the acceleration. The graphs in both figure 3.4 and 3.5 shows the standard trace of WLTC and when scaling with factors of 0.8 and 1.2. During the simulations were five factors used in total; 0.8, 0.9, 1.0, 1.1, and 1.2.

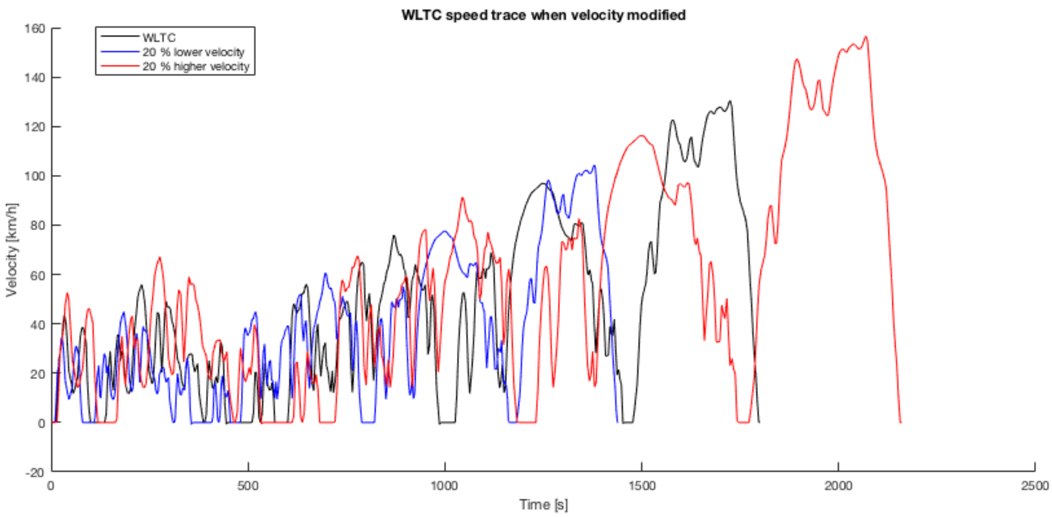

Figure 3.4: *Speed trace of drive cycle WLTC when velocity modified.*

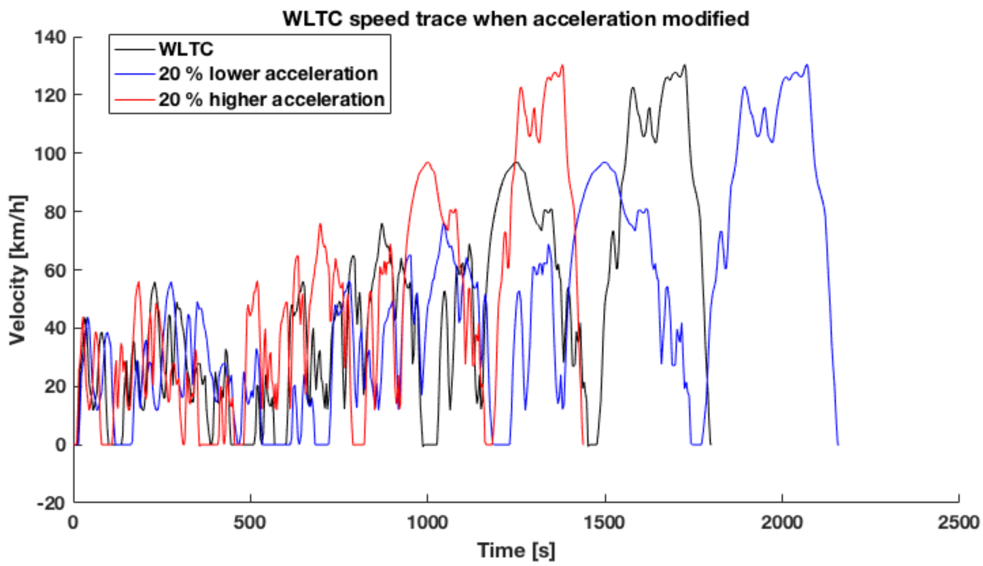

Figure 3.5: *Speed trace of drive cycle WLTC when acceleration modified.*

3.4 Vehicle Simulations

Every drive cycle ended up in nine simulations in order to include both the velocity and acceleration modifying. The traces for speed, time and force were then extracted from GT-SUITE into MATLAB. Parameters for total distance traveled, Open Circuit Voltage and Battery Capacity were also extracted. Two scripts for each drive cycle were created in MATLAB where all the calculations were carried out. The tractive force was calculated according to equation 2.2 and then multiplied with the speed to calculate the tractive power. The average positive power was then calculated as in equation 2.3. The area of the positive tractive power was divided with the total distance traveled according to equation 2.4 in order to get the wheel work. The energy consumption was calculated with the battery capacity and the open-circuit voltage and then expressed in per unit distance.

The wheel work was plotted against the energy consumption, the energy loss and the energy from regenerated braking. All parameters were expressed in the unit Wh/km in order to facilitate the comparison.

3.5 Flow of Project Methodology

The project methodology is presented graphically in a flowchart shown in figure 3.6. The parameters used as inputs to the model are both external inputs from A123 systems and internal inputs from the library in GT-SUITE. The parameters from A123 systems are the cell dimensions, cell weight and cell capacity. The inputs taken from the library of GT-SUITE are the drive cycles; HWY, NEDC, LA92, UDDS and WLTC. The inner-connection between GT-SUITE and GT-POST happens automatically when running the simulations of the model. The values extracted from the simulation results in GT-POST are used as inputs to the MATLAB script where the calculations take place. These values are: total distance traveled, SOC, open circuit voltage, battery capacity, depleted energy, tractive force, current, velocity, time and tractive force. The parameters calculated in MATLAB are tractive power, energy and wheel work. The main equations used can be found in the theory section where equations 2.3 and 2.4 are used in the MATLAB script. Equations 2.1 and 2.2 are built in GT-SUITE and calculated by GT-POST. The outputs from MATLAB are graphs showing the energy usage consumption and sensitivity for the drive cycles when having velocity and acceleration modified. All graphs are presented in the result section.

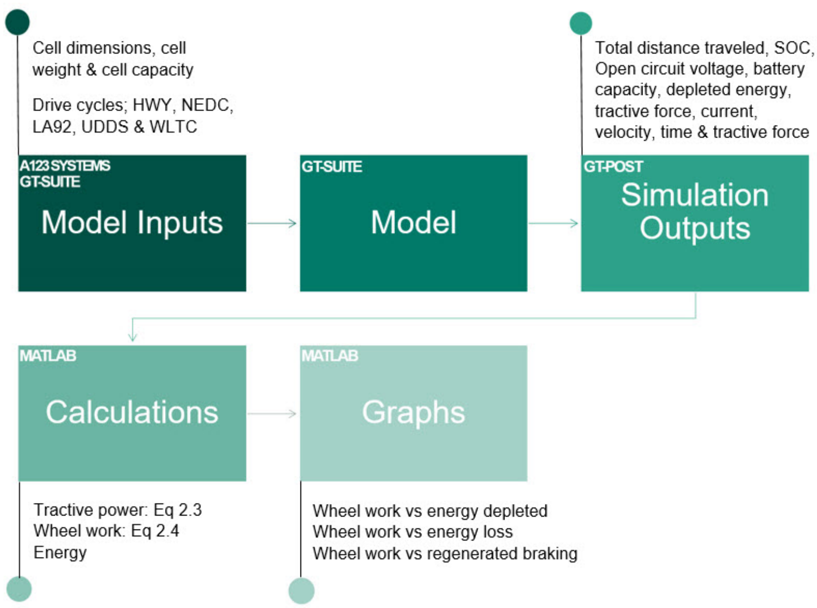

Figure 3.6: *A flowchart of the project methodology.*

4 Result and Discussion

This section present the simulation results for the chosen drive cycles with different driving aggressiveness. All simulations are carried out using GT-SUITE where the values are extracted into MATLAB where the calculations and plotting take place.

Five different drive cycles are used in the simulations to represent a variety of driving styles and traffic conditions. The driving aggressiveness is modeled by modifying the velocity and acceleration of the drive cycles by scaling the speed traces as described in the methodology. The scaling factors used for the modifying are 0.8, 0.9, 1.0, 1.1, and 1.2.

The first set of simulations shows energy consumption in relation to wheel work for all standard drive cycles without any modifying. The results will then be divided into two parts with focus on velocity and acceleration modified speed traces respectively. The focus will be on the energy consumption and the energy losses and the effect of regenerative braking will be investigated to understand the sensitivity trend of the energy consumption better.

Wheel work is the vehicle load in units of energy per unit distance and a parameter that takes average and maximum vehicle speed and accelerations into account. The energy depleted can be expressed in the same units as wheel work which makes it possible to compare the results of the simulated drive cycles. Hence, wheel work is a suitable parameter to use when analyzing the impact of driving aggressiveness on energy consumption sensitivity.[29]

4.1 Energy Consumption

The graph in figure 4.1 shows the wheel work for different drive cycles versus the energy depleted from the battery. The different drive cycles are represented by colored symbols and the sensitivity is shown as a solid black line. One can observe that the sensitivity trend is linear which can be explain by the high efficiency of the electric motor. The high efficiency will generate a similar performance for all drive cycles regardless of the operation point. [30] The most significant difference is between HWY and LA92. HWY has the lowest wheel work and the lowest energy depleted unlike LA92 that has a high amount of energy depleted and wheel work. The reason behind this difference can be seen when comparing their speed traces, found in Appendix A. HWY does not have that big changes in velocity and LA92 consists of a lot of braking as well as starts and stops. The more aggressive way of driving that LA92 shows require more wheel work, which leads to higher energy consumption. The other three drive cycles are closer together in the middle where WLTC have a slightly higher energy consumption than NEDC and UDDS.

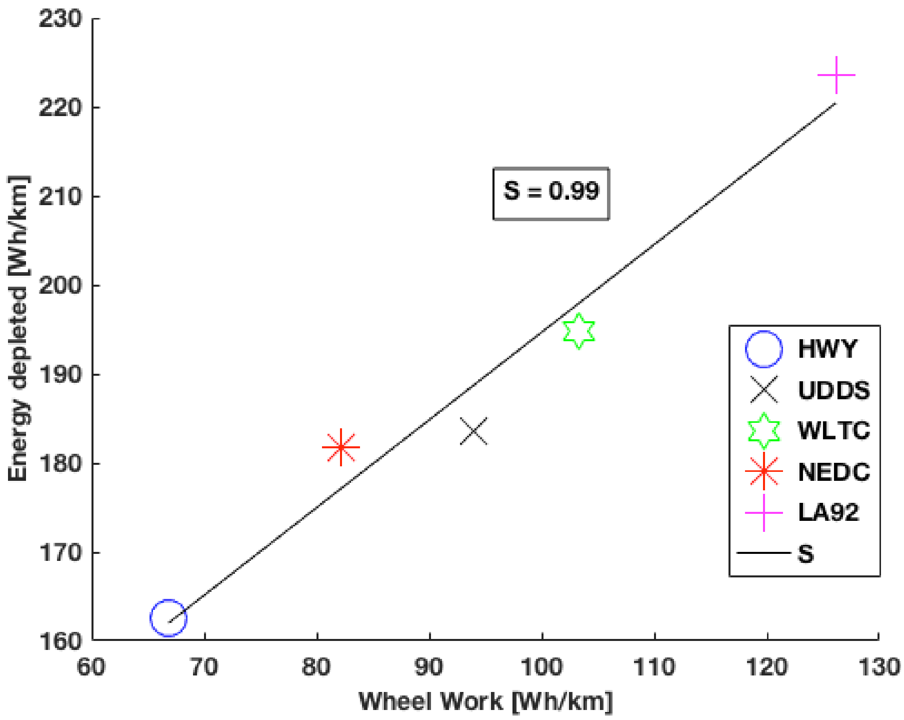

Figure 4.1: *Wheel work versus Energy depleted for different drive cycles.*

4.2 Energy Usage Sensitivity - Velocity Modified

Figure 4.2 shows the wheel work versus the energy depleted for velocity modified drive cycles. The energy consumption sensitivity is represented by the slope of the corresponding straight line for each drive cycle. It can be seen that HWY has the highest sensitivity of $S_{HWY} = 1.55$ which is due to the high velocity. When looking at equation 2.2 for tractive force one can see that the velocity is the most dominated parameter and this will make HWY more sensitive to changes due to its high velocity. This will also shown as HWY having big differences in energy consumption between the different driving aggressiveness points compared to UDDS where the points are more compact. The appearance of UDDS cycle is due to UDDS having a lower average velocity which is also a reason behind UDDS having the lowest energy consumption sensitivity of $S_{UDDS} = 0.98$. The energy consumption sensitivity trend can also be explained by the energy losses and the effect of regenerative braking. Lower energy losses and a higher ability to recover energy will make the drive cycles energy consumption sensitivity lower.

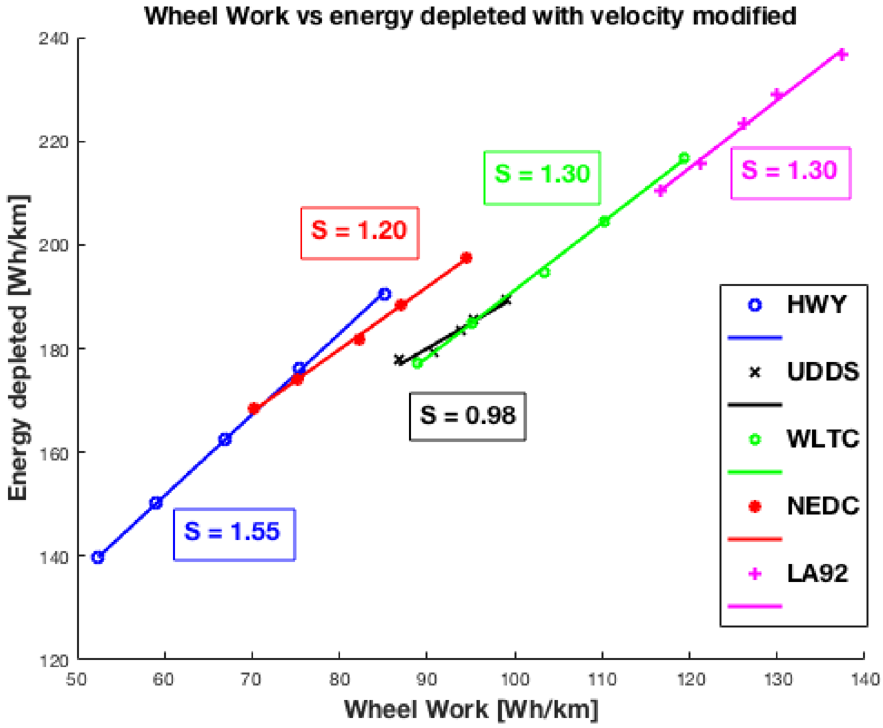

Figure 4.2: *Wheel work versus energy depleted with velocity modified.*

The energy loss plotted against the wheel work can be seen in figure 4.3. It can be observed that HWY has the highest sensitivity of $S_{HWY} = 0.33$ which is a contribution to the high sensitivity for energy depletion shown in figure 4.2. HWY has the highest sensitivity due to its high velocity even though the sensitivity is quite low compared to the ones for energy depletion. UDDS have the lowest sensitivity of $S_{UDDS} = -0.05$ which will decrease the energy consumption sensitivity as we could see in figure 4.2. The energy losses increases for the other drive cycles with increasing vehicle load which will shown as a positive energy consumption sensitivity trend.

The regenerated braking is plotted against the wheel work in figure 4.4. It can be seen that HWY has a low possibility to recover energy by regenerative braking. This can be explained by less braking during the drive cycle. This will contribute to the high energy consumption sensitivity of the HWY cycle. WLTC has a sensitivity of $S_{WLTC} = -0.09$ and is the one with lowest possibility to recover energy among the drive cycles. This due to the WLTC cycle having low braking energy, like the HWY cycle. The most energy are regenerated for UDDS and LA92 which is explained by a lot of braking and their stop and go traffic conditions. This also contributes to UDDS having insignificant energy losses since regenerative braking recharges the battery and with that reduces the amount of energy required and the energy losses. NEDC is the only drive cycle that has a positive trend for energy recovery which could be explained by that it is synthetic and not from real measurements and are working at several constant speeds which will affect the result negatively.

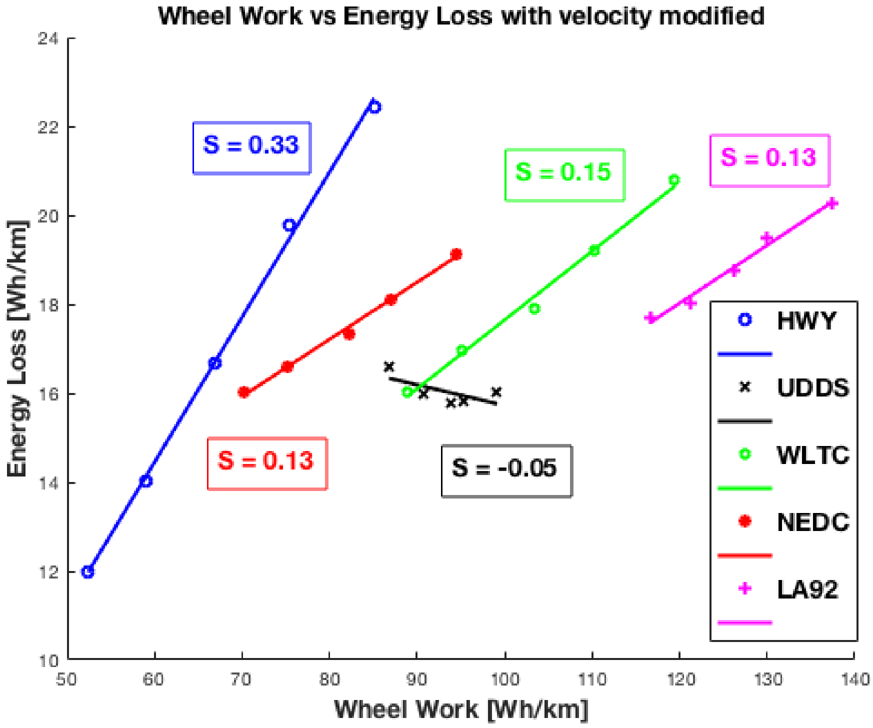

Figure 4.3: *Wheel work versus energy loss with velocity modified.*

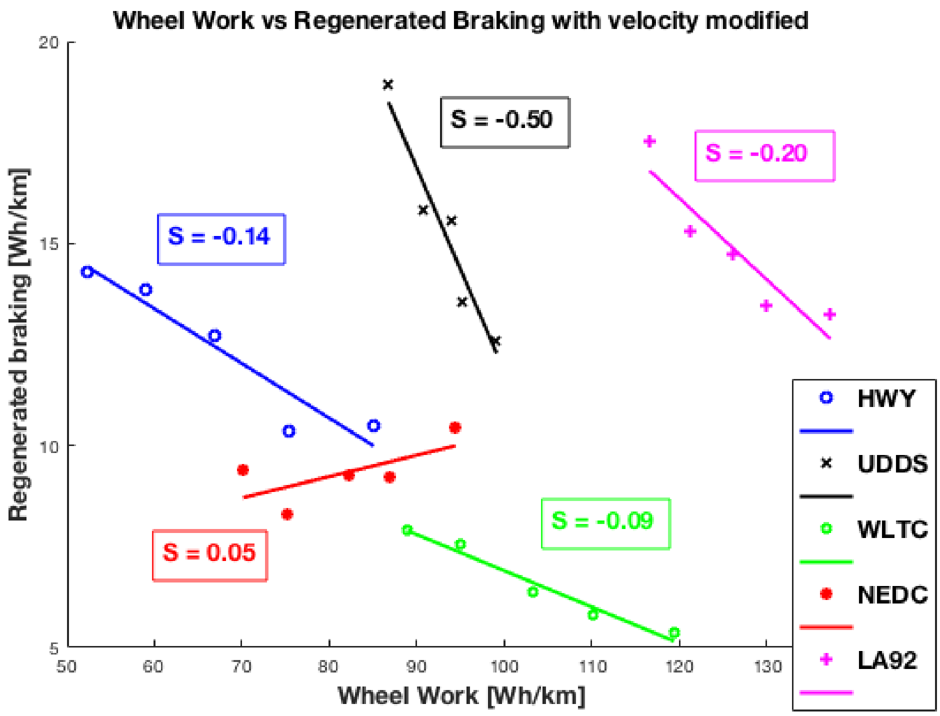

Figure 4.4: *Wheel work versus regenerated braking with velocity modified.*

4.3 Energy Usage Sensitivity - Acceleration Modified

The energy consumption sensitivity for acceleration modified drive cycles are illustrated in figure 4.5. The sensitivity trend does not differ as much as for modified velocities. One can see that UDDS has the highest sensitivity of $S_{UDDS} = 1.16$ and HWY the lowest of $S_{HWY} = 0.82$. WLTC, UDDS and LA92 has roughly the same sensitivity. The energy depleted is lowest for HWY and one can notice that it is not that sensitive to changes in acceleration. HWY has less accelerations than the other drive cycles which will be the main reason behind. LA92 on the other hand has much more accelerations which will show in bigger difference between the different driving aggressiveness. The amount of acceleration in the drive cycles will also correspond to the amount of energy depleted and contribute to the energy consumption sensitivity.

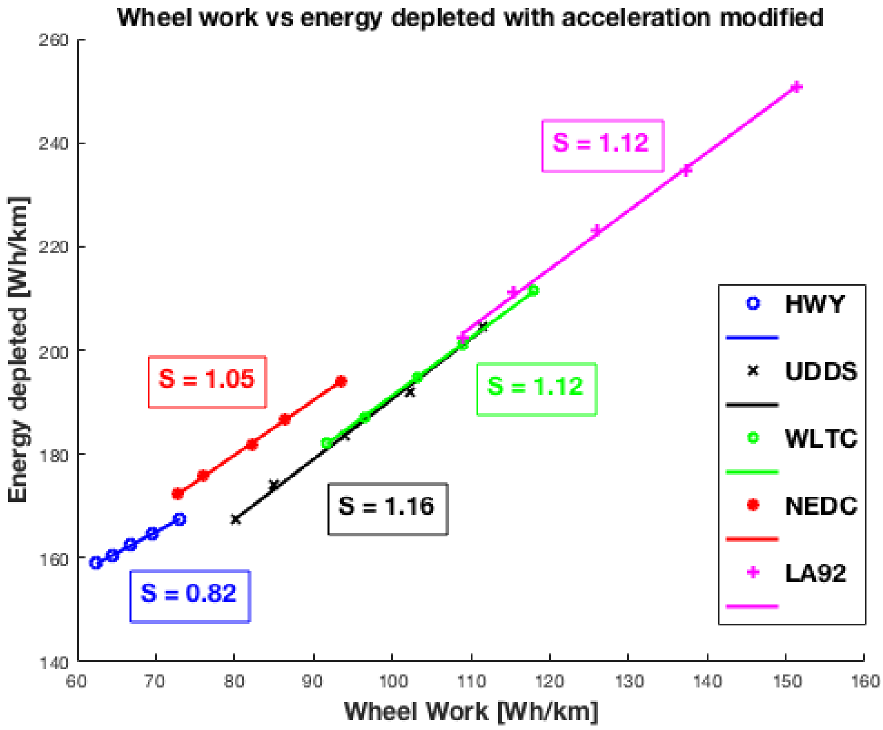

Figure 4.5: *Wheel work versus energy depleted when acceleration modified.*

The energy loss plotted against the wheel work are illustrated in figure 4.6. It can be observed that all cycles are not that sensitive to losses when changing acceleration levels. UDDS have a sensitivity of $S_{UDDS} = 0.072$ which is the highest sensitivity among the drive cycles, even though it is low. This contributes to UDDS having the highest energy consumption sensitivity. It can also be seen that the sensitivity of UDDS is double the value of WLTC which could be the reason for the energy consumption sensitivity of UDDS being slightly higher than for WLTC shown in figure 4.5.

Figure 4.7 shows the regenerative braking for the acceleration modified drive cycles. HWY has the highest sensitivity of regenerated braking which will contribute to its low energy consumption sensitivity. UDDS has the highest possibility to recover energy but has almost zero sensitivity which means that the drive cycle is not affected by the changes in acceleration when it comes to regenerated braking. The same goes along for NEDC, WLTC and LA92 that also has a sensitivity of almost zero. Looking at wheel work instead, it can be seen that more aggressive driving also have an increased vehicle load for all drive cycles, specifically for LA92.

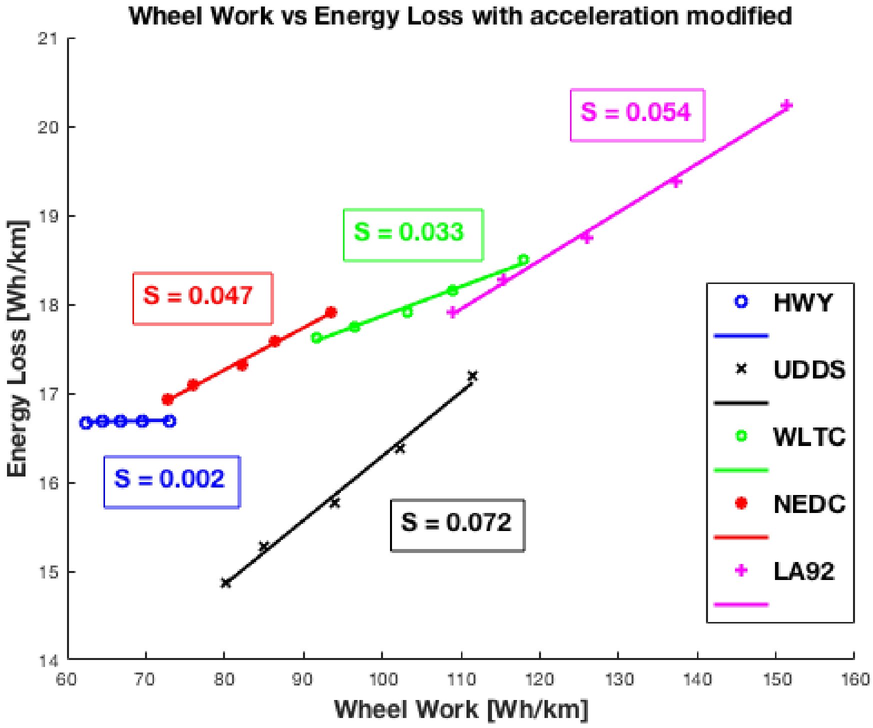

Figure 4.6: *Wheel work versus energy loss with acceleration modified.*

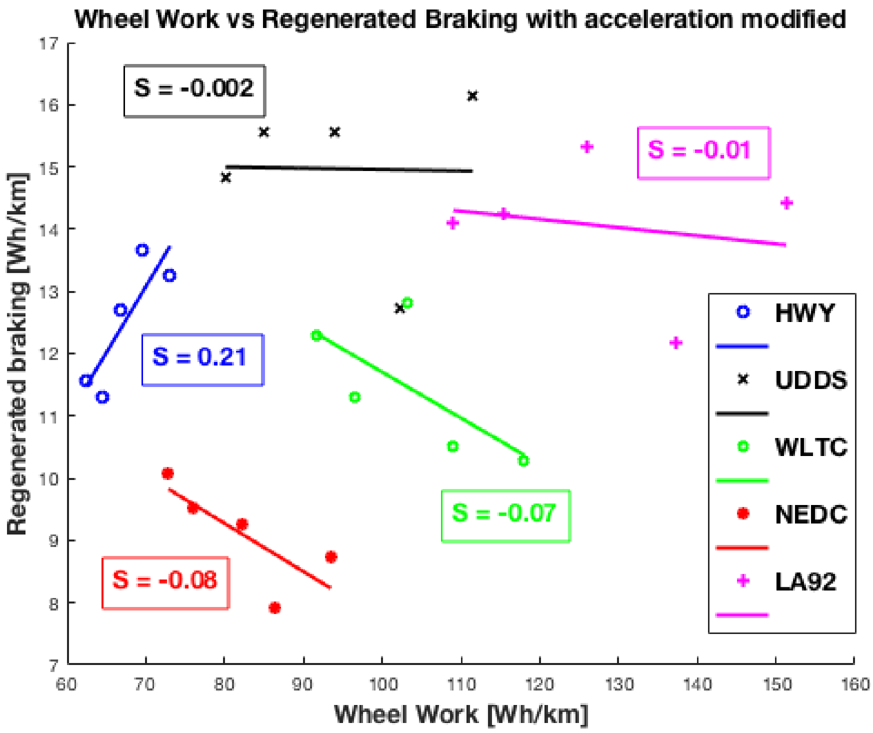

Figure 4.7: *Wheel work versus regenerated braking with acceleration modified.*

5 Conclusion

5.1 Conclusion and Summary

This section summarizes the main conclusions of this work and discusses improvements and possibilities for future work. This thesis has shown the impact of driving aggressiveness on energy consumption sensitivity in an electric vehicle. A battery cell and pack was designed in GT-AutoLion and then implemented into an already existing electric vehicle model in GT-SUITE where the simulations took place. The simulations are made using different drive cycles to represent a range of various traffic conditions. The driving aggressiveness is modelled by scaling the time and speed traces of the drive cycles. This method is used to represent various velocity and acceleration levels.

The aim and motivation behind this work was to strengthen the concept and highlight the benefits of a model based approach and show how a high level of powertrain complexity can be handled. The main objective was to analyze the effects of different drive styles and aggressiveness on electrical vehicle energy usage.

5.2 Key Findings

The primary findings of this work are about the relationship between energy consumption sensitivity of electric vehicles to driving styles and driving aggressiveness. The main conclusions describing the relationship are:

- Energy consumption sensitivity can be explained by examining the wheel work related to energy depletion, energy losses and regenerated braking.

- Wheel work is the energy required at the wheels expressed per unit distance. Depleted energy, energy losses and regenerated energy can all be expressed in the same units which made the comparison between the different simulations possible. Hence, wheel work is a suitable parameter to use for this purpose.

- It is shown that the relation between the energy consumption sensitivity for the different drive cycles are linear. This is explained due to the high efficiency of the electric motor that leads to a similar performance for all drive cycles.

- HWY has the highest energy consumption sensitivity when having the velocity modified. The reason is the high average velocity and that HWY has low possibility to recover energy through regenerated braking and high energy losses. It is shown that HWY is sensitive to changes in driving aggressiveness due to its high velocity.

- UDDS has the lowest energy consumption sensitivity for velocity modified drive cycles. This is due to low average velocity and low sensitivity to energy losses. Another contribution is that UDDS has a high possibility to recover energy which will lower the energy consumption.

- The energy consumption sensitivity was highest for UDDS when modifying the acceleration and lowest for HWY. This was explained in a similar way as for modified velocities where the amount of accelerations in the drive cycles will be the main contribution.

- A more aggressive driving leads to an increased vehicle load for all drive cycles and it is stated that higher driving aggressiveness increases both energy consumption and energy losses.

- High regenerated energy recharges the battery and reduces the amount of energy required at the wheels.

- The aggressiveness have a great impact on the energy depletion and it is important when evaluating the energy consumption.

5.3 Project Achievements

There exists several sources affecting the energy consumption sensitivity and this work focused on driving aggressiveness and explained the effects of energy loss and regenerative braking. This work shows that simulations can predict the energy consumption for an electric vehicle considered given drive cycles and driving aggressiveness.

5.4 Evaluating of Project Steps and Limitations

Originally one of the main objectives was to use real data in the model. The study could then have included some machine learning during the calibration. It would also have made it possible for valuable analysis during comparison with industry. This part was not possible due to lack of data which gave the project another approach. Instead of using data from industry, the simulations were done with values mainly found from GT-SUITE and already establishment drive cycles. These limitation opens up for further work in the subject and possible re-studies.

5.5 Improvements and Future Work

The battery model can be improved by updating the model parameters based on SOC, battery temperature and degradation. One can also achieve a more representative result by considering battery aging.

The project can be developed by using real data instead of standard drive cycles. The results can be compared with measurements and result from similar simulations with a compulsion vehicle or a hybrid. This work can be improved by including more parameters and extend the simulations to get more accurate and realistic results. One approach could be to study the currents and the heat development to see how the temperature in the battery pack is affecting the energy usage.

References

[1] L. A. C. L. X. Li. On the suitability of plug-in hybrid electric vehicle (phev) charging infrastructures based on wind and solar energy. *in Power Energy Society General Meeting, 2009* PES '09. IEEE (2009), pp. 1-8.

[2] Z. Li and A. Khaligh. An integrated parallel synchronous rectifier and bi-directional dc/dc converter system for solar and wind powered hybrid electric vehicle. *in Industrial Electronics* IECON '09. 35th Annual Conference of IEEE (2009), pp. 3779-3784.

[3] O. B. A. Eddahech and J. Vinassa. Real-time soc and soh estimation for ev li-ion cell using online parameters identification. *in Energy Conversion Congress and Exposition (ECCE)* 2012 IEEE (2012), pp. 4501-4505.

[4] S. D. J. Shen and A. Khaligh. An advanced electro-thermal cycle-lifetime estimation model for lifepo4 batteries. *in Transportation Electrification Conference and Expo (ITEC)* 2013 IEEE (2013), pp. 1-6.

[5] Y. Xu. A novel on-line self-learning state-of-charge estimation of battery management system for hybrid electric vehicle. *in Intelligent Vehicles Symposium* 2009 IEEE (2009), pp. 1161-1166.

[6] T. L. A. Hentunen and J. Suomela. Electrical battery model for dynamic simulations of hybrid electric vehicles. *in Vehicle Power and Propulsion Conference (VPPC)* 2011 IEEE (2011), pp. 1-6.

[7] C. Whaling. *Electric drive power electronics: an overview.* URL: `http://electricvehicle.ieee.org/2013/12/02/electric-drive-power-electronics-an-%20overview/`.

[8] U. E. E. et R. V. Helmolt. Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy Environmental Science* **vol. 3**.n %16 (2010), pp. 689-699.

[9] S. Ben. Range Anxiety. *The New York Times* New York (2010).

[10] C. J. Murray. Automakers Opting for Model-Based Design. *Design News* (2010), 5–11.

[11] L. Mandal and R. Cox. A transient-based approach for estimating the electrical parameters of a lithium-ion battery model. *in Energy Conversion Congress and Exposition (ECCE)* 2011 IEEE (2010), 5–11. DOI: `26352640`.

[12] R. Spotnitz. Advanced ev and hev batteries. *in Vehicle Power and Propulsion* 2005 IEEE Conference (2005), pp. 4 pp.

[13] X. Zhang. Fabrication and Electrochemical Characteristics of LiFePO4 Powders for Lithium-Ion Batteries. *KONA Powder and Particle Journal* No.28 (2010).

[14] H. Yiran. Electro-thermal battery model identification for automotive appli- cations. *Journal of Power Sources* (June 2010), pp. 449-457.

[15] D. Edwards and C. Kinney. Advanced lead acid battery designs for hybrid elec- tric vehicles. *in The Sixteenth Annual Battery Conference on Applications and Advances* (2001), pp. 207 –212.

[16] A. Cooper and P. Moseley. Progress in the development of lead-acid batteries for hybrid electric vehicles. *in IEEE Vehicle Power and Propulsion Conference* VPPC (September 2006), pp. 1 –6.

[17] A. B. Battery Association of Japan. *Portable rechargeable batteries (secondary batteries).* URL: `http://www.ba%20j.or.jp/e/knowledge/history03.html`.

[18] C. P. InfoMine. *5 year nickel prices and price charts.* URL: `http://www.infomine.com/`.

[19] H. C. KITCO. *1 year nickel spot chart.* URL: `http://www.kitcometals.com/`.

[20] M. Moshirvaziri. Ultracapacitor/battery hybrid energy storage systems for electric vehicles. *Master's thesis, University of Toronto, Canada* (2012).

[21] K. Yiu. Battery technologies for electric vehicles and other green industrial projects. *in Power Electronics Systems and Applications (PESA)* 2011 4th International Conference on (2011).

[22] J.-M. T. et M. Armand. Issues and challenges facing rechargeable lithium batteries. *Nature* n %1414 (2001), pp. 359-367.

[23] G. Technologies. *Battery Modeling and Simulation.* URL: `https://www.gtisoft.com/gt-suite-applications/integrated-systems/battery-modeling/`.

[24] A. Miller. Technical Service Bulletin - Battery Handling Guidelines. *A123 Systems* Waltham (2013).

[25] Y.-C. Hsieh. Enhanced Coulomb Counting Method for Estimating State-of-Charge and State-of-Health of Lithium-ion Batteries. *Journal of Applied Energy* (2009).

[26] R. G. Jungst. Recycling of electric vehicle batteries. *s.l. : Elsevier Science* (2001).

[27] e. a. Teratani Tatsuo. Energy-saving Technologies for Automobiles. *s.l. : Wiley InterScience* (2007).

[28] a123systems. *Nanophosphate Lithium Ion Prismatic Pouch Cell.* URL: `https://www.buya123products.com/uploads/vipcase/468623916e3ecc5b8a5f3d20825eb98d.pdf`.

[29] B. M. I.. The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles. *MSc Thesis, Massachusetts University of Technology, Boston, USA* (2010).
[30] A. Rousseau. Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity. *SAE Technical Paper* (2007).

A Speed traces for the remaining drive cycles.

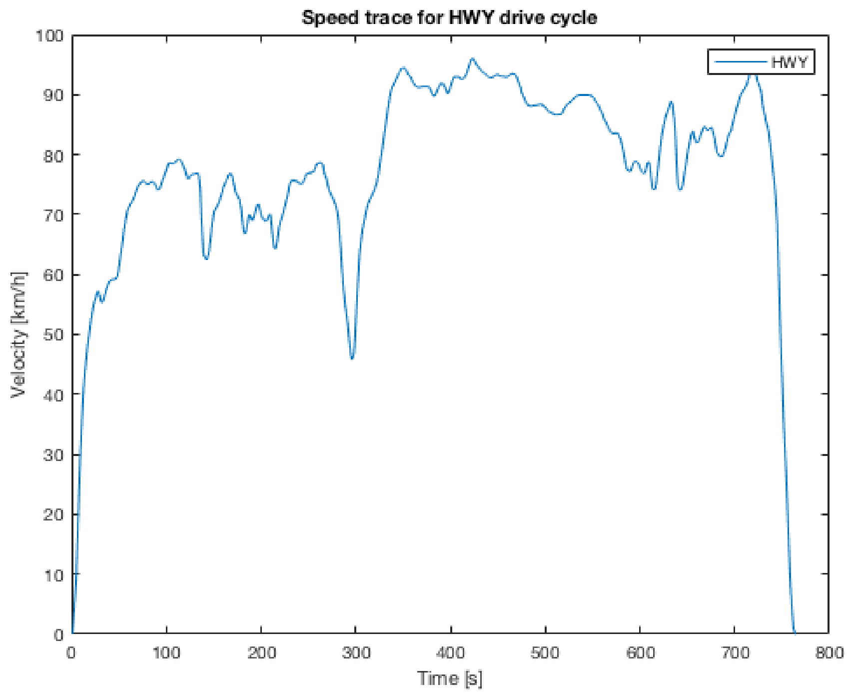

Figure A.1: *Speed trace of drive cycle HWY.*

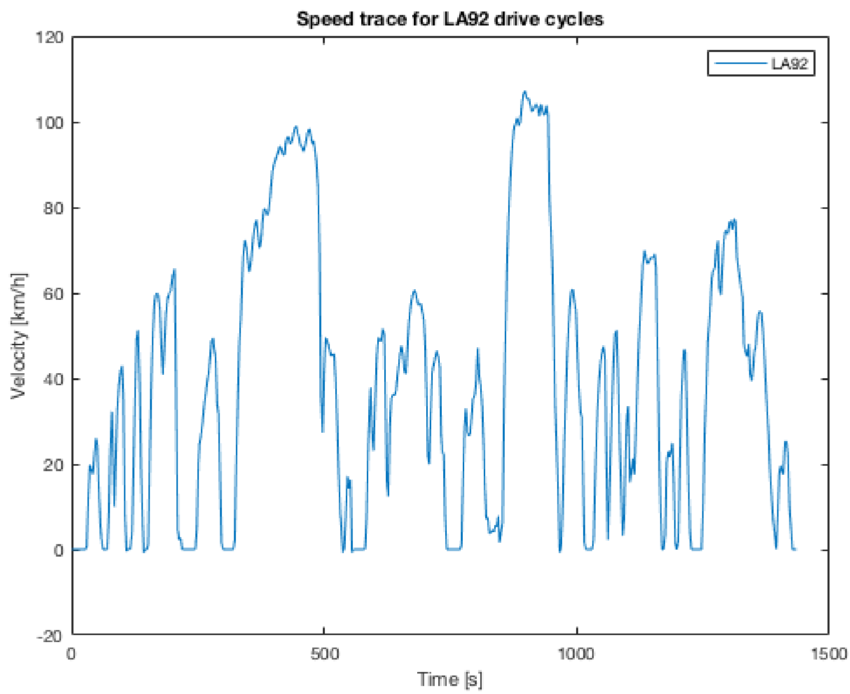

Figure A.2: *Speed trace of drive cycle LA92.*

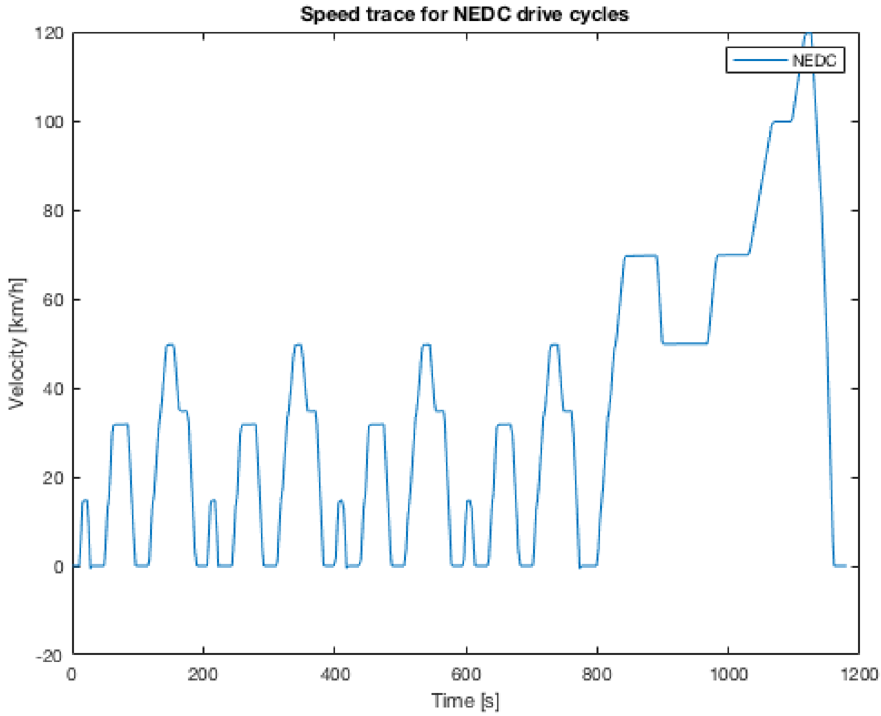

Figure A.3: *Speed trace of drive cycle NEDC.*

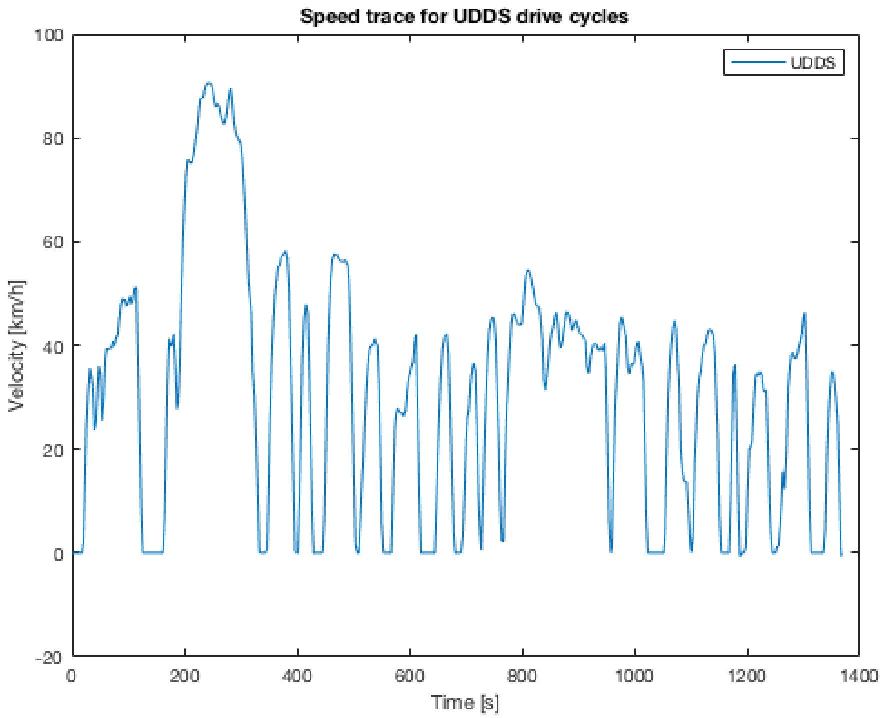

Figure A.4: *Speed trace of drive cycle UDDS.*